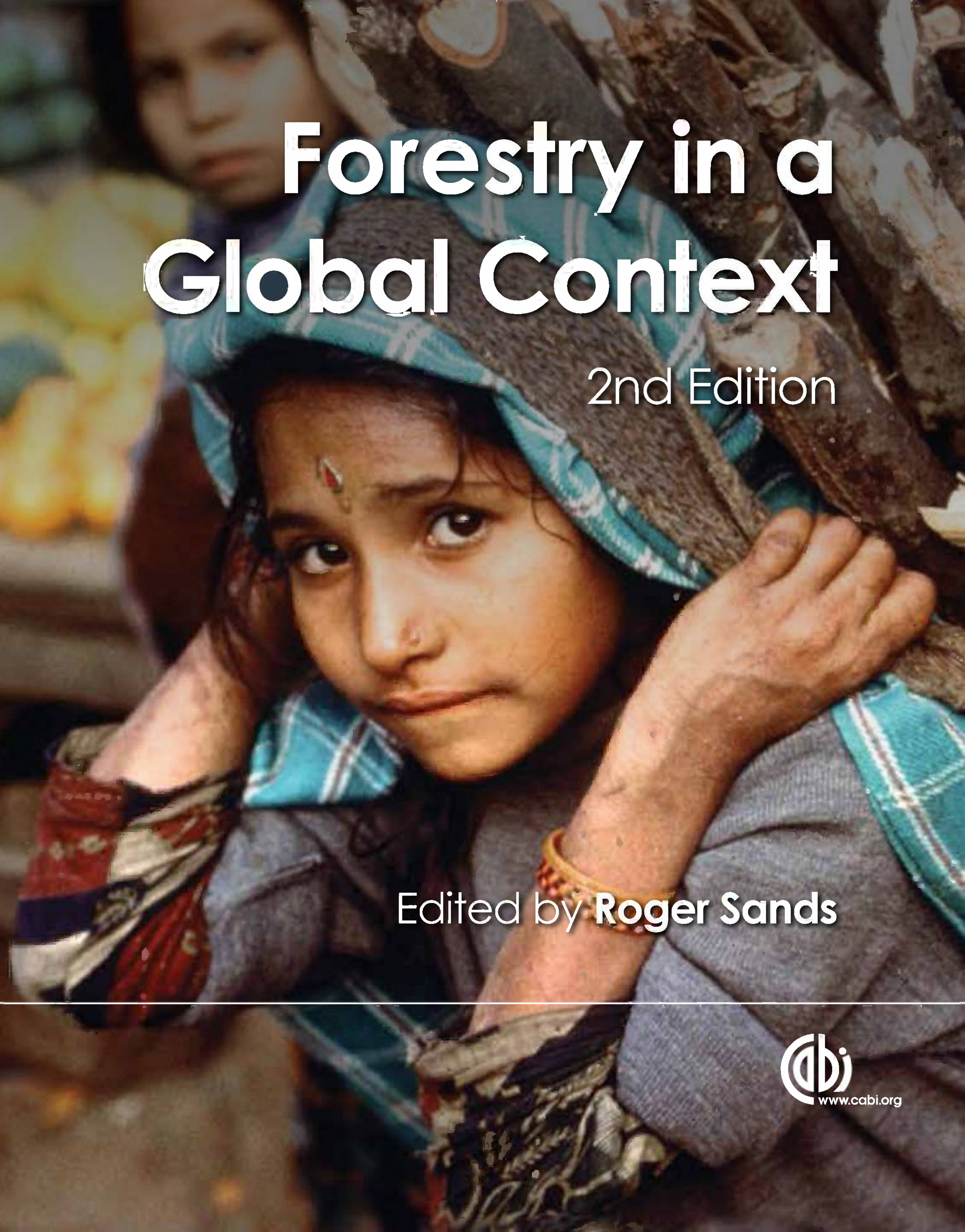

Forestry in a Global Context

2nd Edition

Edited by **Roger Sands**

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Preface

Much has happened in the world of forestry in the 8 years since publication of the first edition. The area of planted forests has greatly increased and its contribution to world roundwood production is probably greater than one half the world total and increasing. Perhaps also the rate of deforestation, although still alarming, is decreasing. Forest certification was relatively small with an uncertain future at the time of the first edition. Now it is well established with a certain future, particularly in temperate forests and in plantations. The use of wood and other lignocellulosic materials to make liquid biofuels is entering commercial viability. There are exciting new engineered wood products. The probability that the world is warming, and largely at the hands of humans, has become even more likely and the role of forest management in either exacerbating or ameliorating this has become more obvious and immediate. Global response to accepting and dealing with global climate change has been spectacularly unsuccessful and disappointing. Despite this, initiatives such as REDD+ have the potential to arrest the rate of tropical deforestation and degradation. Some tropical countries appear to be developing their way out of uncontrolled deforestation. However, much of the tropical developing world, particularly in Africa, is mired in poverty and with associated high levels of deforestation.

Regrettably, sustainable forest management is an ideal rather than a reality in many parts of the world, particularly in tropical forests. It is not difficult to highlight some shocking examples of forest degradation. Even so, there is still cause to be cautiously optimistic about the future. The developed world is growing forests faster than they are cutting them. The amount of forest in protected areas is increasing. There is greater emphasis on forest management for non-timber values. Scientific management is becoming increasingly sophisticated and has delivered real gains. The conservation movement has grown in strength and has greatly influenced forest management. The progress towards sustainable forest management is hampered by socio-economic factors rather than inadequate technology. The continual bickering between parties with alternative points of view on how to look after our forests has not helped.

This book is intended to inform students interested in the interaction between ecology, economy and society. It should also be useful to professionals interested not only in forest management but land management issues in general. Hopefully it will go some way towards dispelling some myths about the role of forests and forest management in society. For example, although counterintuitive to many, industrial timber production is, for the most part, negatively rather than positively correlated with both deforestation and greenhouse gas emissions from forest-related activities. Also, wood has very strong environmental credentials as both a construction material and a fuel.

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1 A History of Human Interaction with Forests

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Forests and Humans Before Agriculture

It is thought that the world was formed about 4500 million years ago and the first primitive life forms appeared about 4000 million years ago. Forests by contrast are relatively recent (about 350 million years ago) but are quite old compared to grasslands (about 25 million years ago) and positively ancient compared to modern human beings as we know them (less than 500,000 years ago). It is interesting to note that dinosaurs are often considered to be evolutionary failures because they became extinct. However, they lasted for 160 million years (70–230 million years ago). Modern humans by contrast have not yet reached 500,000 years and have not stood the test of time as being a viable and enduring species on Earth. Given the propensity of the human race for self destruction and environmental degradation, it is not at all impossible that humans could become quickly extinguished and be scarcely worth a mention over the timescales considered here.

Environmental impacts on plants and animals before humans

The time sequence for the development of forests, grasslands, animals and humans is shown in Table 1.1. For convenience, the developments are boxed into geological periods, but this does not mean that there were sharp and distinct differences across the boundaries. Neither should it be assumed that the process of evolution was smooth and continuous. Rather it was, and is, a process of origin, expansion, maximum diversity and then contraction (Boulter, 2002). There have been a series of mass extinctions followed by sudden accelerations in evolutionary activity. For example, there was a major extinction event about 250 million years ago that wiped out about 95% of all marine species. The development of forests and grasslands before human impact has been shaped by a range of disturbances, including climate change, volcanic activity, changes in the disposition of the land masses, cosmic collisions, changes in sea level and the movement of ice. The land masses have moved about considerably. Within the time period in Table 1.1, two great land masses, Laurasia and Gondwanaland moved together in the Triassic to form the single super-continent Pangea and subsequently parted company, moved around, fragmented and collided, often violently, in the passage to their configuration today. Over the same time period the climate changed from warm to cold to warm to cold, sea levels went up and down, land bridges between land masses came and went, ocean currents changed, large areas of the land masses were periodically covered with ice, meteors collided with the Earth, and wind and water relocated soils. Consequently, the geographic distribution of many plants and animals changed greatly over time.

Gondwanaland (Antarctica, Australia, India, South Africa and South America) started to break up about 130 million years ago at about the same time as the development of angiosperms. As a result, plants that evolved while the land masses were together could be represented in the evolutionary history of all Gondwanal countries, while those that developed after separation could be quite distinctive. For example, *Nothofagus*, *Dacrydium* and *Podocarpus* are present in New Zealand, South America and Australia. *Dacrydium* and *Podocarpus* are conifers whose Triassic ancestors are generally considered to have established across Gondwanaland before it started to split up in the Cretaceous. *Nothofagus* is an angiosperm that

Table 1.1. The development of plants and animals over the last 400 million years with particular reference to forests, grasslands and humans. (Adapted from Calder, 1983; Osborne *et al*., 1996; Futuyama, 1998.)

Geological period	Millions of years ago	Forests and other plants	Animals	Climate	Associated events
Devonian	408–360	Seed ferns	Boned fish Amphibians Life moves on to land	Greenhouse	Mass extinction event (tsunamis) Gondwanaland and Laurasia in collision
Carboniferous	360–286	Forest trees (early gymnosperms, including conifers) Giant lycopsid swamp forests Glossopteris fauna in Gondwanaland	Reptiles Insects	Ice sheets across southern continents Sea level lowers	Gondwanaland and Laurasia continue to collide Coal deposits
Permian	286–245	Gymosperms continue	Warm-blooded reptiles	Warm and dry	Pangea is in place Coal deposits Permian terminal catastrophe (245 million years ago) annihilated most marine species
Triassic	245–208	Conifers, cycads and ferns dominate the vegetation Bennettitales (precursor to angiosperms)	Ancestral dinosaurs	Warm	Norian catastrophe (cosmic impact) extinguished many marine life and reptiles
Jurassic	208–144	Conifers, cycads and ferns dominate the vegetation	Dinosaurs Birds	Warm	Pangea starts to break up Oil formation
Cretaceous	144–66	Angiosperms develop and proliferate	Dinosaurs Marsupials Mammals Pre-primates	Warm Sea level at all-time high at 93 million years ago	Oil formation Cretaceous terminal catastrophe (a cosmic impact) at 67 million years ago extinguishes dinosaurs and most marine animals and plants Gondwanaland breaks up Coal deposits

Tertiary	66–2	Angiosperms largely displace cycads and ginkgo and confine conifers mostly to cool temperate northern latitudes Grasslands develop	Mammals, birds, insects are supreme Grazing animals develop Human evolution through to *Homo habilis*	Warm but a cooling trend Ice in Antarctica Sea level lowers Oscillations in climate Volcanism	Magnetic pole reversals Eocene terminal turnover (37 million years ago)
Quaternary	2–present	Areas of grassland increase at the expense of forests Forest areas expand and contract with the ice ages Human impacts on forest distribution	Human evolution progresses through to modern humans Modern cattle Neanderthals come and go	Cool Successive ice ages Glaciation commences in the northern hemisphere Overall cooling North Africa desertification	Pleistocene overkill Agriculture, civilization, religion Industrial humans, green revolution Space travel and genetic modification Human-induced extinctions of species Human clearing of forests

developed later, while Gondwanaland was splitting up and there is some argument about whether this genus has Gondwanal or Pacific origins. *Eucalyptus* is an angiosperm genus that is almost entirely confined to Australia and it developed relatively recently after New Zealand split from Australia 70 million years ago.

In the northern hemisphere, forests contracted and expanded many times during the multiple recent ice ages of the Pleistocene. Soils and landforms also changed. The glacials were great natural deforestation events of greater magnitude than any anthropogenic (human-induced) deforestation of modern times. The recovery of the forests during the interglacials is testimony to their great resilience. There always remained during the glacials residual vegetation in the warmer areas near to the equator from which re-colonization and further evolution could occur. There was repeated fragmentation and coalescence of this residual vegetation and rates of speciation and extinction were high. The revegetation of bare ground during the interglacials was predominantly by forest rather than other vegetation types. The change in climate was the major factor determining the patterns of re-vegetation, but soil type, competition, migration rate and source of propagules all contributed.

In northern Europe, the pattern of re-vegetation was similar in many respects between interglacials. Iversen (1958) described the sequence of immigration of tree species from the south following the increase in temperature coming out of a glacial as, first, the boreal birch (*Betula*) and pine (*Pinus*) on unleached calcareous soils followed, with further increase in temperature, by a mixed deciduous woodland on soils that had progressed to brown forest soils. As the temperature started to decrease towards the next glacial, the vegetation was replaced by a heath and conifer type and, with further decrease in temperature to the next glacial, by open tundra and steppe on arctic mineral soils. Much of North America was covered by ice in the last glacial. The vegetation patterns in North America today can be divided in very general terms into four based on current climate: a warm dry climate supporting grassland, a cold dry climate producing tundra, a warm wet climate favouring deciduous forest and evergreen rainforest, and a cold wet climate supporting boreal forest. However, the pathway and rate of migration of individual species into these vegetation patterns following colonization of the land exposed from the receding ice was variable and complex, as shown in pollen diagrams from sediment cores (Pielou, 1991). Mannion (1991) and Roberts (1989) reviewed the vegetation changes that occurred during the quaternary ice ages.

Currently, there are about 4000 species of mammals, about 9000 species of birds, about 19,000 species of fish, about 250,000 species of vascular plants, about 1.6 million species of fungi and at least 10 million insect species, most of which are beetles and most of which have not been described and never will be (Rosenzweig, 1995). Table 1.1 features the larger more conspicuous plants and animals. It should be remembered though that fungi and microorganisms have been an integral part of the biota right across this timescale.

In summary, environmental impacts before humans have had a major effect on the nature and location of forests. Recently though, and particularly in the last 10,000 years, humans have shown they also can radically affect the nature, distribution and pattern of forests (by forest clearing, land degradation, firing and species dispersal to mention just a few). Humans now have the technical capacity to create disturbances of similar magnitude and effect to the great mass extinctions of the past and to deforest the planet to the same extent as the Pleistocene ice ages. Hopefully they will not put this to the test.

The development of the forests

The first land plants were bryophytes (liverworts, hornworts and mosses) and these appeared about 425 million years ago. These were followed by vascular plants that were either seedless (such as ferns) or containing seeds (such as conifers and angiosperms). Gymnosperm forests containing cycads, ginkgos and conifers developed quite early (about 350 million years ago) and conifer forests containing *Pinus* (pines), *Picea* (spruce) and *Abies* (fir) still dominate the cool temperate latitudes and the higher elevations of the northern hemisphere today. Conifers are also found in the southern hemisphere (e.g. *Agathis*, *Araucaria*, *Podocarpus* and *Callitris*). However, they have smaller geographic ranges, are somewhat scattered and have been characterized as relicts or living fossils. Angiosperms (flowering plants) developed much later, about 120 million years ago. They have been particularly successful and are still expanding. Conifers are long-lived species, but with a lower reproductive capacity than angiosperms. Consequently, angiosperms have progressively displaced conifers, except for the cooler parts (higher latitudes or altitudes) of the northern hemisphere where the superior adaptation of conifers to withstand seasonal cold has given them an advantage. Angiosperms now dominate the plant kingdom, including forest trees.

The development of grasslands

The grasslands developed about 25 million years ago. Their distribution was largely determined by climate, but soil-type and fire were also important. Grasslands developed and expanded before human development, but human development certainly assisted in their spread (Truett and Greene, 2009). In fact the appearance of the grasslands is critical, and perhaps more critical than any other factor in understanding the relationship between people and forests. Humans developed from arboreal apes in the forest and maybe there is some argument that humans have a deep-seated primordial attachment to the forest and yearn to go back. However, humans are creatures of the grasslands and not the forest. Human evolution accelerated only after, and probably because, the precursors of the human race came down from the trees, walked out of the forest, stood erect and looked into the distance.

The grasslands are particularly people-friendly. They provide the bulk of the food used for human consumption. They spawned the development of animals that graze on grass. These animals were relatively easy to hunt and they supplied improved nourishment to produce hominids with progressively larger brains. Grasses dominate cultivated agriculture. The world's current consumption of edible plants is dominated by the grasses wheat, maize and rice, along with the potato. Grasslands have a well-developed regenerative capacity and because of this they can recover from grazing and can persist in relatively dry environments. As a result, animals feeding from them also can persist in relatively dry environments. In addition, grasslands regenerate after fire and fire promotes grassland at the expense of forests. Grasslands posed some threat for the welfare of forests before humans. However, with the advent of humans and their love affair with grasses, the odds became stacked further in favour of the grasses. The human race as we know it would not have existed without the advent of the grasslands and open country. Humans have flourished by clearing forests and deforestation is an inevitable consequence of the human condition. Most humans do not live in the forests, but a small number of people have always lived in the forests and still do today. In past times these forest dwellers were prominent in riverine incursions into the forest where the riverine system was an important part of their food supply. This is still the case to some extent. However, in modern times deforestation of lowlands has often pushed forest dwellers into the hills. Even though forests are rich sources of biodiversity, they are not a good food source for humans and they have a small carrying capacity for humans.

The development of the human race

The human race evolved over the Tertiary and modern humans appeared in the Quaternary geological periods. The development of the human race alongside climate and associated events is shown in Tables 1.2 and 1.3. The hominid line is considered to come from the African apes, which split from the monkeys about 30 million years ago. About 10–15 million years ago, bipedal apes (the hominid line) developed and separated from other ape lines, which developed into gorillas and chimpanzees. This coincided with a decrease in the amount of dense forest cover in Africa, an increase in the amount of scattered woodland and grassland, and an increase in the variety and availability of grazing animals. This in turn produced an increase in the variety of food available to these ape-men (or pre-hominids). Hominids as such first appeared about 5 to 7.5 million years ago. The first evidence of a stone axe emerged about 2.5 million years ago and this marked the beginning of the Palaeolithic archaeological age (old stone age). This was at about the same time as polar glaciation and global aridity accelerated the already existing trend from forest to woodland to grassland (savannah) in Africa.

Homo habilis, a scavenger, appeared just over 2 million years ago and lived at the forest fringes and in the woodlands and was predominantly a vegetarian. *Homo ergaster* appeared about 1.9 million years ago and *Homo erectus* about 1.7 million

Table 1.2. Early evolution of humans and associated climate, forests and other plant communities, animals and other events. (Compiled from Calder, 1983; Tattersall, 1993; Vrba *et al.*, 1995.)

Period	Epoch	Millions of years ago	Humans	Forests and other plant communities	Animals	Climate	Tectonic and other events
Tertiary	Paleocene	65–53	Early primates	Angiosperms continue to expand at the expense of gymnosperms	Early horses	Equable, warm and wet	North America separates from Europe Rockies form
	Eocene	53–36	Higher primates			Equable, warm and wet	Australia separates from Antarctica India collides with Eurasia Eocene terminal turnover
	Oligocene	36–23	Extinction of primates in northern hemisphere	Grass develops and covers large areas	Cats, dogs, whales Apes and monkeys split	Equable, cool and dry	Sea level falls
	Miocene	23–5	Hominids diversify in Africa		Separation of hominid apes from other apes Antelopes, grazing animals Orangutans Modern cats and dogs Elephants	Warm, wet seasonal moving to cool, dry seasonal	Miocene disruption Antarctic deeps freeze Volcanic activity Northern glaciers Mediterranean dry-out and recovery Himalayas uplift
	Pliocene	5–2	*Homo habilis* (2 million years ago) Transition from forest dwelling to woodland dwelling Diet predominantly vegetarian	Cooling and drying in Africa about 2.5 million years ago causes some forests to change to woodland and grassland	Camels, bears, pigs, baboons, modern horses, early cattle Extra grassland favours development of grazing animals	Warmer seasonal, but cooling off about 2.5 million years ago	Andes uplift Current ice ages begin Oldowan stone axe (2.5 million years ago)
Quaternary	Pleistocene	2–0.01	*Homo ergaster*, *Homo erectus* and *Homo sapiens* (see Table 1.3)	(see Table 1.3)	(see Table 1.3)	Cool to cold	Ice ages (see Table 1.3)
	Holocene	0.01–present	*Homo sapiens* out-competes all other hominids (see Table 1.4)	Cultivation of plants (see Table 1.4)	Domestication of animals (see Table 1.4)	Warmer (interglacial)	Age of agriculture and development of civilization (see Table 1.4)

Table 1.3. Human development and associated climate, forests, other plant communities, animals and other events during the Pleistocene geological epoch (2 million to 10,000 years ago) and the Palaeolithic archaeological timescale (2.4 million to 10,600 years ago). (Compiled from Calder, 1983; Tattersall, 1998; Goudie, 2000.)

Period (years ago)	Humans	Forests, other plant communities and animals	Weather	Associated events
2,400,000–2,000,000	*Homo habilis* (a scavenger who frequented the forest margins and woodlands in Africa)	Accelerated rate of change of forest to woodland to grassland in Africa Further proliferation of grazing animals	Cold and dry Current ice ages begin	Beginning of the Palaeolithic age (stone age) First evidence of stone tools
2,000,000–1,400,000	*Homo ergaster* (1.9–1.4 million years ago) and *Homo erectus*, both in Africa Better suited to the grasslands than the forests Omnivorous Migration out of Africa	Grasslands continue to develop in Africa	Glaciation (2 million years ago)	First evidence of controlled use of fire Acheulean hand axe
1,000,000	*Homo erectus* migrates to China and Java (and perhaps earlier)			
800,000–700,000	Early hominids in Spain (800,000 years ago)		Interglacial	
600,000			Glacial	
500,000	Perhaps the origin of modern *Homo sapiens* in Africa		Interglacial	
400,000–300,000	*Homo heidelbergensis* in Europe Language	Wood used for dwellings, fuel, charcoal and tools	Glacial	Earliest shelters made from tree saplings Convincing evidence of controlled use of fire
200,000	*Homo neanderthalensis* were foragers and scavengers Early *Homo sapiens* were hunter gatherers		Interglacial	
150,000	Convincing evidence of modern *Homo sapiens*			
100,000	Population of *Homo sapiens* about 5 million		Glacial	Art, music, symbols, more advanced tools, elaborate burials
40,000–30,000	*Homo sapiens* widely spread globally (Cro Magnon man in Europe)		Glacial	
27,000	*Homo neanderthalensis* becomes extinct		Glacial	
20,000–10,000	*Homo sapiens* is the only surviving hominid and is widely distributed (but not in Ireland, Polynesia, Madagascar, New Zealand, the Caribbean or Antarctica)	Megafauna extinction throughout the world but not in Africa	Glacial	Early cultivation and domestication of animals Use of fire (deliberate or accidental) to promote grassland

years ago. *Homo ergaster* (African *Homo erectus*) and *Homo erectus* were clearly anatomically more suited to the grassland than the forest, and hunting commenced in a very rudimentary form. Consequently, meat became more prominent in the diet and the trend away from scavenging towards hunting and gathering commenced. *Homo ergaster* also provided the first sketchy evidence of the controlled use of fire (about 1.4 million years ago), although evidence of shelters containing hearths was much later (about 400,000 years ago). The movement of the hominids out of the forests not only triggered acceleration in the rate of human evolution, but also marked the start of their achievements as long-distance travellers. *Homo ergaster* and *Homo erectus* migrated out of Africa via land bridges that became exposed at a time of low sea levels (Tattersall, 1998). The migration of hominids from Africa throughout the world coincided with the Pleistocene ice ages, which began about 2 million years ago and are still in progress. The marked changes in climate caused separation and re-joining of hominid populations and these conditions were ideal for human evolution and diversification.

Early *Homo sapiens* (archaic humans) developed about 1 million years ago and modern *Homo sapiens*, anatomically the same as we know them today, developed at least 100,000 years ago and possibly up to 500,000 years ago. There have been differences of opinion over whether modern humans developed from multiple sources or from one original source. Recent evidence supports that modern humans originated in Africa and that they migrated to other parts of the world, progressively out-competing all other archaic humans, including the Neanderthals (*Homo neanderthalensis*). Consequently, *Homo sapiens* is the only hominid surviving today. There is also some uncertainty about when hominids developed language. The development of language is considered to be a major factor in the evolution of humans and a key feature in the progressive increase in brain size that occurred from early hominids through *Homo habilis* to *Homo erectus* to *Homo sapiens*.

Dwellings or shelters, made from tree saplings, were evident 400,000 years ago and these contained hearths. Wood was also used widely from 400,000 years ago for fuel, charcoal, drying, ladders, artefacts and tools. Indeed the use of wood may have been much greater than we think because it readily decays and is not persistent in the archaeological record. In fact Tyldesley and Bahn (1983) considered that the use of wood in the Palaeolithic was so widespread that the age should more appropriately be called the Palaeoxylic (old wood age) rather than the Palaeolithic (old stone age). Most attention has been given in the literature to the use of stone axes for hunting and less attention to the tools used in felling trees and preparing wood for various end uses. The stone axes and tools of the day, however, would have met the need (Cole, 1970). The evidence for human presence, in Europe at least, in the relatively short-lived warm interglacials was scant compared with the longer colder glacial periods (Mannion, 1991). The interglacials were forested and the glacials were not. This reinforces that, by and large, humans were not forest dwellers and preferred open areas.

The impact of humans and their ancestors on the environment 50,000 and more years ago was small and inconsequential. This was because the populations were small and scattered and they had not yet developed the technologies and tools to have a significant effect on the environment. The expansion of the grasslands, although of great benefit to humans, was not at this stage assisted by humans. It would be misleading to suggest that grassland was overtaking forests globally on a grand scale. Grassland expansion occurred locally and humans chose to live in these areas. Global changes in vegetation were dominated by the ice ages and the forests were the prime re-colonizers during the interglacials.

Hunter-gatherers and forests

Modern humans hunted to get their meat and gathered plant food where they could. This continued until the ‘age of agriculture’, when humans found they could grow their own food and domesticate their own livestock. It is difficult to put a start and end point to this period. Hunter-gathering replaced scavenging perhaps 500,000 years ago, but the record of hunter-gatherers and how they lived is strongest from about 50,000 years ago. Human evolution appeared to take a quantum leap forward in technology and art about 40,000 to 50,000 years ago (Diamond, 1998), from which time also there was convincing evidence of widespread geographical dispersal of humans across the world and undisputed evidence of humans having a significant impact on the global environment. It is generally reckoned that the age of agriculture began about 10,000 years ago. There are, however, records of early agriculture as far back as 18,000 years ago. Also, some hunter-gatherers, such as the Australian aborigines, completely bypassed the age of agriculture and first confronted other humans from the industrial age less than 250 years ago. Murdock (1968) lists 27 modern hunter-gatherer groups that have existed recently enough to be studied and published by modern ethnographers. Currently about 0.001% of the world's population live by predominantly hunting and gathering.

Hunter-gatherers were by necessity close observers of nature. There was a strong selective pressure to ensure that they were good ecologists. They needed to be so in order to provide year-round sustenance. They had considerable knowledge of the plants around them, their flowering and fruiting patterns and their value as a food source. They knew the migratory patterns of the animals and the pattern of the seasons. They were nomadic because they quickly depleted local food reserves and because their food supplies were seasonal (Bush, 1997). Modern hunter-gatherers show survival skills that contemporary humans have lost. The close association between hunter-gatherers and the natural world is still evident in modern hunter-gatherers and is an important component of their folklore and spirituality. Indeed, it is their close association with the land that has caused most misunderstanding and conflict between modern hunter-gatherers and their industrial and agricultural co-inhabitants. Hunter-gatherers appear to have been well resourced and this is largely due to their intimate association with the land, plants and animals. Their lifespans were relatively short, but this was because of warfare and hunting accidents rather than starvation or infectious diseases. As a result, populations were kept low. The populations of more recent-day hunter-gatherers have fallen because of exposure to infectious diseases, habitat removal and competition with agriculturalists. Forest clear-cutting has completely destroyed the hunter-gatherer's environment in parts of Borneo and the Philippines (Southwick, 1996).

Hunter-gatherers, though good ecologists, were not especially good conservationists. They had no real concept of the finite nature of natural resources or of sustainable management. When they depleted the reserves around them, they just moved on. Their numbers were small and so, for the most part, their impacts on the environment were correspondingly small. Probably they were the first human agents of seed and plant dispersal because of their nomadic nature. The amounts of wood that they extracted from the forests for fuel and shelter would have been negligible. However, there were two areas where hunter-gatherers did have a significant effect on their environment: the extinction of large animals and the depletion of forest area. In both of these their controlled use of fire was an important factor.

Many large animals (megafauna) became extinct during the Pleistocene (Pleistocene overkill) ranging in time from 40,000 years ago in Australia to about 12,000 years ago in the Americas. There is some difference in opinion over the cause of these mass extinctions. Some consider that climate change was the major cause, but others suggest that hunter-gatherers were a major contributing factor and probably the main cause. These megafauna had escaped many severe climatic cycles prior to the Palaeolithic. Their sudden disappearance in the Palaeolithic coincided with the time that modern humans were diversifying and developing superior hunting technologies and also competing with these large animals for habitat. Also, it is a matter of record that when humans first entered oceanic islands in more modern times they were directly responsible for the extinction of the dodo in Mauritius, the moa in New Zealand, giant lemurs in Madagascar and the big flightless geese of Hawaii (Diamond, 1998). However, the matter remains controversial.

Fire was the first product of the natural world that humans learned to 'domesticate' (Pyne, 1995). Hunter-gatherers used fire to manipulate vegetation patterns and continue to do so to the present day. They used fire to increase the area of grassland, to inhibit woody regeneration on grassland, to provide green regeneration to attract grazing animals, to deprive game of cover, to drive game out of cover, and to promote and harvest insects and edible plants. Hunter-gatherers deliberately lit fires, but also took advantage of fires lit from lightning strikes that most often would be left to burn out. For thousands of years hunter-gatherers put the land to the torch. The Indians in North America used fire to keep the prairies as open range and when the fires were withheld the trees came back. The hunter-gatherers of southern Africa used fire to maintain the grazing lands of the veldt. When Magellan rounded the southern tip of South America, he saw many fires lit by the indigenous peoples and he named this part of South America, Tierra del Fuego (land of fire). The Australian aborigines burned the land whenever they could and the frequent low-intensity fires favoured open countryside rather than forest (Flannery, 1994). Indeed, Australian aborigines were very sophisticated in their use of fire frequency and fire severity to create a range of hunting and gathering options (Gammage, 2011). The Australian aborigines have been called 'fire-stick farmers'. It is possible one of the reasons they did not develop cultivated agriculture is because of their success in using fire to optimize their hunting and gathering.

The ecosystems produced by this continual firing not only tolerated fire but actually encouraged it and even required it for their maintenance. It is an over-simplification to say that fire promotes grassland over forest. Grasslands appear to be favoured by more frequent, less intense burns and forests by less frequent, more intense burns. However, fire sometimes promotes heath or shrub country rather than grass. Also some forest types are extremely well adapted to fire. Grasslands that are either under-grazed or over-grazed are susceptible to encroachment by woody perennials. However, on balance, the net effect of hunter-gatherers burning the vegetation whenever they could probably was an increase in the area of grassland and a consequent decrease in the area of forest. For example, the continual firing of the forests of New Zealand by Polynesians (Maori) in pre-European times in order to hunt the now extinct moa reduced the forest cover from 79% to 53% (Mark and McSweeney, 1990). Probably an equally important consequence of the burning by hunter-gatherers has been the profound effect that this has had on the composition and structure of both forested and non-forested ecosystems. This, in turn, has strongly influenced how they should be managed.

Modern hunter-gatherers tend to be forest or forest-fringe dwellers. This is consistent with the observation made earlier that the technological advancement of the human race depended on leaving the forest and occupying and promoting open areas.

Forests and the Age of Agriculture

Barker (2009) discusses the transition from hunter-gatherers to agriculturalists. The age of agriculture can be defined as the period in which humans cultivated plants for food production and domesticated animals for meat production, for milk and for the harnessing of animal power for ploughing and other activities. Agriculture commenced about 10,000 years ago. The earliest records come from New Guinea, Peru and Iran. The earliest crops cultivated were grasses: wheat and barley in the Middle East, rice in South-east Asia, millet in Africa and maize in the Americas. Potatoes, peas, lentils, beans, capsicum and gourds were also important early crops. Table 1.4 shows the sequence of events during and past the age of agriculture.

Agriculture developed first in the grasslands and open woodlands. For example, the agricultural origins of the Incas of the Andes, the Pueblos of North America and the Bantus of Africa began in the open country where they had lived as hunter-gatherers (Winters, 1974). However, early agriculturalists would soon have learnt that crop productivity was best on fertile soils with good rainfall and these are the very soils that originally would have supported forests. As such, the incentive to clear forest for agriculture probably occurred quite early in the age of agriculture. There is evidence of widespread deforestation having occurred in temperate forests during the Mesolithic and the Neolithic (Goudie, 2000) and over a wider area and at an accelerated rate thereafter, particularly in northern Africa, Mesopotamia, the Mediterranean and temperate Europe (Dimbleby, 1976). This deforestation needs to be considered alongside the naturally occurring reforestation that was occurring in Europe, the Mediterranean and North America during the interglacial Mesolithic, approximately 8,000 to 10,000 years ago (see Roberts, 1989). Today there are extensive areas of agricultural and grazing land that arose from clearing forests, mostly on the best soils. Some of this clearing happened so long ago that it is forgotten as a deforestation event.

The early agriculturalists would have found that fire produced an initial burst of fertility but that their yields declined after cultivating an area for a few years (through nutrient depletion) and also that weeds progressively overtook the cultivated areas. They responded to this by abandoning the cultivation, moving on, burning a new area and starting again. Of course they did not understand the scientific basis of why they needed to do this. This marked the beginning of slash and burn agriculture (or shifting agriculture) that continues to this day. Slash and burn agriculture can be quite responsible and sustainable, providing it is done at a low enough intensity to allow the vacated site to completely re-vegetate and recover. The early

Table 1.4. Human development and associated events from 10,000–1,900 years before present. (Adapted from Mannion, 1991 and others.)

Period (years ago)	Humans	Plants and animals	Forests	Technology	Environment
10,000–8,000 (Mesolithic)	Shifting (slash and burn) agriculture Population about 5 million	Cultivation of wheat, barley, peas, lentils, flax and vetch and domestication of cattle, goats and sheep (all in the Near East)	Interglacial reforestation in the northern hemisphere Beginning of deforestation to support farming and grazing Fire used to promote grassland over forests	Axes used to fell forests	Incipient soil erosion
8000–5000 (Neolithic)	Trend from shifting to settled agriculture Agricultural communities in China	Reduction in number of cultivated plants Farming and grazing more productive Domestication of the pig, horse (Russia), llama and alpaca (South America) Cultivation of potato, capsicum, beans and maize in tropical America Rice in China	Continued deforestation Cultivation of the olive Decline of elms in Europe Commencement of the deforestation of southern Britain	Smelting of copper in Anatolia and Thailand Agricultural tools	More soil erosion and more widespread
5000–3000 (Bronze Age)	Great riverine civilizations commenced in Mesopotamia, Egypt and Pakistan Hierarchical societies and trade	Monocultures Transfer of plants and animals between regions Domestication of rice in India and Pakistan	Greatly accelerated deforestation to support farming, grazing and smelting Cultivation of peaches, apricots and citrus	Smelting of copper Irrigation Wheeled carts Plough Textiles Arts and crafts Saws	Accelerated soil erosion, siltation, salinization, desertification, overgrazing and abandonment of non-productive soils Infectious diseases Climate change towards drier conditions in Mesopotamia, Mediterranean and North Africa
3000–1900 (early Iron Age)	Civilizations in Greece, Rome, India and China Population reaches about 200 million	Further reduction in the number of food crops, and intensification of the production of food crops Continued transfer of plants and animals between regions.	Deforestation particularly to support smelting and shipbuilding Beginnings of silviculture (coppicing, thinning, pruning, tree breeding, plantation establishment)	Smelting of iron Glass Rudimentary agricultural technology (composting, terracing, fallowing, fertilizing, breeding)	No significant change in climate Soil erosion and land degradation continues

agriculturalists probably never or rarely returned to a vacated site and therefore their slash and burn agriculture was relatively benign. (Slash and burn agriculture as practised in recent times, however, can be quite damaging and plays an important role in the current deforestation of tropical forests.)

Settled agriculture

Some hunter-gatherer groups developed limited agriculture but maintained predominantly a hunting and gathering lifestyle (such as in New Guinea). Others embraced agriculture and grazing as their main form of subsistence and progressed from 'shifting' agriculture through to 'settled' agriculture where communities developed in settlements with larger numbers of people living at closer quarters. The higher densities of population brought health problems. Settled agriculturalists had worse teeth and bones, caught more communicable diseases and had a lower life expectancy than shifting agriculturalists (Cohen, 1989). It is likely that the plains and valleys supporting settled agriculture were initially deforested in part by Neolithic agriculturalists. This trend continued in the early Bronze Age, such that later accessible forests were mostly confined to the hills and mountains.

Smaller settlements grew into larger settlements and in some instances into sophisticated city-states. This heralded the beginning of hierarchical societies and 'civilization'. The key to the reason why some agriculturalists moved on to civilization and others did not was primarily access to good soil and plants suitable for domestication. The first great civilizations developed from about 5000 BC (7000 years ago) on the fertile soils of the flood plains of the Tigris, the Euphrates, the Nile, the Indus and the Yellow Rivers. These soils were so fertile that they could support crops in one place for longer and support a higher density of people. The rivers continuously replenished soil fertility by depositing alluvial silt during floods. They also supplied water for irrigation and a conduit for transport.

Continuous cultivation of the same soil, even fertile soil, requires special care (maintenance of soil organic matter and replenishment of soil nutrients). If not, the soil will become infertile and degraded. Similarly, if animals are grazed continuously on the same land, and particularly if the number of animals is too great, the pastures will not regenerate and the soil will become degraded, sterile and subject to erosion by water and wind. Both of these misfortunes were evident in the early days of agriculture and regrettably are not unusual in parts of the world today. Neolithic farmers responded to this by using some of the basic agricultural techniques that have stood the test of time. They used manure and other fertilizers to maintain soil fertility, terracing to control erosion, fallow to rest the soil and rotation with legumes to enrich soil nitrogen (Hughes, 1994). Even so, as the population increased and concentrated in settlements, more land had to be found to sustain crop yields and animal numbers. This was achieved by clearing forest. Indiscriminate clearing of forests, particularly on slopes, promoted soil erosion and downstream sedimentation that, later in the Bronze Age, choked irrigation canals and watercourses and land-locked coastal ports. This further reduced the crop and pasture yield on cleared land and even more forest was felled to compensate. Deforestation was also necessary to provide fuel and wood products for the developing civilizations.

The rise and fall of civilizations

The trigger for the development of civilization came when humans first found they could produce more food than they needed for themselves. This meant there was time available for leisure and not everybody was needed to be involved in food production. Food surpluses led to trade and the increase in non-productive time meant other activities such as arts and crafts and other cultural activities could be developed. Human populations and particularly the density of humans living in close proximity increased. It was inevitable that hierarchical societies would develop and equally inevitable that the dominant groups would move to protect their positions. Thus, rulers conscripted police to enforce laws, priests promoted ideologies to enslave the poor and underprivileged, and armies were raised to steal resources from neighbours. Societies were segregated based on wealth and influence and the lower castes were usually slaves, or little better off than slaves. Also, because of the gross distortion of available wealth, the rich were profligate consumers of anything they could find, including an outrageous consumption of forest products.

The civilization of the human race is arguably the greatest achievement in human evolution. However, when humans removed themselves from their close association with the land, they lost the empathy with the land that the hunter-gatherers had developed in order to survive. This was the beginning of the ecologically flawed idea that humankind was separate from, rather than being intrinsically part of, nature. Only a minority of people were involved in producing food and these people were often the most underprivileged and least influential. The influential, used to surpluses and indeed dependent on them to maintain or extend their position, looked further afield when local supplies became inadequate. Population increases led to increased consumption of wood for fuel and shelter. Technological advances, particularly the smelting of metals, increased wood consumption (and therefore deforestation) further. The wealthy in the early civilizations were very dependent on wood to maintain their lifestyles and wood consumption, particularly for fuel for metal smelting and pottery, could be staggering.

A distinction needs to be made here between forest logging and forest clearing. Deforestation occurs when trees are felled and the land is cleared for a land use other than forestry. Forest cleared for agriculture and grazing is the most common example. Logging of forests is not deforestation if the area of forest is not reduced and the forest subsequently regenerates. However, during the golden civilizations, logging was done in a most destructive manner, with no attention being given to regeneration strategies. Many forests became seriously degraded.

When forests were cleared or became degraded near to the centres of population, they were progressively exploited further away. Inevitably this reached the point at which the stronger communities were able to take (steal is probably a better word) the wood from weaker neighbours. This heralded the beginning of colonialism. Invasion greatly accelerated deforestation. Not only were forests needed to provide ships and other apparatus of war, but also invaders often destroyed the forests to deny timber to their enemies. Alternatively, they burnt the forest to entrap their enemies. The citizens of vanquished cities transmigrated to the countryside and into the hills, where they cleared more forest to grow crops.

A model for the rise and fall of civilizations is given in Fig. 1.1. This model best fits the cases for the civilizations of Mesopotamia and the Mediterranean, but elements of it are universally applicable. The reasons why these civilizations ultimately declined are various, but they all had the predisposing factor of poor soil management. They became weakened because they were unable to practise sustainable agriculture, which led to an inability to feed themselves. The forests were major casualties and these areas today are seriously degraded landscapes. The age of the golden civilizations of Sumeria, Babylonia, Assyria, Phoenicia, Egypt, Greece and Rome was a period of environmental mismanagement from which the regions have never fully recovered. Certainly climate change played a role, particularly in northern Africa, but there is no doubt that humans gave it very good assistance. It would be unreasonable to single out these ancient civilizations as environmental vandals without peer. Post-classical and modern societies often have done worse. Indeed, there have been cycles of devastation and recovery of forests right across the history of the human race, from the Bronze Age to the present. The ancient civilizations lasted for quite long times, many thousands of years in some instances. Also there is evidence that they understood some of the environmental problems that they were causing and they took steps to try and remedy them. Whether or not modern civilizations, with all their technological knowledge, will last as long as these ancient civilizations, is not yet known. Certainly modern civilizations have all of the same ingredients that were instrumental in the environmental degradation and the demise of earlier civilizations. Modern humans now have the knowledge to sustainably manage agricultural and forest systems and an understanding of the consequences of not doing so.

The role of sedimentation in the rise and fall of civilizations is two-edged. Sedimentation is not necessarily a bad or destructive thing. The early Bronze Age civilizations developed on floodplains whose fertility depended on upland soils being eroded and carried downstream. This sedimentation would have occurred without the impact of humans, but it is possible that Mesolithic and Neolithic humans assisted it by clearing forests upstream. Without this soil erosion these civilizations would likely not have developed. Civilization was spawned by soil erosion. However, with continuous felling of forests upstream and with poor soil conservation practices on cultivated land and overgrazing, the sediment loads became so large that they became an uncontrollable nuisance rather than a benefit. These same river valleys that

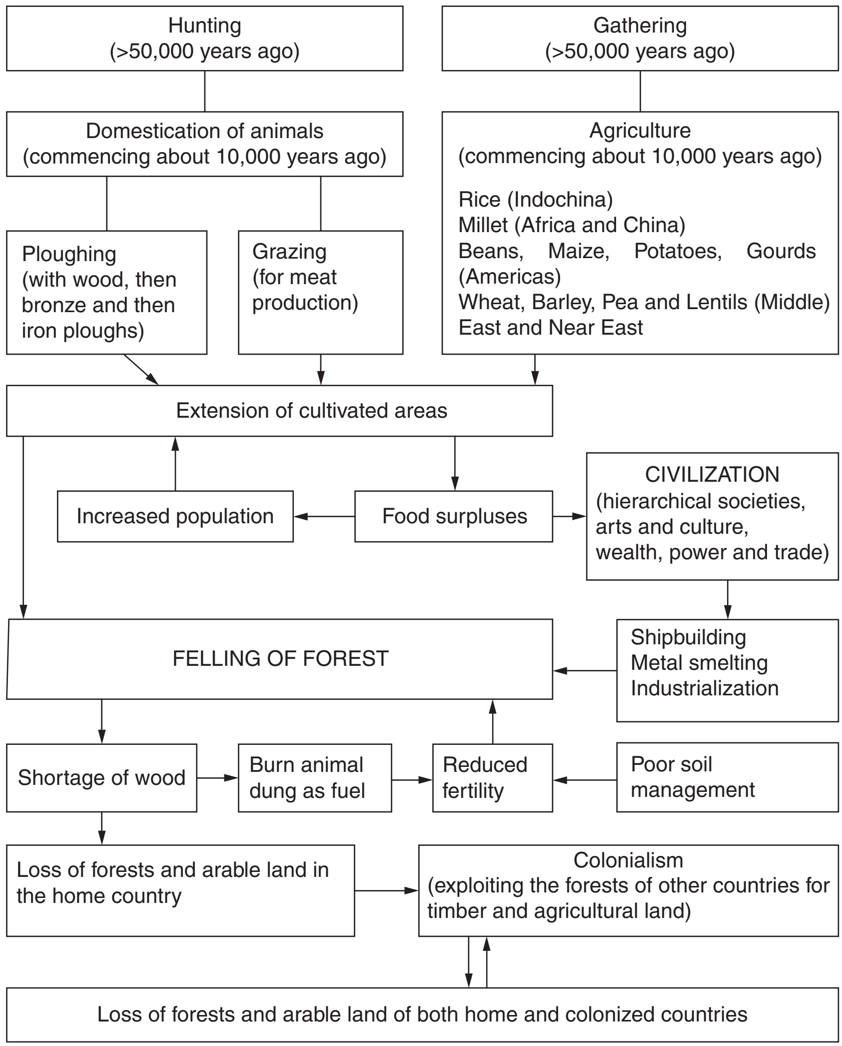

Fig. 1.1. The relationship between the rise of the ancient civilizations and the fate of forests. (Modified from G.B. Sweet, unpublished.)

supported the ancient civilizations still owe their inherent fertility today to soil erosion.

Over the last 10,000 years or so, humans have reduced the global forest cover from about one half of the global land surface area to less than one-third. Most of this deforestation has occurred in the temperate and subtropical regions and it is only in recent times that there have been significant incursions into the tropical and boreal forests. Also until recently, deforestation occurred close to where people lived. There has been a strong pattern of deforestation accelerating alongside increases in population and a pattern of forest recovery occurring after human populations move out of an area. Nowadays however, many more people live in large cities and transport has improved to the extent that forests of the most far-flung regions of the world are readily accessible. It is not practical to comprehensively review all regions of the world. Therefore a few representative examples are given here as case studies. This begins with the civilizations of Mesopotamia and the Mediterranean, then looks at forests in Europe from the Dark Ages through to the 20th century and ends by looking at the impact of colonialism on forests using the Americas and Asia as examples. Williams (2003) provides a more comprehensive history. In addition, Easter Island will be used as a graphic example of the impact of catastrophic over-exploitation of a finite forest resource.

Mesopotamia

Mesopotamia comprises all of the country dominated by the twin rivers, the Tigris and Euphrates. This covers all of present-day Iraq and parts of Syria, Turkey and Iran. The fertile soils of the floodplain led to the region being called the Fertile Crescent. Settled agriculture and subsequent city-states developed here because the soil was fertile, suitable wild grasses were accessible for cultivation and the rivers provided water for irrigation. The productive soils were limited to the floodplain, which was surrounded by less hospitable and often dry countryside. Consequently, crop productivity, particularly on the lower plain, needed to be supported by irrigation. Settled agriculture commenced at about 5550 BC, from which arose a series of dynasties and empires. Sumeria developed first in the south of the floodplain and Babylonia followed in the middle of the floodplain. The Babylonian civilization came to an end after successive invasions from the Kassites, Elamites, Assyrians and eventually the Persians in 539 BC.

Initially the plain was peopled from agricultural villages in the uplands moving onto the plains. Written language was first evident at about 4000 BC and progressively these agricultural communities developed most of the trappings of civilization: hierarchical societies; the plough; the wheel; food surpluses; trade; building in stone; wood and wood-fired bricks and clay; wood-fired pottery; wood-fired smelting of copper ores to make tools and weapons; crafting with fine metals; sculpture; spinning and weaving in linen; and leather work. The temple was a main feature of the cities and this was usually mighty in size and required considerable labour and material in construction and maintenance (Hawkes, 1973).

Populations increased and the proportion of people directly involved in producing food reduced. As a result, the productivity expected from a given area of cultivated land area increased. At first this was achieved. Irrigation canals were built and the fertile alluvium brought down in the floods prolonged crop productivity, but not indefinitely. Siltation progressively increased and choked the irrigation canals and considerable labour had to be directed towards keeping the canals free of silt (Dasman, 1968). This dredging resulted in the canals being up to 10 metres above the surrounding fields (Hughes, 1994). Southwick (1972) reported that, after 3000 BC, silt from the Tigris and Euphrates Rivers filled in the Persian Gulf 180 miles from its origin. Crop yields were reduced and forests were felled to provide new land for cultivation as well as for providing wood. The felling of the forests exacerbated the problems on the plains. The upland areas exposed by deforestation or forest degradation were prone to soil erosion and even more silt moved into the river basins. The eroded soils exposed saline rocks and mineral salts, which also moved down to the plain, and soil salinization and irrigation with saline water further reduced crop yields. Salinization of the lower plain led to the more salt-tolerant barley replacing wheat as the staple cereal. Ultimately, the yields of barley fell to about 40% of their earlier yields. This was probably the main reason for the collapse of Sumeria and the centre of civilization in Mesopotamia moving north to the mid plains of Babylonia, where there was a much lesser problem with salinity (Jacobsen and Adams, 1958; Vogt *et al.*, 2007). However, Babylonia eventually also succumbed to land degradation and low crop yields and ultimately the great Babylonian civilization was weakened to the extent that it became vulnerable to invaders.

The Mesopotamian civilizations were large consumers of wood. Perlin (1989) reviewed the use of wood in Mesopotamia. The scene is set in the Epic of Gilgamesh, one of the earliest stories ever written. The epic was Sumerian, but was translated into Akkadian at the beginning of the Babylonian period (Saggs, 1995). An English translation is provided by Sandars (1960). The legend is set in about 2700 BC in Uruk in southern Mesopotamia, where Gilgamesh, the ruler at the time, had to penetrate the surrounding cedar (*Cedrus*) forests to provide the timber to build his city. In order to do so, he had to overcome the ferocious demigod Humbaba, who was guardian of the forest. The presence of dense forests accessible to the river plains at this time is no legend. The forests of the Zagros range east of Babylonia were the first to be exploited and they provided oak (*Quercus*), cypress (*Cupressus*), pine (*Pinus*) and juniper (*Juniperus*). The rulers of Lagash, another city-state in Sumeria, progressively raided the cedar forests of the Amanus Mountains from about 2350 BC in order to build their grandiose cities. The third dynasty at Ur in 2100 BC was the pinnacle of Sumerian civilization and wood was extensively used for construction and to provide the fuel for smelting metals. Poplar (*Populus*) and willow (*Salix*) were taken from local forests; cedars were imported from the Amanus Mountains; juniper, fir (*Abies*) and sycamore (*Platanus*) were taken from northern Syria; and other timber was imported from northern Arabia and India. Later cedars were accessed from as far as the Lebanon range (Makkonen, 1969) and Crete (Perlin, 1989).

Timber became a precious commodity and wars were fought to secure access to forests. Wood was so scarce in Babylon that rented houses had no doors and tenants had to take their doors with them. Administrators took strict measures to slow down the consumption of firewood and to curtail unauthorized cutting of trees in the Babylonian forests. Firewood prices soared and this was reflected in the asking price for commodities that required heat in their manufacture (Perlin, 1989).

The Mediterranean

The forests in the Mediterranean are characterized by more than 5000 years of continuous and often intense co-existence with humans. Most of the Mediterranean was well forested in areas of adequate rainfall at the beginning of the Bronze Age (5000 years ago). Except for the edges of the Sahara in North Africa, there has been no significant change in climate over the Mediterranean for the past 5000 years. Therefore, deforestation events since then cannot be attributed to changes in climate.

Before human intervention, pines and oaks occupied most of the land below 1000 metres elevation. After human intervention much of this became covered by *maquis*, a cover of small woody shrubs, which after repeated destruction by fire, overgrazing or clearing is replaced by a community of low tough shrubs called *garigue*. With even more extreme disturbance, *garigue* becomes a grassland that is resistant to grazing. In the western and northern parts of the Mediterranean basin, deciduous forest with oaks, beech (*Fagus*), elms (*Ulmus*), chestnut (*Castanea*) and ash (*Fraxinus*) occurs in a zone between 1000 and 1500 metres. This zone is missing in the south and the east, possibly because it has been eliminated by persistent human removal over time or maybe it never existed in these parts. Above 1500 metres in undisturbed environments are coniferous forests containing pine, cedar, fir and juniper (Hughes, 1994).

Significant deforestation and forest degradation occurred in the ancient Mediterranean and this has continued to the present day. This was particularly so in the south and the east and near to centres of population. Neolithic humans cleared some forests on the plains for agriculture and Bronze and Iron Age people extended this into the foothills. The forests on the upland slopes and mountain ranges were not cleared for agriculture, but were extensively exploited for timber, often in a most destructive manner. Consequently, much of the area of forest in the Mediterranean classified as forest today is degraded. Because of difficulties and cost of transport, accessible forests were the first exploited and the more inaccessible forests had a temporary reprieve. A substantial proportion of the Mediterranean forests only became accessible when railways were built in the 19th century (Meiggs, 1982). Another common element across the Mediterranean was overgrazing by cattle, sheep, pigs and goats. A particular menace was (and remains) the goat, which enjoys wandering into wooded areas destroying the young regeneration and reaching up into small trees to eat the foliage. Hughes (1994) quotes the poet Eupolis to demonstrate that goats eat almost everything available to them, including trees.

> We feed on all manner of shrubs, browsing on the tender shoots of pine, ilex, and arbutus, and on spurge, clover, and fragrant sage, and many-leaved bind weed as well, wild olive, and lentisk, and ash, fir, sea oak, ivy, and heather, willow, thorn, mullein, and asphodel, cistus, oak, thyme, and savory.

Continuous uncontrolled grazing is the major reason why many degraded and over-cut forests of the Mediterranean have not regenerated from classical times to the present.

The cedars of Lebanon

The cedars of Lebanon were famous in the ancient world and are held in great respect, almost in glory, in the ancient literature. The Lebanese cedar (*Cedrus libani*) came from the Lebanon range, which runs parallel to the eastern seaboard of the Mediterranean Sea between Beirut and Tripoli. Cedars were also found in the Taurus Range on the Cicilian plain and the Amanus Mountains in Syria, but it was the cedars of Lebanon that received most acclaim. The cedars made Phoenicia a dominant maritime power and trading nation. The cedar was valued for its high-quality durable wood that was close grained and easy to work. The trees were also large and suitable for roof beams in temple construction and in making large doors. People would go to great lengths to get the cedars of Lebanon and were prepared to transport them considerable distances. The Mesopotamian civilizations used them for building their temples, as did King Solomon in the combined kingdoms of Judah and Israel. Cedars and other species of the Lebanon Ranges were used routinely in Egypt for shipbuilding, building construction and furniture. The Lebanon Range also contained a number of other tree species, including evergreen oaks, cypress, junipers, firs and pines. Phoenicians, Egyptians, Hittites, Hebrews, Assyrians and Babylonians all had a stake in using the cedars. When Alexander the Great sacked Persepolis, the Persian capital, in 331 BC, the wooden pillars of the royal palace were made of cedar from Phoenicia (Winters, 1974). Prior to human exploitation, the cedar forests were extensive and magnificent and the dominant species over the Lebanon Range. As recently as the First World War, the remnants of the cedars of Lebanon were still being cut. Today the cedars in Lebanon are rare and found only in a small number of sparse, scattered and degraded populations (Meiggs, 1982). However, they are still plentiful in the Taurus Range in Turkey.

Minoan Crete

Crete was well forested before the Minoan civilization, which began about 3000 BC and was very well developed by 1700 BC. Indeed, the presence of these forests was a major factor in the development of the Minoan civilization. Cypress was prominent in the forest, but fir, pine, oak, olive, ash, maple, black mulberry, tamarisk and possibly cedar were also found (Meiggs, 1982). The Minoans had a passion for building elaborate palaces and wood was widely used in construction. Wood was used for columns, beams, doors, windows and furniture, and also inside mud-brick walls. Minoans had a very good knowledge of the different properties and uses of wood from different species. Minoan Crete became a major nautical power and an important trading post and much wood was used in shipbuilding. Most wood, however, was used as fuel in making bronze, in cooking, making sacrifices and in the preparation of lime for making plaster for the walls of the palaces. Because of the ready supply of wood, Minoan Crete was probably an exporter of both bronze and timber to the Near East.

Eventually deforestation of Crete caused timber to become scarce. Evidence for this was in the reduced use of timber in construction and its replacement with gypsum. There was a greater amount of recycling of bronze. Relatively more charcoal and less wood was used as fuel. Minoan Crete changed from being an exporter of wood to being an importer from the nearby Mediterranean mainland, particularly Messenia in south-western Greece. Timber became more and more difficult to obtain, and shipbuilding was reduced in quantity and quality. The Minoan fleet became smaller and less reliable, resulting in Minoan Crete losing its nautical superiority and advantage in trade. In 1450 BC Minoan Crete was overtaken by the Mycenaeans, who subsequently used Crete as a sheep-grazing outpost. Sheep grazing ensured that degraded forests could not regenerate.

Mycenae

Mycenaean Greece occupied the southern section of the Peloponnese Peninsula. After 1450 BC, the Mycenaeans replaced the Minoans as the main traders with the Near East, and this included the trading of timber. At this time Mycenaean Greece was well forested on the hills, although the plains had been deforested to some extent by Neolithic and early Bronze Age agriculturalists. Oaks were prevalent on the plains, pines along the coast, firs in the hills and alder and poplar in the marshes (Loy, 1966). Mycenaeans became major exporters of bronze and ceramics, both of which required wood as fuel. Timber was used in building and vehicle construction and their strong shipbuilding industry gave them dominance in trade. The Mycenaeans, like their Minoan predecessors, had a penchant for palaces and large houses, which required large amounts of wood for their construction and upkeep.

The Iliad and the Odyssey are epics attributed to Homer and historically set in Mycenaean Greece. They both frequently refer to forests and to particular tree species. Homer clearly had a respect for woodsmen and craftsmen in wood and he knew the main uses of different woods. Homer frequently compared the falling of a warrior in battle with the felling of great trees. Meiggs (1982) gives many examples. A typical example from the *Iliad* (13. 389–391) is when Asios, killed by Diomedes, 'fell as an oak falls, or a poplar, or a tall pine, which craftsmen cut down in the mountains with their newly whetted axes to make ship-timbers'. This quote, if it is to be taken literally, encapsulates several factors about forests in Mycenaean Greece. It shows that different species were recognized and named, that tree felling with axes was common practice, that trees were felled in the mountains (which may mean that the plains had already been cleared) and that timber was used in shipbuilding. Another quote from the *Iliad* (4. 482–487) says that Simoeisios, after being speared by Ajax, 'fell to the ground in the dust like a poplar that has grown up smooth on the edge of a great marsh, and its branches grow at the top. A chariot-maker cuts it down with his gleaming iron axe to bend a felloe for a specially fine chariot, and so it lies drying out by the river banks' (Meiggs, 1982). This quote reinforces that poplars grew in or at the fringes of marshes, but it also shows that there was a preference for knot-free timber for certain end-uses and that the principles of timber seasoning were understood. It could be a mistake to take Homer too literally as he wrote his epics at least 400 years after the events described and his information about Bronze Age Mycenae would have been passed down through the years. The use of the iron axe in the latter quote suggests some poetic licence. Also there was confusion about species identification, not only by Homer, but right across Mesopotamia, the Near East as well as in the Mediterranean (Thirgood, 1981). Homer mentions axes, usually bronze, quite often and with great respect. This respect was transferred to the woodworker, whose particular skill as a craftsman was recognized and who must have had an important and influential place in society. Homer does not mention saws. Although the Romans claim to have invented saws made of iron, there is good evidence of bronze and copper saws being used in Minoan Crete and ancient Mesopotamia and Egypt (Makkonen, 1969).

Mycenaean Greece followed the typical pattern of rise and decline shown in Fig. 1.1. The buoyant economy caused an unprecedented increase in population, necessitating the clearing of forests further away to provide agricultural and pastoral land for increased food production and more timber for fuel and shelter. For example, authorities in Messenia gave tax concessions to settlers who would clear the more remote hilly areas of forests and bring them into agricultural production (Perlin, 1989). Consequently, settlement moved into the hills. Woodcutters, bronzesmiths and potters moved north in the Peloponnese Peninsula, away from the centres of population and into higher country where the forests remained. However, in due course, poor soil management took its toll. Crop yields were reduced because of declining soil fertility. Sparsely vegetated soils were prone to erosion by wind and water. This was particularly so on denuded hillsides, where large amounts of soil eroded and were deposited as sediments downstream. The bare eroded hillsides greatly increased run-off after rain and promoted flooding.

Homer frequently refers to devastating forest fires and floods that uprooted trees and carried them along in the torrents. Forest fires would not necessarily cause significant deforestation unless agriculturalists and pastoralists moved in to occupy the burnt areas and it is likely that this happened to some extent. The clearing of upland forests may have exacerbated the floods and the consequent sedimentation of the rivers of the plains, but floods would still have occurred irrespective of forest clearing. It is easy to overstate the singular role of deforestation in causing floods and increasing sedimentation to streams. Any form of vegetation removal from upland sites will expose soil to erosion and increase the run-off and sediment load to streams. Deforestation, poor agricultural practice and overgrazing would all have contributed to the large-scale soil erosion and sedimentation that occurred in the late Bronze Age of Mycenaean Greece. Inevitably the stage was reached in which there was not enough arable land to support the population and not enough readily available timber to support the wood-based industries. Mycenaean Greece received some respite by importing grain and timber from Troy but eventually, from about 1200 BC, Mycenaean Greece became impoverished, population numbers crashed and the inhabitants migrated to better sources of food, fuel and shelter or else retrogressed to a subsistence economy (Perlin, 1989).

Attica

Attica, the countryside around Athens, was well forested in the 6th century BC. Agriculturalists had already cleared some of the soils and probably most of the better soils. Theophrastus (De Historia

Plantarum), writing in the 4th century BC but looking back through the centuries, recognized the common practice in agriculture of taking the best soils and leaving the worst soils to the forests when he wrote 'use your rich soils for grains and thin soils for trees' (see Thirgood, 1981). The general pattern that developed was grain on the plains, vineyards and orchards on the foothills and middle slopes leaving forests of pine, oaks and firs on the mountains, which also served as summer grazing. At this early stage, however, the boundaries would have been quite diffuse and there still would have been significant areas of forest remaining on the plains. Olives (*Olea europaea*) were cultivated and elm and poplar were planted as fodder trees. At the end of the 6th century BC, timber was readily available and most of it would have been used for fuel. Also the Athenian navy was small at this time, having fewer than 100 ships (Meiggs, 1982).

The situation changed from the beginning of the 5th century BC. Persia controlled the forests of most of northern Greece and all of Asia Minor and was particularly concerned with denying Athens access to shipbuilding timbers. However, with the ready access of local timber in and around Attica for shipbuilding and silver from the mines at Laurium to finance it, Athens increased the size of its navy and became the leading maritime power of the area. This was the most important factor in the victory of the Greek States over Persia at the battle of Salamis in 480 BC. However, the Persians inflicted enormous damage on the houses and buildings of Attica. Supremacy of naval power was again the key to the eventual victory of Athens over Persia in 469 BC (Meiggs, 1982), after which the Athenians were in a position to rebuild their sacked city with style and splendour. The golden age of Athens began. It was accompanied by the inevitable pattern of greatly increased wood consumption to support grandiose building construction (such as the Parthenon), to provide fuel (particularly for the silver mines of Laurium) and to provide shipbuilding timbers for a city-state with greatly increased population (Gomme, 1933) intent on maintaining supremacy of sea power (Perlin, 1989). By far most of the wood consumption was for fuel. Hughes (1994) estimates that 90% of the wood consumption over the whole of the classical Mediterranean was for fuel, particularly for metal refineries and pottery kilns.

Eventually and inevitably, Attica became progressively deforested and this was reflected in an increase in the price of wood and the adoption of passive solar designs to maximize the penetration of winter sun into the living areas of the houses. Athenians imported timber from the nearby island of Euboea and further afield. Macedonia and Thrace became the major sources of shipbuilding timber and the Athenians established trading cities on the coast to access these forests. Athenians, after one unsuccessful attempt, eventually took control of Amphipolis, a trading city accessing the plentiful forests of Macedonia. This allowed Athens to supplement its dwindling timber supplies and also to prepare for the forthcoming protracted war with Sparta, the Peloponnesian war. Recognizing that Athens had maritime superiority, the Spartans fought back by targeting the forests. When the Spartans invaded Attica they cut down most of the trees and laid the landscape bare. This not only denied Athens access to local timber to maintain its fleet, but also the bare hillsides became very badly eroded, the amount of run-off increased greatly and previously arable lowlands became unproductive mosquito-infested marshes. People living on the land that became marshes re-settled elsewhere, which placed additional pressure on the arable land base. The Spartans then captured Amphipolis in 422 BC, further denying timber supply to Athens (Thirgood, 1981; Perlin, 1989).

The Peloponnesian war lasted from 431 BC to 404 BC. For most of this time neither party had a decisive victory and there was also a short truce in the middle of this period. However, the amount of timber required to sustain this protracted war was immense and Perlin (1989) gives a range of graphical examples of this prodigious consumption. Athens unsuccessfully invaded Sicily in 415 BC to get access to timber supplies of Italy and Sicily, and in the process lost almost all of its fleet. However, Athens reached agreement with Macedonia to supply timber so that it could rebuild its fleet and subsequently destroy the whole Spartan fleet off the coast of Asia Minor. Sparta had an agreement with the Persian governor of Asia Minor to have access to the forests of Phrygian Mt Ida (Hughes, 1994) and Sparta rebuilt its fleet. In 404 BC, Sparta surprised the entire Athenian fleet while it was beached and its crew were on land looking for food (Perlin, 1989). They destroyed the whole fleet and Athens was defeated. There are numerous examples in the classical Mediterranean of security of access to forests being the key to maritime superiority, which in turn determined the balance of power (Hughes, 1994).

At the end of the Peloponnesian war, Attica was an environmental mess. There had been wide-scale deforestation and fertile soil on the hill country had eroded and left relatively impermeable sub-soils that shed more rainfall to marshes and the sea. Consequently, the upland soils stored less water and previously reliable springs dried up. The dreadful state of Attica alarmed some 4th century BC Athenians. It is clear that some writers of the period appreciated some of the basic aspects of managing landscapes to retain their productivity. Plato (Critias, 111c) appreciated what Attica had been like and what it had become:

> The result is that Athens is now like one of the small islands, the skeleton of a sick body with barely any flesh on it. In those early days the land was unspoilt: there was soil high upon the mountains, and what we now call shrub had fields full of rich earth. There was abundant timber on the mountains and of this you can still see the evidence. Some of our mountains can now only support bees; it is not long ago that trees from these mountains supplied roof-timbers for the largest of our buildings, and the timbers are still sound. And there were many other tall trees cultivated which provided food in plenty for livestock. The year's rain did not, as now, run off the bare earth into the sea, but the water coming down from the hills was preserved underground and fed springs and rivers. One can still see sacred memorials where springs once existed.

This is also the period in which Theophrastus (370–285 BC), a pupil of Aristotle and Plato, wrote his *Aetiology of Plants and Enquiry into Plants*, which was the most extensive and reliable treatise of the period on the classification, description and uses of plants and particularly trees. It is not until Pliny and his *Natural History*, completed in AD 77, that there was a work of comparable stature. It is also somewhat ironic that significant advances in the standards of agriculture were made during the environmental degradation of the 5th and 4th centuries BC. Superior breeds of plants and animals were selected, manures and mineral fertilizers were used, crops were rotated and a literature on agricultural practice developed. Perhaps this was a response to the shrinking of the arable land base necessary to support a burgeoning population.

The Romans destroyed Corinth in 146 BC and Greece came under Roman control. The cultured Greeks resented the less cultured but militarily superior Romans. Rome's record of environmental management is a poor one and Greece felt the impact of this. Rome sacked Piraeus in 86 BC and cleared most of the remaining trees on Attica (Meiggs, 1982). The Greeks had a relatively conservative ethic and recognized that the land needed to be rested. Rome on the other hand had a more aggressive approach, considering it could maintain soil fertility without the need to rest the soil. Rome replaced the small-scale peasant farm of the Greek city-states with large-scale, centrally organized, slave-based farming units to feed Rome and its dominions (Thirgood, 1981). Indeed Toynbee (1935) attributes this as the main reason for the eventual collapse of the Greek city-states.

Macedonia

Macedonia was a relatively well-forested part of the Mediterranean. In the 4th century BC, Athens imported its wood from Macedonia because it had none of its own. Other powers in the region wanted control of the Macedonian forests and a succession of alliances and betrayals ensued to try to achieve this. Eventually Phillip of Macedonia, father of Alexander the Great, conquered Amphipolis in 356 BC and consequently had complete control of the supply of timber to the whole of Greece. Phillip used his abundance of timber as bribes and incentives to turn governments against each other and to further his own cause. Later the Macedonians used their forests for their own development and subsequently became the dominant power in much of the world known to them at that time. This continued until Rome conquered Macedonia in 167 BC. Macedonia became a Roman province in 148 BC and the Romans, recognizing the relationship between timber and the balance of power, prohibited the Macedonians from felling their own trees (Perlin, 1989).

Rome

Before Rome came to prominence it was surrounded by forest. Indeed, most of Italy and its neighbouring islands were extensively forested. Fir, spruce (*Picea*) and pine were found at the higher elevations and beech, oak, hornbeam (*Carpinus*) and linden (*Tilia*) at lower altitudes. When the Etruscans controlled Rome in the 6th century BC, supply of timber greatly exceeded demand and relatively little forest clearing had occurred to support agriculture. After the Gauls sacked Rome in 390 BC there was pressure to quickly rebuild the city and citizens were given permission to cut timber wherever they pleased, providing they constructed their home within one year (Meiggs, 1982). There still remained, however, extensive forests around Rome. In 310 BC, the Ciminian Forest, about 100 km from Rome, was reported by Livy as being so dense that it was impenetrable. The protracted wars between Rome and Carthage in the 3rd century BC required a navy and the ships were built in Rome made from timber, especially fir, probably from the Apennines. Carthage was finally defeated by the end of the 3rd century BC and Rome had acquired Spain, Corsica and Sardinia. In the 2nd century BC, Greece, Macedonia and Syria became Roman provinces. The Roman Empire at its zenith in the 1st century BC had some degree of control over all of the lands surrounding the Mediterranean and Western Europe as far as Britain.

During this colonial expansion, Rome changed its agricultural practice from subsistence farming on small properties to a trading enterprise based on broad-scale agriculture and grazing, often using slave labour. The population of Rome greatly increased and lowland forests around Rome and elsewhere in Italy were cleared to provide land for agriculture and grazing. Timber was taken from the higher and more remote forests to meet the greatly increased consumption of wood for fuel and construction. When supplies became scarce, Rome moved into her colonies and repeated the exercise. Thus large areas of forest in North Africa and Spain were cleared to provide grain to Rome. When Rome ran short of timber in Italy, it imported timber from Spain, North Africa, Gaul and Britain. Even though there was considerable deforestation and environmental degradation at the hands of the Romans, Italy was spared the full brunt of this because Rome exported much of its destructive behaviour to the colonies.

Many of the forests of Italy were under state control with systems of management and regulation. Forest guards not only guarded the forest from unauthorized activities, but eventually came to control cutting, harvesting, hunting, watershed protection and silviculture. Sacred trees and groves were set aside as reserves. Coppicing, thinning, pruning, plantation establishment, tree breeding, controlled pollination and introduction of exotic species all occurred to some extent (Thirgood, 1981). However, the insatiable appetite for food and fuel overcame any semblance of sustainable management.

The Roman colonies brought considerable wealth to Rome and the citizens of Rome responded with excesses. The dramatic increase in population meant a boom in private housing construction. Hellenistic influences in the 2nd century BC encouraged more elaborate public building construction and over the next several hundred years there was a passion for greater and more magnificent buildings. Timber species were fir, pine, oak, elm, chestnut, poplar and cypress. The architects of the day had good knowledge of their wood properties and uses in construction. Building activity was assisted by the relatively regular occurrence of disastrous fires in the city. Julius Caesar initiated an unprecedented building boom commencing about 50 BC, which continued after his assassination in 44 BC through to and following the death of Augustus in AD 14. Italy was still well forested at the start of the building boom and it was only in the later days of the empire that Italian forests came under significant pressure, particularly for fuel. The amounts of timber used in construction would have been small relative to the amounts of wood or charcoal used in cooking, heating and cremation.

Wealthy Romans used large amounts of wood to centrally heat their villas. Also Romans had a penchant for hot baths and the amount of wood required to support this habit was prodigious. Emperors competed for constructing the most elaborate public baths and towards the end of the empire there were over 900 public baths, some catering for more than 2000 bathers at a time. Whole forests close to Rome were cleared to support the habit and considerable effort was directed towards searching far and wide for wood to fuel the baths. Industries requiring wood as fuel developed in parallel with the rise of the empire. The amount of wood-fired bricks increased and wood fuel was used for smelting iron and bronze and for making pottery. Water pipes and aqueducts were made from lime-based concrete or clay, both of which required wood fuel. Glass manufacture developed in the 1st century BC and subsequently consumed large amounts of wood as fuel. Towards the end of the empire there were clear indications of shortage of wood for fuel. Charcoal was substituted for wood, fired bricks became thicker and used less mortar, glass was recycled, and there was a return to mud-brick construction. Fuel shortages progressed to the colonies. Shortage of local supplies of fuelwood around smelting operations in southern France and in Britain caused the smelters to relocate to better-forested areas (Perlin, 1989). Copper mining in Cyprus and iron smelting on Elba depleted the islands' forests, although there was still significant amounts of forest on Cyprus at the end of the Roman Empire (Meiggs, 1982). Silver mining in Spain over 400 years was particularly destructive of the forests, precipitating a shortage of silver and a dilution of the amount of silver in coinage. This was caused by shortage of wood and not shortage of silver ore (Perlin, 1989).

Rome, like Greece, suffered the general pattern of environmental degradation shown in Fig. 1.1. Over-population and urbanization promoted deforestation, soil erosion, siltation, overgrazing and loss of soil fertility. A flood in Rome in 241 BC inundated the lower parts of the city and blocked up the sewers. This in itself was not necessarily an indication of deforestation. However, it coincided with the time when the population of Rome began to increase, in turn accompanied by agricultural expansion. Records indicate that floods increased after that date (Hughes, 1994). Deforestation caused significant erosion in Italy. Silt from deforestation of the Tiber River catchment landlocked Rome's coastal port. The Po River catchment was originally covered in forests but the lowlands were cleared for agriculture, followed by the foothills and then some of the higher country. Consequently, by the time of Christ, marshes had developed near the coast and some coastal settlements had become surrounded by water. Modern deforestation of the headwaters of the Po has greatly contributed. Today, Ravenna (the coastal port in the times of the Roman Empire) is 10 km from the sea and the riverbed is up to 3 metres higher than the surrounding floodplain over 350 km of its course (Winters, 1974).

Agriculture expanded at the expense of forests. Rome offered free possession to anyone who would clear the forest and bring it under cultivation. The prevailing attitude was that progressively clearing the forests for agriculture was a sign of progress. Rome was particularly efficient at deforesting its colonies. For example, by the end of the 1st century AD, North Africa was sending sufficient grain to meet two-thirds of the requirement of Rome's population of approximately 1 million people (Meiggs, 1982). The cultivated area to support this enterprise was originally covered in good-quality forest. Rome depended on its colonies to supply its food and if the harvests failed the consequences for Rome were dire. Towards the end of the empire, famines in Rome were not unusual.

Like their Greek counterparts, the Romans understood some of the basic principles of good agricultural practice and developed a literature in this area. Animal (including human) manures were used, composting was recommended, rotation with legumes was practised, limestone and chalk were used as fertilizers, marble was burnt to make fertilizer, soils were fallowed, weeds were controlled by ploughing, and hill country was terraced to prevent soil erosion (Hughes, 1994). Even so, the soils lost their fertility. Lucretius (translated by Humphries, 1968, see Hughes, 1994) recognized decreasing harvests.

> But the same earth who nourishes them now
> Once brought forth, and gave them, to their joy
> Vineyards and shining harvests, pastures, arbors,
> And all this now our very utmost toil
> Can hardly care for, we wear down our strength
> Whether in oxen or in men, we dull
> The edges of our ploughshares, and in return
> Our fields turn mean and stingy, underfed,
> And so today the farmer shakes his head,
> More and more often sighing that his work,
> The labour of his hands, has come to naught.
> When he compares the present to the past,
> The past was better, infinitely so.

Columella (Rust 3.3) noted that no one alive in his day could recall when the harvest produced as much as four times the seed that had been sown. Clearly the agricultural principles espoused in the literature, particularly by Columella, were not followed. Also clearing for agriculture probably moved onto marginal lands with soils of lesser fertility. The frequent wars that the Romans instigated greatly disrupted agriculture. Armies lived off the land, targeted crops for destruction and conscripted or killed farmers, thereby denying them the opportunity to maintain their terraces and manure the soil. Siltation studies show that catchment erosion was most rapid when there was war in that catchment. Declining agricultural production in Italy was supplemented by imports from the colonies and much cultivated land in Italy was given over to pasture. The inevitable consequence of agricultural decline was famine and depopulation (Hughes, 1994).

While it is true that good fertile soils support good forests, the reverse, that good forests must grow on good soils, is not necessarily true. Pliny partly recognized this when he said 'A soil in which lofty trees do brilliantly is not invariably favourable except for those trees: for what grows taller than a silver fir? Yet what other trees could have lived in the same place?' (Hughes, 1994). Given time, forests can support large trees even on relatively infertile soils. They do so by being very efficient at recycling nutrients. A significant proportion of the nutrients on the site are contained in the trees and when these trees are felled for agriculture, the nutrients are lost from the site. Roman farmers cleared good forests only to find that the soil was not good for permanent agriculture.

Towards the end of the Roman Empire both capital and labour became scarce in Italy and depopulation continued. Cultivated land and pastures were abandoned and reclaimed by the forest. The country was weak, disorganized and ripe for invasion by the Goths and the Vandals in the 5th century AD (Thirgood, 1981). This marked the end of the Roman Empire and the start of the 'Dark Ages'. There were many factors contributing to the decline of the Roman Empire. The reduction in agricultural productivity and the environmental degradation through deforestation, soil erosion and overgrazing were major contributing factors. A period of restoration of the forests began after the fall of the Empire.

The Mediterranean after Rome

Considerable regeneration of forests would have occurred during the Dark Ages. In the Middle Ages and beyond, however, cycles of depletion and regeneration of forests occurred up to and including the present. Overall, there has been a net decline in the forests since Roman times and today the forests and woodlands of much of the Mediterranean are very degraded, fragmented and much reduced in area. They are largely restricted to poor soils in the higher country. In classical times there was little concern about the plight of the forests and little appreciation of the consequences of over-exploitation. However, it would be unfair to blame the classical and pre-classical civilizations for the deforestation and forest degradation evident in the Mediterranean today. There were still relatively extensive tracts of forest in the better-watered and/or less accessible country at the end of the classical period. The Mediterranean remained a centre of civilization for many centuries after the fall of the Roman Empire. The centre of activity was first in the east around Constantinople, but later moved to the west around the maritime republics of Pisa, Genoa and Venice, and later Spain and Portugal. The rise of these maritime trading powers and the consequent increase in population and living standards re-imposed the need for clearing forest for agriculture and timber. It also heralded the beginning of a whole new era of colonialism, because other continents had now become accessible.

Many of the forests that were severely exploited recovered and indeed have been through several cycles of exploitation and recovery. These cycles happened at different times in different places. For example, deforestation of Crete was a factor in the demise of the Minoan civilization in 1450 BC and yet cypress imported from Crete was used for the construction of the Venetian fleet in the Middle Ages. In the 16th century, the Idhi mountain range in Crete was covered in cypress; a century later it was described as a barren spot (Meiggs, 1982). The city of Iraklion is located near the site of ancient Knossos, the major city of Minoan Crete. In the 17th century AD, Iraklion repeated the deforestation of the ancient Minoans such that no more local supplies of firewood were available (Clutton, 1978; Perlin, 1989). The forests on Cyprus provided timber for shipbuilding (Meiggs, 1982) and bronze smelting (Perlin, 1989) in the Bronze Age. This depleted the forests on Cyprus and the kings on Cyprus responded by conservatively managing their forests only to have subsequent rulers take advantage of their efforts and deplete the forests further (Hughes, 1994). Meiggs (1982) gives evidence describing the gradual clearing of the forests on the plains of Cyprus in the 3rd century BC, but noted that Cyprus was well forested in the 4th century AD. At the beginning of the 14th century, Cyprus was extensively deforested to grow sugar cane for two centuries (Westoby, 1989), after which the sugar trade found alternative sources of supply. Some recovery of the forest in Cyprus followed. In the 18th and 19th centuries Cyprus again increased its population and the forests were seriously depleted for fuel, and overgrazing by goats hindered their recovery. Cyprus today has well-managed forests and sets a fine example to surrounding countries (Thirgood, 1981). Despite the deforestation and the degradation of the Po Valley by the Romans, parts of the valley were still well forested in the 5th century AD because they acted as shelter to the invading barbarians (Winters, 1974). After the decline of Rome, the population of Italy collapsed and the forests regenerated. Good local timber was available to the Renaissance centres of Rome, Florence, Venice, Pisa and Genoa, and the cycle of deforestation, soil erosion and overgrazing started over again. These city-states prospered and their populations increased, as did the proportion of the population not directly involved in producing food. Accordingly, they became big importers of food, which they obtained by deforesting areas of the wider Mediterranean. Venice and Florence responded to the pressure on the forests by establishing silvicultural regimes that mark them as the pioneers of European forestry. North Africa was extensively deforested by the Romans, but recovered following the decline of the empire. It then became depleted yet again on the establishment of a pastoral culture (Thirgood, 1981). Essentially deforestation over the Mediterranean occurred where populations increased and reforestation occurred where populations decreased and people moved out of the area.

These examples are testimony to the wonderful capacity that, given time, forests have to regenerate and recover after even the most destructive logging. This should not be used as an excuse to degrade forests with cavalier abandon. The forest degradation and deforestation in the Mediterranean have been associated with depletion and extinction of wildlife. The replacement of wildlife with the domestic goat and the feral cat has been disastrous. Arguably the most destructive agent in arresting or delaying the recovery of degraded forests has been overgrazing. It follows that the best way to promote regeneration and recovery of degraded forests over the whole of the Mediterranean is to protect the area from grazing.

There is no doubt that the ancients were responsible for extensive deforestation, overgrazing, soil erosion and scarring of the landscape. However, their capacity to degrade was limited by population, technology and transport. The worst period for environmental degradation in the history of the Mediterranean was the late 19th and 20th centuries. The region now supports very large and rapidly increasing human populations. Improved transport and technology have provided access to previously inaccessible forests. Wars aided deforestation in classical times and this was also the case in the 20th century in which the First and Second World Wars were particularly hard on the forests of Italy and Greece. In the context of the forests of the Mediterranean having gone through a series of cycles of degradation and recovery, the forests are now (hopefully) at the end of a particularly intense destructive phase and looking forward to recovery. Over the last 30 years or so the pressure on the Mediterranean forests for fuel, agriculture and grazing has declined (Ball, 2001). There has been considerable progress made in forest management by some countries in the region.

Easter Island

Easter Island is a remote island in the southern Pacific Ocean about 3750 km west of Chile. It was settled by Polynesians, perhaps in the 5th century (contested), at which time the island was covered by mainly palm forest. At first, and for many centuries following, food production was easy, allowing plenty of free time for the inhabitants to develop an advanced civilization. By the 10th century the islanders had developed religious observances that necessitated the construction of giant stone statues (Moai). By the year 1500, hundreds of the giant statues had been constructed. As the population further increased to perhaps 15,000, trees were cut down for agriculture, fuel, housing and canoes and particularly for the transport of their large statues. From 1500, shortage of wood meant people had to live in caves and by 1600 the island was almost completely deforested. Soil was leached and eroded and agricultural productivity declined. Canoes could no longer be built and so islanders were marooned on their own island, unable to escape their fate. Their society disintegrated. Post 1800 European introduction of disease (tuberculosis) and animals (rats and sheep), together with slave raiding, contributed to their demise (for further details see Diamond, 2005; Peiser, 2005; Hunt and Lipo, 2006; West, 2008).

Temperate Europe (with particular emphasis on England, France and Germany)

The Romans not only depleted forests in their vicinity, but also depleted the forests of Spain, the Rhone Valley in France and southern England and Wales (Westoby, 1989). After the fall of the Roman Empire, England had only 15% of its area as forest. Most of continental Europe, on the other hand, was still well forested until the Middle Ages.

Dimbleby (1976), however, provided evidence of significant deforestation having occurred in temperate Europe in the Mesolithic and Neolithic. This suggests that some recovery of the forests had occurred prior to the onslaught of the Romans. It is probable that almost all of the forested areas in temperate Europe have come under the influence of human interventions at some time or other and that wilderness as such does not exist.

The peasants revolt

Although the details of the history of forests in Britain, France and Germany differ, there are some common threads. Before the Middle Ages, the occupants of the land were somewhat similar to the hunters, gatherers and early farmers of the Neolithic. The forests were used as communal property for fuel, building materials, hunting and supplementing their food supply. The occupants lived in close proximity to the forests and had a strong conviction that they had a right to use the forest. Their customary rights to the forest developed over a long period. The attempted repression or extinction of these rights caused great dissent in all three countries over a period of 1000 or more years, up until the time the rural culture was replaced by an urban culture in the 19th century. In other parts of the developing world where a rural culture still exists, the repression of customary rights to the forest remains a significant issue today.

Two ingredients came together to mount an onslaught on customary rights. The first of these was a power structure with the capacity to enslave or subjugate, and the second was recognition that the forests have value. The power structure that developed was one where the aristocracy (kings, barons, dukes, lords, princes, clergy or whoever) demanded that the peasant work for them first and for themselves last. The epitome of this was the development in medieval times of the feudal structure where the peasant or serf ostensibly was given a small parcel of land by his feudal lord who extracted a proportion of the harvest as rent. The peasant might have some rights to use cleared land for grazing and to use the forest for fuel and other needs. This reinforced the peasants' belief that they had inalienable customary rights to the use of the forest. Feudalism essentially bound the peasant to the land for life, with no chance of a reprieve. The second ingredient was the realization that the forests have value and the overriding value placed on the forests by the aristocracy was as a resource for hunting for pleasure and for food. The aristocracy therefore set about appropriating the forest for their own pleasure, systematically eroding the customary rights of the peasant to the forests and instituting and enforcing draconian penalties for poaching and trespass. Also, because the aristocracy controlled the forests, they could provide timber and fuel to those who could pay their price and it also put them in a strong position during periods of shortage in wood supply. By the Middle Ages, much of the forest was in the hands of the aristocracy and the church. While this caused great bitterness among the peasants, it had the one advantage of protecting the forests from undue exploitation (Barton, 2002). The first serious attempts at forest management in Europe were to manage game rather than regulate timber supply. Forest history in Europe is dominated by the struggle between the aristocracy to extinguish customary rights and the peasants to keep them.

In Britain, William the Conqueror strengthened his hold over the royal forests by producing, after the Battle of Hastings, the 'Charter of the Forest'. This was a set of forest laws aimed at legitimizing his and future kings' rights to greater control over existing forest and to acquire new forest. The term forest in England in medieval times was used quite loosely. Effectively it was any unoccupied land that was not cultivated, on which the native vegetation of the district grew and that may or may not have included trees (James, 1981). William also commenced the Domesday Book, which in essence was an inventory of what he could claim, or intended to claim, as his own property. This included the forests. William's forest laws upset the English barons, but it took a further 200 years before they could respond. A new 'Charter of the Forest' issued in 1225 was directed at reducing the power of the king over the forests, but it had little effect on the plight of the commoners. The Charter was re-enacted more than 20 times over the next 150 years, which serves to emphasize the importance that the kings placed on the forests and the mistrust that the barons had in the kings. The power of the king over the forest fell away during the 16th century, largely owing to indifference and corruption. Ownership and control of the forests still lay in the hands of the powerful few and attempts to enclose common land were met with great resistance from the tenant farmers until such time that customary rights were permanently extinguished.

The English tenant farmer relied on the forests for fuel, grazing land and food, and in lean times this could make the difference between life and death. They resisted any attempts to curtail these rights. The Peasants' Revolt against the landed clergy in England in 1381 was one of the first examples of organized resistance. The legend of Robin Hood, who 'steals from the rich to give to the poor', epitomizes the anger that the peasants felt about the unreasonable demands of their landlords and the erosion of their customary rights in the forests. Poaching was one of the main forms of resistance, but occasionally it was outright forest destruction. In 1723 the British Parliament passed the 'Black Act', which created 50 new capital offences, including hunting, stealing or wounding deer, unauthorized cutting of trees and even blackening the face as a disguise (Westoby, 1989). Retribution against offenders was swift and terrible and castration of offenders was not uncommon.

Similarly in France, royalty, the nobility and the church progressively took possession of the forests during the Middle Ages. As in England, the principle purpose was for hunting and the conservation of game. Again this had the unplanned but welcome outcome of conserving the forest. The feudal system that developed in the 12th century conferred communal privileges and rights, but these were always at risk of being eroded by the nobility. Ordinances regulated forest use in France from the 12th to the 17th centuries. By the middle of the 17th century, however, forest devastation, poor management and crimes against the forest had progressed so far that Colbert recognized that 'France will perish for lack of woods' (Grober, 2007). He instituted the forest ordinance of 1669 to bring some order into the use of the forests and to prosecute those who did not comply (Fernow, 1907). The conflict between forest owners, gamekeepers, foresters and forest guards on the one hand and poachers and peasants exercising what they considered to be their customary rights on the other, progressed from the 12th century through to the beginning of the 20th century. Following the French Revolution in 1789, nearly 3 million hectares of forest were confiscated, becoming part of the national domain, which the peasants interpreted as their common property. 'Theft' of timber and fuel and other 'crimes against the forest' increased. The forest code of 1827 was imposed to conserve the forest and to regulate yield, but the peasants saw this as a further erosion of their rights to collect fuel and timber and to graze their animals. This led to violence over the next couple of decades. Westoby (1989) recounts a piece of savagery where the peasants would cleave a log with an axe, force the hand of the forester into the cleavage and then withdraw the axe. After the mid 1800s the number of crimes against the forest decreased. By the end of the 19th century the social order had changed to the extent that the customary rights of the rural poor were no longer an important issue for them, effectively extinguished.

In Germany after about 400 AD the people were mainly herders, gardeners and hunters. Outside of their immediate yard and garden, all property was communal and their rights to the forest were at first unchallenged. The forests largely remained communal property until the 13th century, but customary rights were eroded over time. As early as the 7th century there were tracts of forests controlled by the kings and the nobility. The overriding value of the forest to the nobility was for hunting, but they also extended their income, influence and territory by clearing land for agriculture and grazing and by selling timber. It was at this time that the German word 'forst' originated, from which the English word 'forest' is derived. The word for normal woodland was 'silva', but it was called 'forst' if it was necessary to secure a property against the interests of other claimants (Kiess, 1998). From the 7th century, the kings forbad trespass on their forests and in the 10th century they extended this to territory not belonging to them. They established banforests, which under special forest laws enforced by forestmasters consolidated the right of the kings to hunt exclusively wherever they chose. The wooded areas were not continuous over the country, but occurred as a mosaic with cleared land. The size of the forest, as in England, was often expressed as the number of pigs it could support. This demonstrates that the forests had some agricultural significance. The hunting rights of the sovereign remained supreme, however, and ensured that the forests, irrespective of ownership, were not devastated (Kiess, 1998). The kings granted land to barons, bishops and officials in return for hunting rights and the barons and bishops in turn declared the ban for their own use, which ultimately meant that the commoners had restricted customary rights to hunt and fish in the forests. This practice of higher ranking persons granting land to lower ranks in return for service marked the beginning of the feudal system in Germany. By the time it trickled down to the lowest rank (the vassal), the rights to use the forests were somewhat reduced, although not yet extinguished (Fernow, 1907).

The preoccupation of the nobility with the right to hunt helped to conserve the forest. As in England and France, however, the progressive whittling away of property and customary rights among the common folk led to resistance and sometimes outright rebellion. From the 12th century until the 18th century, squatters appropriated forested land without regard for property rights (Fernow, 1907). Again, as in England and France, penalties for trespass and poaching were severe. Westoby (1989) recounts an act by the Archbishop of Salzburg (in Austria) who in 1538 publicly executed a poacher by having him sewn into deer skins and thrown to the bloodhounds. The church (Catholic and later Protestant) was a major forest owner in Germany. There was a peasant rebellion in southern Germany in 1525, which, among other things, sought to restore the customary rights to hunt, fish and collect wood from the forest. This rebellion was savagely suppressed by the union of Protestant princes, the Swabian League, with the apparent approval of Martin Luther, who strongly supported the property rights of the princes (Westoby, 1989).

After the Middle Ages, from the start of the 16th century, the feudal system deteriorated and more modern organizations of property and power took their place, but the displaced feudal vassal still retained some residual rights to the use of the forest (for grazing stock and collecting litter and wood). From the 16th to 19th centuries there was considerable pressure on the forests. It was during this period that the foundations for silviculture and management were established and many restrictions on forest use were introduced. However, effective forest management was seriously impeded by the exercise of the residual customary rights of the rural landowner/tenant until these rights were effectively extinguished in the 19th century. The restrictions on forest use in Germany had a profound flow-on effect on political and socioeconomic thought. Karl Marx's path to socialism began with his concern over the laws relating to the theft of wood from the German forests.

The fate of the forests

England was extensively deforested by the Romans and therefore the availability of agricultural land has not been a major issue since. In continental Europe, however, clearing forest for agricultural land was a major cause of deforestation after the Middle Ages. The same general principles applied to the deforestation of England, France and Germany as applied in classical times. Deforestation followed increases in population and living standards. The pressure was taken off the forests during the periods of low population following the sacking of Rome in the 5th century and the Black Death in Europe in the mid 14th century. For 200 years following each of these events, the forests had time to recover.

Population and wealth increased in the 12th, 13th and first half of the 14th century. This was also an active period of deforestation, for farmland in France and Germany and for wood products in England. Germany was extensively deforested during this period and ordinances for strict felling and forest use were issued in response. The first prohibition of clearing in Germany was in 1165, followed by ordinances to limit the cut, preserve the best trees and to use only dry wood. In England in 1184, the Assize of Woodstock proclaimed forest laws, distinct from common law, which controlled forest use mainly to protect deer. Over the next 200 years, forest legislation in England was mainly about the rights of the king or his barons to the game rather than for the care of the forest.

The hold of the kings and nobility over the forests had weakened considerably by the 16th century, after which the emphasis on the use of the forests switched from hunting to the provision of wood. This marked the start of another period of pressure on the forests, which was most intense in the 17th and 18th centuries. This was a period of great devastation of the forests, caused by increased fuelwood consumption (for cooking, heating, smelting metals, manufacturing glass, producing salt), building construction, pit props for mining, shipbuilding (England and France), fires (Germany), civil wars, famines, clearing land for agriculture (mainly Germany and France), poor forest management, theft of firewood and forest products, browsing of regeneration by game, lack of forest inventory, and corruption and ignorance of officials. In France, the forest area decreased from about 35% at the beginning of the 16th century to about 25% by the middle of the 17th century (Ball, 2001). Following the 1762–1776 famine in France, tax concessions were given to farmers to encourage them to clear even more forest for agriculture. The shortage of firewood in England in the 17th century prompted the burning of wheat stubble, weeds and animal dung, which reduced the fertility of the soil. The reduction in forest area and the poor condition of the residual forest in all three countries promoted a raft of regulation to limit forest use and the development of rudimentary forest management.

In England during this period (16th to 18th centuries) there were regulations to protect coppice, promote regeneration, retain underwood, limit forest clearing, conserve firewood, limit the use of wood as a fuel for smelting iron, deal with unlawful cutting, limit agistment of grazing stock to ensure food was available for deer, encourage the planting of trees, and change ship design (James, 1981). Colbert's French Forest Ordinance of 1669 recommended replacing local regulation and customary use with a national policy and, following the French Revolution of 1789, even more forest land came under state control. Regulations on forest use included control of grazing, hunting, replanting, road building, conservation of firewood and restriction of felling and clearing. The Forest Code of 1827 imposed further limitations on use of French forests. In Germany the first regulations were to protect the forests for hunting, but these later progressed to conserving timber. Regulations restricting forest use included imposing diameter limits for felling, using building codes to ensure that wood was used efficiently, encouraging alternatives to wood in building construction, having hedges and ditches instead of wooden fences, using poorer woods for fuel, using windfalls in preference to standing trees, prescribing economies in charcoal burning, substituting turf and coal for firewood, regulating the use of litter and protecting regeneration from grazing. Eventually no felling of trees at all, on private or public land, was permitted without permission of a designated forester (Fernow, 1907). Devastation of forests in other countries in temperate and boreal Europe occurred over roughly the same timescale. Regulations to control forest use were introduced into Denmark and The Netherlands in the 18th century and into Norway and Sweden in the late 19th century (Ball, 2001).

The rise of silviculture and forest management

Pollen records demonstrate that the very early agriculturalists in Western Europe deliberately encouraged and may even have planted hazel and other species around their homes. They understood coppicing and pollarding, and also thinning and spacing to encourage the growth of favoured trees. The ancient Romans were perhaps the first to establish a body of silvicultural practice (coppicing, thinning, pruning, tree breeding, cross pollination, plantation establishment), but at the onset of the Dark Ages this information became lost and had to be rediscovered 1000 or more years later. Rudimentary ideas about seed trees and diameter limits for felling were established in Germany before the end of the 15th century, but it was from the 16th century onwards that England, France and particularly Germany made progress in silviculture and management in direct response to the over exploitation of the forest occurring over this period. Silviculture and forest management progressed from trial and error in the 16th century through to scientifically based technologies in the 18th century and beyond.

In England, the preoccupation was growing oak, particularly to support the shipbuilding industry. The main silvicultural systems were coppice and coppice with standards. Coppicing occurs when cut stumps (stools) or their root systems vegetatively sprout (coppice). Coppice with standards is a combination of coppice with older and larger trees that originate from seed rather than stools. A statute in 1482 allowed the closure of forest areas for 7 years to prevent grazing of regeneration and coppice. An Act in 1543 introduced thinning as a silvicultural tool and established that a minimum number of 12 trees per acre should be left. Towards the end of the 15th century, oak and beech seed were being directly sown into the forest and the first oak plantation established from seedlings rather than sown seed was established in the mid 16th century. By the beginning of the 17th century, nurseries for raising oak and beech seedlings were more common. In 1664, Evelyn published his *Sylva*, in which he recommended that cutting of coppice should follow a regular plan to ensure sustained yield. Evelyn's *Sylva* is the pivotal discourse on early silviculture and forest management in England. Later in the 17th century coppice was being grown on fixed rotations and in the 17th and 18th centuries there was a considerable increase in the area of forest set aside for timber production. These came from enclosing and managing existing forest areas and hedgerows. The forests were coppice alone or under standards of mainly oak, ash, birch, hazel and alder. However, in addition to coppice there were increasing areas of plantations being established.

The crown forests remained in poor condition into the 19th century because of poor management and corruption, damage from grazing stock and commoners still exercising their residual customary rights. Crown forests improved, however, under the tenure of the Commissioners of Woods and Forests in 1810 and the Forestry Commission in 1923. Ultimately it was realized that the oak plantations were not capable of producing timbers of a suitable size to the navy quickly enough and landowners turned to the faster growing conifers. Even though the conifers Norway spruce (*Picea abies*), silver fir (*Abies alba*), European larch (*Larix decidua*) and Corsican pine (*Pinus nigra*) had been introduced from continental Europe in the 16th to 18th centuries, an escalation in the planting of conifers did not occur until Douglas fir (*Pseudotsuga menziesii*), Sitka spruce (*Picea sitchensis*) and giant fir (*Abies grandis*) were introduced from North America. Scientific forestry and higher forestry education did not begin in England until the end of the 19th century. This was largely due to the influence of French and particularly German foresters (James, 1981).

The development of silviculture and forest management began earlier in France and Germany than in England. In Germany, the first example of a forest being divided into felling areas was in 1359 and the first undisputed evidence of a conifer plantation being established was in 1368. An oak plantation was recorded in 1491. Coppice and coppice with standards was developed by 1450 and cutting limits were imposed in 1488. The retention of seed trees after logging to allow regeneration was introduced in 1524 and the protection of seed trees against wind damage was achieved in 1565 by leaving groups (and later strips) of trees around the seed trees. By 1530, there was the recognition that thinning improved growth rates of the residual stand. By 1580, coppice was being grown in planned rotation lengths and in the 17th century a literature on seed and nursery management developed. In 1720, the shelterwood silvicultural system for protecting the young developing crop was introduced and from the mid 1700s, plantations of firstly oaks but later conifers were established to enrich poor areas of native forest or to plant waste land. Agroforestry (Waldfeldbau) was promoted in 1744 as a means of diversifying farm incomes. The first account of the scientific basis of thinning was in 1761 and in 1764 discounted cash flow analysis was first used for comparing management regimes. Volume tables were first produced in 1770 and yield tables in 1785. By 1788 the concept of a 'normal' forest and of sustained yield was well understood (Fernow, 1907). A 'normal' forest is a mathematical construct, an ideal that does not occur in reality. A normal forest is one with a range of age classes, such that if the oldest age class is periodically removed, the next oldest age class will take its place over the period between this and the next harvest. By so doing, a sustained yield and a constant age class distribution will be maintained. The same principles apply to an uneven-aged forest where the age class distributions are segregated vertically on the same area of ground rather than horizontally on different areas of ground.

There is a significant German literature on silviculture and forest management in the 18th century, of which Carlowitz (1713), von Moser (1757) and Stahl (1772–1781) are perhaps the most significant contributors. Forestry textbooks were written and lectures on forestry presented at universities. Several forestry schools were established towards the end of the 18th century. The first was established in Ilsneburg in 1768 and the most influential in Zillbach in 1795, later transferred to Tharandt in Saxony in 1827. Students from this school established forestry schools at Nancy in France (1825) and in Spain (1848). Forestry schools were established in Austria and Russia early in the 19th century and in England and the USA in the latter part of the 19th century (Westoby, 1989). The German influence was strong in the early forestry schools and in the development of forest science in these countries (Lorentz in France; Brandeis and Schlich in England; and Fernow in the USA and Canada).

In the 19th century the forests of Germany became increasingly consolidated into the state and a lively discussion ensued about the relative merits of different silvicultural systems (selection, shelterwood and clearcutting). Selection systems are where single trees (or small groups) scattered all over the forest are removed more or less evenly and continuously. This supposedly mimics the 'natural' forest, where large individual trees die and fall over to make place for natural regeneration. The shelterwood system is where the larger trees are felled progressively rather than all at once so that some protection is offered to the young regenerating crop. Clearcutting occurs when coupes of a specified size are clear felled at intervals to develop and maintain a range of age classes over the forest.

In France (as in England), forest management was more by restrictions on forest use than by active silvicultural intervention. Colbert's ordinance of 1669 enshrined in law the requirement to keep a certain number of seed trees for all forest types under all climates and all soils and to some extent this inhibited the development of silviculture for the next two centuries. This continued until French forest practice came under German influence. However, France was the first to recognize the role of forests in protecting soil and, since the beginning of the 19th century, France has established large areas of plantations to stabilize previously deforested and overgrazed areas, particularly coastal sand dunes and mountain slopes (Barton, 2002). These forests now form an important part of the French forest estate. A School of Forestry at Nancy was created in 1825 and still exists today. It promoted German-style forest science. This was not always easy, because it was sometimes challenged as being unpatriotic. The argument between the relative merits of coppice and selection (French) versus shelterwood (German) was a major issue (Fernow, 1907).

Europe today

German and French professors and foresters established forestry as both a science and a profession and presented it to the world. Even so, the development of scientific forestry in Europe was preoccupied with timber and game. Other roles of forests were not well understood or acknowledged. It was not until the 19th century that the role of forests in protecting soil and water was first appreciated in France. Even though the concept of sustained yield was well developed before the end of the 18th century, the concept of ecologically sustainable forest management, which includes all of the values of the forest, is a relatively modern concept that developed over the 20th century. Indeed, Hume and Kant, the 19th century philosophers wrestling with the relationship between humans and nature, still believed that clearing of forests improved climate. Environmentalism and the conservation movement began in the late 19th century and foresters played an important role in this. The conservation movement had an important influence on the development of forestry in the 20th century and this will be discussed at greater length in later chapters.

The pressure on the forests of temperate Europe started to ease from the 19th century. (This 'transition' in France is shown in Fig. 1.2. Prior to about 1830, forest cover decreased when population increased. However, after a transition at about 1830, forest cover increased as population increased).

The reasons are complex but there are several contributing factors. The economic situation saw a

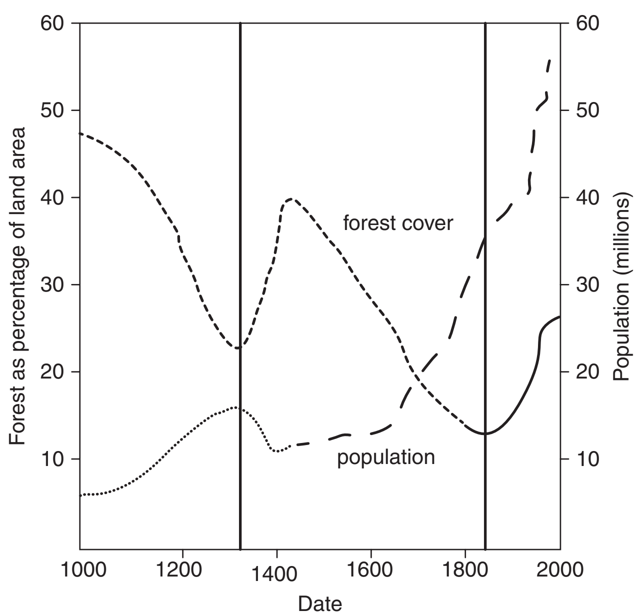

Fig. 1.2. Trends in forest area and population in France. (From Mather *et al.*, 1999.)

movement of people from the country to the city, and there was no longer the pressure of the rural poor on their immediate forests. Iron replaced wood in ships and coal and later oil and gas replaced fuelwood for both domestic and industrial uses. Substitutes for wood were found, transport improved and sources of wood from outside Europe became more accessible and more economic. Rural population growth eased and living standards rose. Scientific forest management increased yields and more intensive plantation forestry produced wood on a smaller land base. Agricultural production became more efficient and also required a smaller land base. The pressure to deforest to provide land for agriculture no longer applied and indeed was reversed. Because of overproduction in the agricultural sector in the later part of the 20th century, incentives were put in place to take agricultural land out of production. Perhaps one pivotal factor heralded the end of the wood age and the beginning of the coal age. This was the discovery in the midlands of England of a feasible way of smelting iron using coal instead of wood and charcoal. This, together with the harnessing of steam power, marked the beginning of the industrial revolution and placed England, which hitherto had been lagging, at the forefront of industrial progress.

Today Europe has a net annual increase in forest area and several countries report that the annual growth rate of their forests exceeds their harvest. For example, Sweden's forests were seriously depleted in the 17th century because of fuelwood requirements for its iron smelting industry. Today Sweden is a major exporter of wood products to the European community. Its annual increment, however, still exceeds its harvest. Growth ring analysis has shown that some of the forests of Europe are growing faster now than before. Improved forest management must be contributing to this but, ironically, two interacting environmental problems have assisted. Atmospheric concentrations of carbon dioxide have been steadily increasing since the beginning of the industrial revolution and this has the capacity to increase the rate of photosynthesis and therefore forest productivity, providing other factors such as the supply of water and nutrients can support the increase in productivity. Air pollution from coal burning in the industrialized parts of Europe has added nitrogen to forest soils. Perhaps it is this combination of increased carbon dioxide in the atmosphere supported by increased soil fertility that is responsible in part for the increased productivity that has been observed.

In many respects, Europe in the 17th and 18th centuries represents the situation in many developing countries today and maybe is an example of what these countries might look forward to and indeed might aspire to. However, Western Europe imports wood from other countries, including tropical countries (United Nations, 2001) and therefore has a responsibility to promote sustainable forest management in the countries from which it imports.

There has been a trend across Europe since the 18th century away from an intimate mixture of forest, pasture and agriculture to a landscape in which these areas have become separate, larger and more distinct (Kirby and Watkins, 1998). Also there has been the tendency for forest management to concentrate on one or a few productive species, predominantly conifers. Recently there has been a move by some to modify management to produce what is closer to the composition of the original forest on the site (a 'near natural' forest) even if this is at the expense of reduced productivity. The difficulty of course is agreeing on what was the original composition.

Colonialism

The colonial exploits of the ancient Greeks and Romans and the impact of this on the forests has already been discussed, as has that of the Italian medieval city-states. These were limited in their geographical spread. The European maritime powers after the Middle Ages 'discovered' and colonized the 'new world', which must have seemed to them to be an infinite resource ripe for plunder. The result was a new onslaught on the forests, and particularly the tropical forests, which until this time had largely escaped wide-scale deforestation.

The tropical forests of the Americas

There is a long history of agriculture and forest clearance in South and Central America (Barraclough and Ghimire, 1995). A new phase in deforestation began with the invasions by the European maritime colonial powers of Portugal, Spain, France, Holland and Britain, all of whom had some part to play in the deforestation of tropical Central America, the Caribbean and South

America from the 16th to the 19th centuries. The early explorers, being used to a temperate forest that had been subject to repeated bouts of deforestation, were awestruck by the size and magnificence of the forests that they found, as well as by the wide variety of exotic plants and animals. The areas of forests were so large that they were considered to be infinite. The richness of the forest suggested to the colonizers that the soils were very fertile. Madeira, just 150 miles off the African west coast and 'discovered' by the Portuguese in 1420, was so densely forested that the Portuguese named it 'isola de madeira' or 'island of wood'. When Columbus 'discovered' Hispaniola in the Caribbean, he reported that it had 1000 varieties of trees growing so high that they nearly reached the sky (Perlin, 1989). The wide-scale deforestation of the lowland forests of tropical America began in about the year 1500. This was mainly to meet the demand for sugar in Europe. The Caribbean Islands and the east coast of Brazil were particularly badly affected by the sugar trade. The sugar trade was an especially shameful episode in human relations (slavery and collapse of indigenous populations), but the effect on the forests was also a disaster. Large areas were cleared for sugarcane plantations and displaced persons were forced to migrate to outlying forested areas where they felled more forests in order to grow the basic essentials for survival. The development of sugarcane monocultures exposed as a myth the supposed fertility of rainforest soils. Most of the nutrients were contained within the deforested crop and the residual soil fertility was poor. Continuous cropping of sugar on the same area led to reduced yields and the need to clear more forests. Also the milling of sugarcane required very large amounts of fuelwood. Later in the 19th century the hill forests of Central America were cleared for coffee and bananas, and in the 20th century for cotton and beef. However, the greatest rate of deforestation of the tropical forests of the Americas was in the second half of the 20th century and it is still proceeding. Central America had 40 billion hectares of forest in 1950 and this has since been more than halved.

The tropical forests of Asia

India and South-east Asia had long periods of civilization, trade and forest exploitation prior to the arrival of Europeans. However, European colonists promoted deforestation by enforcing cash crops for export rather than subsistence farming. This had the additional effect of pushing the rural population to clear more forest land for subsistence farming. The general quality and utility of the timber was better in Asia than in tropical America (except for the Caribbean) and therefore there was a greater emphasis on the forests of South-east Asia for speciality timbers. Teak was plundered by the British for shipbuilding and sandalwood was prized by the Chinese above all as a trading commodity. As a result, traders with China hunted this species to near extinction. In contrast to South and Central America, the indigenous populations of South-east Asia did not disintegrate and populations did not crash. Many countries of this region regained their independence from the colonizing powers shortly after the Second World War. However, the strong influence of outside countries (particularly Japan, China and the European Union) continues in the region and the pressure on the forests remains.

The United States of America

The European colonial powers were also responsible for accelerating forest removal in Africa and in temperate climes of Canada, Australia, New Zealand and the USA. The USA is used here as an example.

The forests of the USA were strongly influenced by their indigenous peoples for the 8000 years or so following the last recession of the ice. They cleared land for their maize-based agriculture and periodically burnt the countryside to improve the habitat for game and wild plant food (Williams, 1989). Fire promoted an extension in the area of grassland and the development of fire-dependent forest types. In 1600, just before European colonization, forests and woodlands occupied about one half of the land area of the USA. In 2000, the figure was about one third (FAO, 2010). Timber exports to the colonial powers (especially shipbuilding timbers for England) contributed a little to forest loss, but the major cause of deforestation was for agriculture to feed the growing population of settlers. The new settlers also needed wood, particularly fuelwood and wood for fencing, but deforestation for wood products was relatively insignificant compared with deforestation to support agriculture. Even so, the extensive deforestation could barely meet the demand of the increasing population for wood. There was a burst in population growth during the 19th century and forest clearance kept pace with this. The population increased from about 5 million in 1800 to more than 110 million in 1920, during which time the area of land used for agriculture increased from about 8 million hectares to about 167 million hectares. By the end of the 19th century the forests were in a mess. Forests that had not been cleared for agriculture were left in a very poor and degraded condition. Forest removals had greatly exceeded forest growth and slash fires following clearing had escaped and created havoc. Wildlife populations had been seriously reduced and many animal species were threatened. However, there was a turnaround in the 20th century, particularly after the First World War.

While the trend in increasing population continues to the present day, the area of cropped land quite suddenly stabilized after 1920 and is much the same today. This 'transition' in the USA was even more sudden than that recorded in Europe one century earlier. There are several reasons for this. During the 20th century the USA changed from a rural society of mainly subsistence farmers to an urban industrialized economy. The efficiency of agricultural production increased enormously through crop breeding, pest control, the use of fertilizers and a reduction in the use of draught animals. Consequently, crop yields per hectare increased many times. In parallel with this, there was an increase in the efficiency of the use of wood. Fuelwood comprised more than one half of the wood used during the 19th century and more than 90% of the total energy consumption at mid century. Towards the end of the 20th century, fuelwood was about 3% of the total energy consumption of the USA, with two-thirds of this being from industrial waste (MacCleery, 1994). The price of wood relative to competing materials increased and consequently wood substitutes became more common as less wood was used in construction. Wood processing plants became more efficient and generated less waste.

The standard of forest management improved by using scientific forest management backed by well-trained foresters and forest scientists. There has been significant investment in forest research and intensively managed and highly productive plantations have been established. The mean annual increment (growth rate) of US forests has increased considerably since the First World War. The USA has recorded an increase in forest area over the period 1990–2010 (FAO, 2010), despite the fact that it has the greatest roundwood production and per capita consumption of forest products in the world. However, like Europe, the USA imports timber products and therefore has a responsibility to promote sustainable forest management in the countries from which it imports. The US forests remain very vulnerable to fires, pests and diseases, due in part to bans being placed on harvesting in publicly owned forests. In the latter part of the 20th century there has been a shift in log supply from public forests in the north-west to private forests and plantations in the south-east.

During the 19th century there was a growing concern about the adverse effects of forest clearing and poor forest management on biodiversity, water and soils. Early environmental writers (Thoreau, 1854; Marsh, 1864) prompted public concern, which in the 20th century grew into an environmental movement whose aim was to protect the non-timber values of the forests and to reserve national forests. The environmental movement progressed during the 20th century from disorganized groups of concerned citizens to an organized and politically influential movement that has had a major influence on US forest policy and practice. Virtually all of the public forests (about 40% of total forests) are now protected areas.

Retrospective

Much of this chapter has been about historical deforestation and poor forest management. However, the chapter ends on a positive note. The developed world is growing forests faster than they are cutting them. The amount of forest in protected areas is increasing. There is greater emphasis on forest management for non-timber values. Scientific management is becoming increasingly sophisticated and has delivered real gains. The conservation movement has grown in strength and has greatly influenced forest management. Sustainable forest management has become a catchword for the future. However, most forests in the world are not sustainably managed and examples of destructive forest management are still easy to find. Even so, there is reason to be guardedly optimistic about the future.

One factor that stands out when looking at the history of human interactions with forests has been the resiliency of the forests. By and large the forests recovered whenever humans left them alone and kept their grazing animals away. It appears that deforestation to provide land for agriculture has stabilized in the temperate (developed) zone. Perhaps there is hope that the current bout of deforestation in the tropical (undeveloped) zone will also stabilize as tropical countries become more developed and pass through the pain of the transition from a rural subsistence culture to an urban industrialized culture. This will be further discussed in Chapter 6.

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2 Forests of the World

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Factors Determining the Type and Distribution of Forests

The growth of plants (and animals for that matter) depends on photosynthesis, arguably the most important chemical reaction on Earth. This is the chemical reaction that manufactures the basic substance from which virtually all living organisms are constructed. The reaction occurs in plant leaves, which are displayed to intercept light because the reaction requires solar energy. Carbon dioxide from the atmosphere enters the leaves via pores in the leaves (called stomata) and reacts with water from the soil to form carbohydrate (the basic substance of life) and oxygen. The reaction requires certain elements (nutrients) from the soil and occurs with the assistance of a special light-absorbing pigment called chlorophyll. This is a gross oversimplification of a complex reaction, but it will suffice for the purpose. The opposite reaction to photosynthesis is respiration, in which carbohydrate reacts with oxygen to produce carbon dioxide and water. This reaction releases energy and is necessary for maintaining metabolism in both plants and animals. It is also the chemical reaction of combustion and decomposition of carbohydrate organic matter.

It follows that for a plant to be growing (increasing in biomass), photosynthesis (A) must exceed respiration (R). For an actively growing tree a value for the photosynthetic respiratory ratio (A/R) of 10 would not be unusual. Photosynthesis minus respiration is called net photosynthesis (An) and in order for a plant to survive and grow, An would have to be positive. Forests are communities containing trees, understory species, animals, soil microorganisms and decomposing organic matter. In forest communities, A/R is less than that of single trees and may be greater than 2 for an actively growing forest like a plantation, but close to 1 for a climax community such as a tropical rainforest. If A/R is less than 1, then the ecosystem is in decline. A forest ecosystem comprises all of the biotic components of a community as defined above plus the abiotic (physical and chemical) components such as the water and soil. The interactions in space and time among and between species in a forest ecosystem are the subject of Forest Ecology. This will not be pursued here, but is well represented in the literature, such as by Kimmins (1997).

The stomata can open and close, thereby controlling the amount of carbon dioxide that enters the leaf for photosynthesis and, at the same time, the amount of water that is evaporated (transpired) from the leaf. Photosynthesis does not occur in the dark (at night) and therefore stomata shut at night to conserve soil water. Stomata open in the light (during the day) to let in carbon dioxide for photosynthesis. However, stomata may close or partly close during the day to conserve water if the plant senses low water content in the soil, or high temperature and low humidity in the atmosphere. The consequence of closing stomata during the day to conserve soil water is a reduction in the rate of photosynthesis and therefore growth. By understanding the factors that control photosynthesis and respiration, it is possible to define the environmental conditions that favour forest growth. Forests require light (but not too much) and warm temperatures (but not excessive). They need an adequate supply of water, nutrients and oxygen from the soil. It follows that the nature and location of forests depends primarily on the climate and soil, but it is also modified by disturbance.

Climate

The key climatic factors determining the nature and location of forests are air temperature and availability of water, and these two factors interact in determining the nature and location of forests. (Radiation is also important, but this is closely correlated with temperature.) Temperature decreases with increasing latitude and altitude and is influenced by distance from the sea and by ocean currents. The availability of water depends on the balance between precipitation and evapotranspiration.

Figure 2.1 shows the relationship between climate (defined by air temperature and water availability) and the type and distribution of plant communities. Forest communities are shaded in this figure. Figure 2.1 shows that plant communities become more productive and complex as the climate becomes warmer and wetter and this is particularly so for forests. Forests grow under wet rather than dry conditions and there are more types of forest in warmer regions than in colder ones. The wettest and warmest climate of all supports the most biodiverse and productive forest of all, the tropical rainforest. Generally speaking, the warmer and wetter the climate, the higher the productivity (Table 2.1) and the greater the biodiversity (Fig. 2.2). Figure 2.2 shows that in the tropics, as rainfall increases, so too does the number of tree species, tree height, the number of tiers and the number of epiphytes.

Figure 2.1 shows that for any given temperature regime, there are a range of possible vegetation types, depending on the availability of water. The availability of water depends on the balance between precipitation (P) and evapotranspiration (E). There are more forest types possible under a warmer than a cooler climate because of the influence of evapotranspiration. Potential evapotranspiration (Ep) is the evaporation from a continuous cover of vegetation having no water deficiency. In general terms this will occur if P is greater than Ep. Ep increases with increasing air temperature and decreasing relative humidity. If the vegetation has a water deficiency (P less than Ep), then the actual rate of evapotranspiration (Ea) will be less than Ep and Ep/Ea will be greater than 1. The greater the value of Ep/Ea, the drier the vegetation type (see left-hand side of triangle in Fig. 2.1). The impact of evapotranspiration is the reason why, for example, 500–1000 mm annual rainfall might support very dry forest in the tropics, but moist forest in the cool temperate zone and wet forest in the boreal zone. If Ep/Ea is greater than 1 (water deficiency), only dry forest types can persist and then only in the warm temperate to tropical latitudinal regions (Fig. 2.1).

The effect of latitude and altitude are basically the same, both affecting temperature. A good example of the interacting effects of temperature and water availability can be seen in the forest types in Oregon, USA. There is a large range in temperature (<10°C to 30°C mean summer temperatures) and water availability (150 mm to 3000 mm annual rainfall) at various positions across the transect from the coast across the coastal range into the valley between the Coastal Range and the Cascades and then over the Cascades to the dry interior. The forest types segregate into those mainly constrained by low temperature, those mainly constrained by high water stress and those constrained by neither (Fig. 2.3).

Soils and topography

Soils anchor plants and provide them with water and nutrients. The ideal texture for a soil is a loam, which has both adequate water and air. Coarser soils (sands) have more air and less water and finer soils (clays) have more water and less air. The deeper the soil is the better, because this increases the store of available water and nutrients. Plants require a range of essential elements (N, K, Ca, Mg, P, S, Cl, Fe, B, Mn, Zn, Cu, Ni, Mo) from the soil in order to survive and grow. Soil organic matter is important because it assists in providing nutrients (particularly N) and beneficial soil microorganisms. The long-term health of forest ecosystems depends on the recycling of nutrients released from decomposing litter and the ability of forest ecosystems to recycle nutrients means that they can develop on quite poor soils. Littoral rainforest can even develop on coastal sand dunes. Soils with extremes of pH can be toxic to plants and promote nutrient deficiencies. Forests prefer and promote slightly acid soils. Compacted soils restrict root growth.

Usually soils at the top of a ridge are shallower and those near the valley floor are deeper. Aspects facing the sun (south in the northern hemisphere and north in the southern hemisphere) receive more radiation, and are warmer and drier. Soil on steep slopes is generally shallower, drier and more erodible than on less steep areas. Consequently, forest type and productivity can change from valley floor to ridge top, from one side of a ridge to another and across a change in soil type, which may be gradual or sudden. Within a local region, changes in soil type can cause quite marked changes in forest productivity and in species composition. A good example of a sudden change is in the Lamington National Park in south-eastern Queensland (Australia), where well-developed subtropical rainforest on soils derived from basalt suddenly

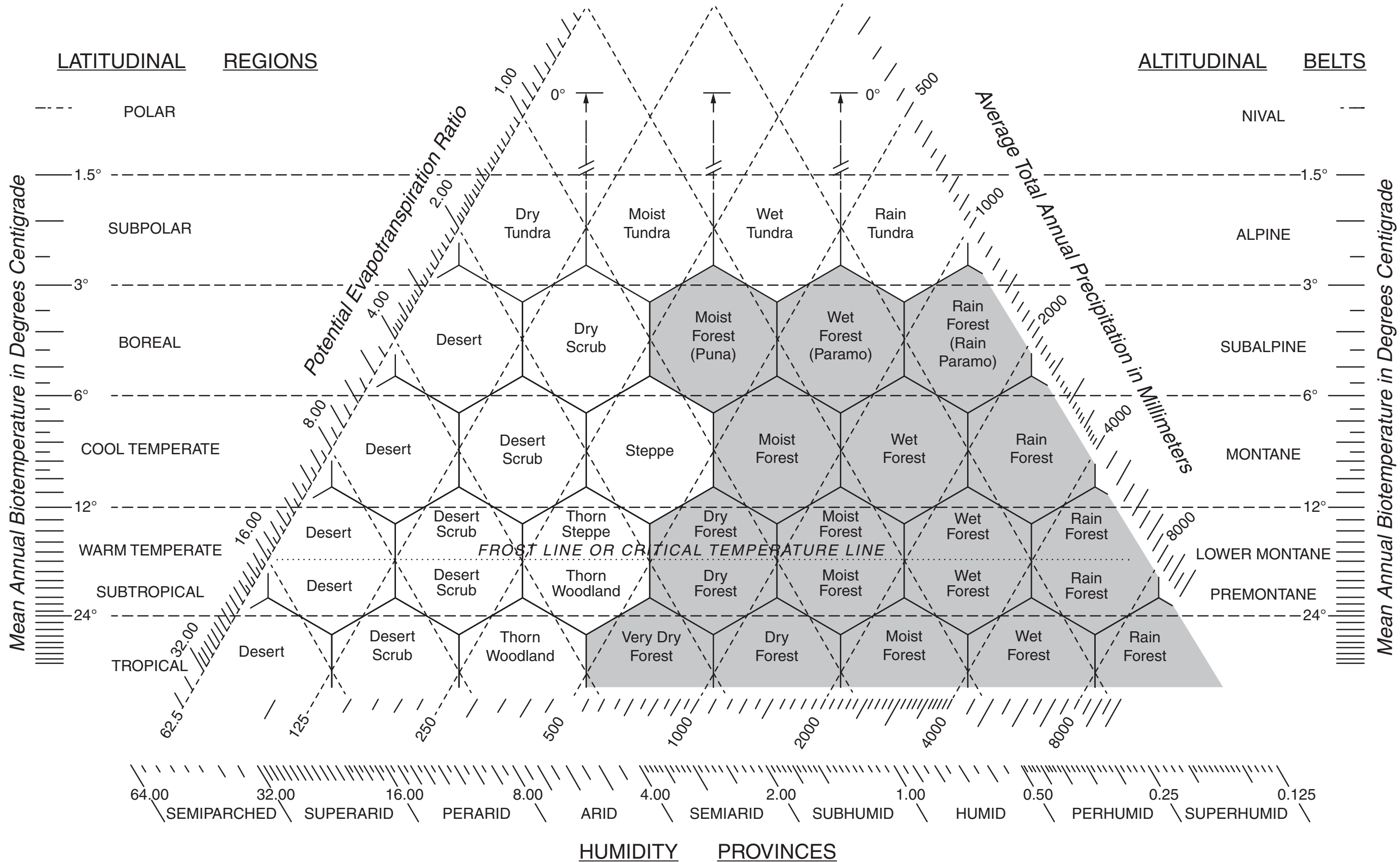

Fig. 2.1. Classification of the vegetation of the world based on temperature, rainfall and evapotranspiration. (Modified from Holdridge *et al.*, 1971.)

Table 2.1. Productivity of different types of vegetation. (Modified from Lieth, 1976.)

Vegetation type	Net primary productivity (kg/m^2/year)
Forests	
Tropical rainforest	1.75–2.8
Tropical deciduous forest	1.0
Temperate humid forest	1.0
Temperate dry forest	0.8
Boreal forest	0.65
Woodland	
Dwarf and open scrub	0.6
Tundra	0.16
Desert scrub	0.07
Grassland	
Tropical grassland	0.8
Temperate grassland	0.8
Desert	
Dry desert	0.003
Ice desert	0.0
Cultivated land	0.65
Fresh water	
Swamp and marsh	2.0
Lake and stream	0.5

changes to a low heath community on phosphorus-deficient soils derived from granite. Because of the strong relationship between soil type and productivity, soil survey is an important part of any plantation establishment programme.

Disturbance

Large areas of forest have been modified by disturbance. Disturbances can be independent of humans (non-anthropogenic), such as windstorms, earthquakes, volcanism, fire from lightning strikes, landslips, floods, erosion, siltation, droughts and disease. Disturbances caused by humans (anthropogenic) include deforestation, reforestation, burning, grazing and species dispersal. Humans can also contribute to non-anthropogenic sources. Forests are dynamic ecosystems in a state of flux with continuous cycles of germination, growth, maturity, senescence, decay and regeneration. Superimposed on this, however, are changes to the structure of the community following a disturbance. The term 'succession' is used to describe the sequence of change in community structure following disturbance. There has been an intense debate in the literature about the finer details of forest succession (West *et al.*, 1981). Simply stated, the progress of change following disturbance moves through a sequence of community structures called 'seres' until finally a 'climax' community is reached, where some sort of stability is imagined.

Reoccurring or persistent disturbance can prevent a particular sere from progressing towards its climax or can reverse its direction. For example, overgrazing in the Mediterranean has pushed forest communities to shrub communities and finally to

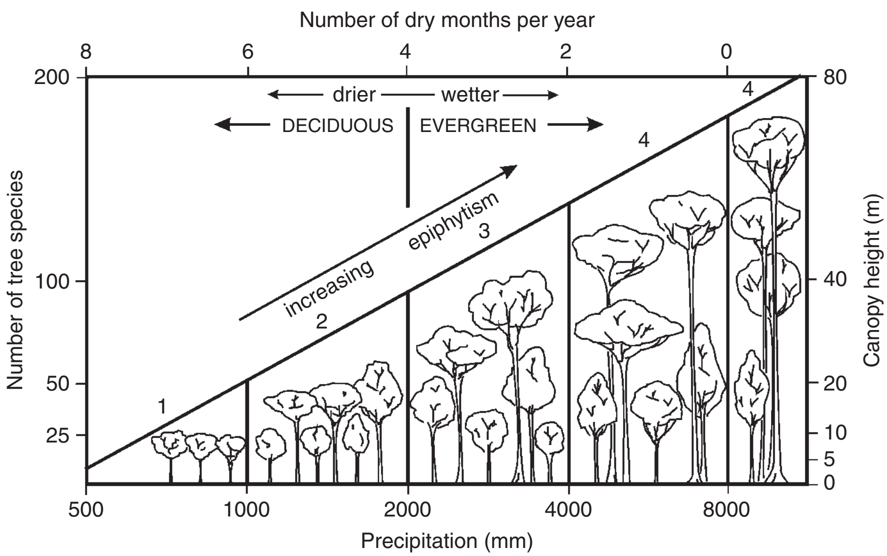

Fig. 2.2. The relationship between water availability and tree development in tropical forests. (From National Research Council, 1982.)

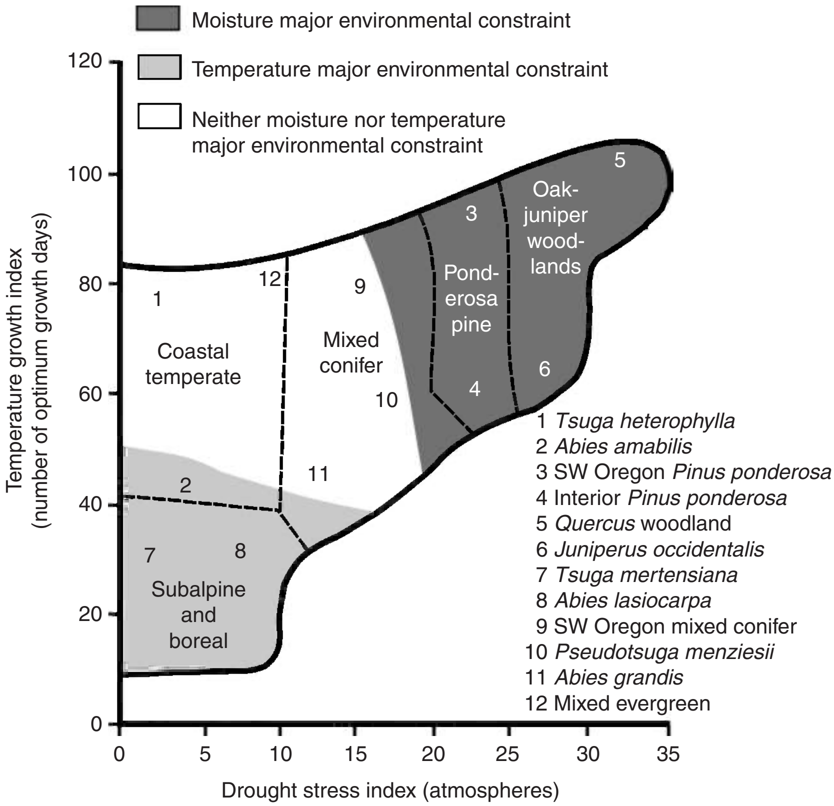

Fig. 2.3. Distribution of some of the major forest zones within an environmental field based on moisture (maximum plant moisture stress during the dry season) and temperature. (From Franklin and Dyrness, 1973.)

grassland that is resistant to grazing. Also, deforestation and fire in Kalimantan has left large areas of *Imperata* grassland that are not regenerating to forest. Much of the cultivated and grazing land across the world that occurs in temperature and water availability zones suitable for forest would revert to forest if it was abandoned and not maintained in a periodically reoccurring state of disturbance.

There are many examples of forest types maintained by fire. Individual tree species may have adaptations to resist damage from fires, to resprout after fires, or to promote seed dispersal and germination after fires. Larch, Douglas fir, *Acacia* and many pines, particularly those with serotinous cones, may be favoured by fire. Jack pine (*Pinus banksiana*) is a very good example of a tree that is very well adapted to frequent burning. The Australian flora has been moulded by fire and has adaptations over the whole range from extreme fire resistance to the opposite where the plant is adapted to be flammable so that it will burn. *Eucalyptus regnans* forest of south-eastern Australia is a good example of the latter. These magnificent trees regenerate in the ash bed after very intense wildfires that essentially 'clear fell' the site. The seeds germinate in the ash bed and the young seedlings are favoured by open space and plenty of light. The forests are very productive and produce large amounts of ground cover as potential fuel for a wildfire. Usually the forests are too moist to burn, but on the occasions when extreme fire weather follows a dry period (a few times a century), these very flammable forests burn and again reduce the area to an ash bed. The cycle recommences. If these forests could escape fire for long enough (hundreds of years) they would progress to a climax of cool temperate rainforest, but the forests have adapted to promote their burning and therefore to hold themselves in this seral stage.

Consequently, these forests often are close to even-aged monocultures, whose age is determined by the fire event that created them. This has implications for management. These forests can be successfully regenerated if large enough gaps are created such as occur in an intense wildfire. Clear felling of small coupes will work, whereas silvicultural systems that remove single trees or small groups of trees may change the forest to something else.

Classification of Forest Types

There is confusion in the literature about the definition of forest types. Angiosperms are called 'hardwoods' and conifers called 'softwoods'. However, some angiosperms (e.g. balsa, *Ochroma lagopus*) have soft wood and some conifers (e.g. yew, *Taxus* spp.) have hard wood and so the terms hardwood and softwood are confusing and unhelpful. Also the term 'broad-leaved' is commonly used to describe non-coniferous tree species and 'needle-leaved' to describe coniferous species. However, some angiosperms have needle-like foliage (e.g. *Casuarina*) and some conifers have broad leaves (e.g. *Agathis*). The combined term 'deciduous hardwood' has often been used, particularly in northern hemisphere temperate countries, to distinguish angiosperms that are deciduous in winter from conifers. However, some conifers are deciduous (e.g. *Larix*) and a very large number of angiosperms in tropical regions are deciduous in the dry season. The distinction between evergreen and deciduous species is clear and unambiguous, as is the distinction between angiosperms and conifers. The terms hardwood, softwood, broad-leaved and needle-leaved are unsafe and will not be used in this chapter. However, these terms are endemic in the literature. Trees are either angiosperms or gymnosperms and the great majority of gymnosperm trees are conifers. Also there can be considerable confusion about common names. Australia serves as a good, although in no way unique, example. European colonists of Australia named Australian native species with familiar names such as ash (*Eucalyptus regnans*), beech (*Gmelina leichhardtii*), walnut (*Endiandra palmerstonii*), hickory (*Argyrodendron trifoliolatum*), maple (*Flindersia brayleyana*), birch (*Bridelia exaltata*), elm (*Aphananthe philippinensis*), oak (*Casuarina*, *Grevillea*), cypress (*Callitris*) and pine (*Araucaria* and *Agathis*). The timber industry added to the confusion by naming species or species groups with names that are supposed to give them a marketing edge. For example, Tasmanian oak is a marketing name for a group of eucalypt species containing *Eucalyptus regnans*, which is also called ash. Blue gum represents a range of different species, depending on region, and the ultimate confusion occurs when *Eucalyptus tereticornis* is called blue gum in Queensland but red gum in other Australian states. The only way to be sure is to give a tree its scientific name, and this will be done throughout this chapter.

Forest types and their distribution

There are several classifications of forest type and distribution in the literature. The one used by FAO (2001a) has been adopted here because it is a simple system based on the climatic variables already discussed – temperature and water availability. *Ecosystems of the World* (edited by Goodall), which comes in many volumes, is another valuable source of information. Goudie (2009) is another. FAO (2001a) divided the world into ecological zones within domains Plate 1. The domains are tropical, subtropical, temperate and boreal, and are based on temperature variability throughout the year. These correspond largely, though not exclusively, with latitude. Ecological zones within domains have largely been determined on the basis of amount and distribution of rainfall and humidity. Consistent with Fig. 2.1, Plate 1 shows that forested zones occur where it is not too dry or too cold. There is evidence, however, that control of overgrazing would extend the areas of forest into drier areas in some instances. Also there are large areas of non-forested land that occur in ecological zones that are warm and wet enough to support forest. This can be seen by comparing Plate 2, which shows actual distribution of large tracts of continuous forest, with Plate 1, which shows the zones capable of supporting such forest. These areas of non-forested land were deforested to support agriculture, grazing and urban development and they would revert to forest if they were abandoned. The remaining tracts of continuous forest cover are confined largely to the tropics and to the boreal zones of the northern hemisphere (Plate 2). Mountain forests are considered as separate zones in Plate 1 because mountain climates can be quite different from those of the low country surrounding them.

Tropical forest

Tropical forests contain 70% of the world's plants and animals, 70% of the world's vascular plants, 30% of all birds and over 90% of all invertebrates. Tropical forests straddle the equator where the climate is warm to hot and frosts are absent throughout the whole year. The main climatic factor that distinguishes forest types in the tropics is the length and severity of the dry season. With increasing distance from the equator, rainfall becomes seasonal and forests need to withstand progressively longer dry periods. High temperatures influence the availability of water during dry periods. As the length and severity of the dry season increases, the forests pass through a sequence from tropical rainforest to tropical moist deciduous forest to tropical dry forest to scrub to thorn and ultimately to grassland. Through this sequence, the number of tree species per hectare is reduced, epiphytes and lianas become reduced and then disappear, trees become smaller and more scattered, buttressing is reduced and bark becomes thicker. Conifers are rare and angiosperms dominate.

Tropical rainforest

Tropical rainforest (tropical moist evergreen forest) occurs in the warm, humid and wet regions straddling the equator. Temperature, relative humidity, rainfall and day length are relatively constant throughout the year. The main occurrences are: in the Amazon basin of South America; the Congo basin in equatorial West Africa; the west coast of Madagascar; parts of Mexico, Central America and the Caribbean; north-east Australia; New Guinea; and insular South-east Asia. Tropical rainforests are the most complex and biodiverse ecosystems of all and the level of endemism is high. The Amazonian rainforest is the most biodiverse ecosystem in the world. The Malay Archipelago has 25,000 to 30,000 plant species of which one third are trees (FAO, 2001a) and the Democratic Republic of the Congo has 11,000 plant species, 1100 bird species and 400 mammals (Tchatat, 1999). Because of the large number of families, genera and species, it is difficult to select a few representative samples. Genera *Dipterocarpus* and *Shorea* are important commercial species in the South-east Asian tropical rainforests. There can be more than 200 species of trees per hectare in tropical rainforests and the number of species is so large that few people can identify them all. Timber species are often sold in assemblages without individual species identification. Trees are typically shallow rooted and buttressed and there is relatively little litter on the forest floor because it is very quickly decomposed. The soils are not necessarily fertile and can quickly lose their fertility if the forest is cleared. Most of the nutrients in the tropical rainforest are stored in the biomass, in contrast to forests from cooler areas where most of the nutrients reside in the soil. Tropical rainforests are very efficient at recycling nutrients and if the trees are removed from the site or burnt on site, a large proportion of the nutrients can be removed from the ecosystem, leaving the residual nutrients in the soil prone to leaching from the heavy tropical rains.

Tropical rainforests are home to some indigenous peoples who rely on it for their subsistence. They provide them with a range of non-wood forest products, such as breadfruit, mangoes, avocados, Brazil nuts, durian, jack fruit, edible oils, tannins, resins, bamboo, rattan, fodder and spices.

Tropical moist deciduous forest

Tropical moist deciduous forest is found adjacent to tropical rainforest. These forests still have a high annual rainfall, but with a distinct dry season. Extensive tropical moist deciduous forests occur north and south of the tropical rainforests in Africa and South America. In Africa the genera include *Marquesia*, *Berlinia*, *Laurea*, *Brachystegia* and *Acacia*. Most of the area, however, is wooded grassland and extensive clearing has occurred for agriculture. In South America the flora is very rich, with families *Leguminosae* and *Myrtaceae* well represented. The zone is a mosaic of grassland, tree savannahs and woodland with patches of more dense forest (FAO, 2001a). In India and South-east Asia, there are many species from a wide range of families. These forests occur in monsoonal climates and are sometimes called monsoonal forests. *Tectona grandis* (teak) from Thailand and *Shorea robusta* (sal) from northern India are important commercial species. Angiosperms predominate, but conifers are represented by *Pinus merkusii* in South-east Asia and *Podocarpus imbricata* and *Pinus latteri* in southern China.

In the tropics the deciduous habit occurs in the dry season, as an adaptation to conserve soil water and thereby reduce water stress in the trees. This is in contrast to the temperate zone where the deciduous habit occurs in winter as an adaptation to protect the tree from freezing temperatures. Not all the species in the tropical deciduous forests are completely deciduous, but most would shed some if not all of their leaves during the dry season. Many of the trees flower in the dry season and consequently deciduous forest, moist or dry, can be very colourful. Rubber (*Hevea brasiliensis*) is a deciduous tropical tree from Brazil, but that has been planted extensively in Malaysia.

Tropical dry forest

Tropical dry forests occur when the dry season becomes longer and more severe. There are extensive areas in Africa and also occurrences in northern Australia, India and eastern Brazil. The trees are smaller and more scattered, are often deciduous or semi deciduous and tend to be spreading in habit. *Leguminosae* is an important family (*Amburana*, *Caesalpinia* and *Mimosa* in South America, *Acacia* in Africa and Australia, *Curatella* and *Byrsonima* in Mexico and Central America). Dry deciduous dipterocarp forests and woodlands are common in South-east Asia as well as woodlands of *Tectona grandis* and *Pinus merkusii*. *Eucalyptus*, *Melaleuca* and *Callitris* are important species in northern Australia. Frequent fires and collection of fuelwood have reduced large areas of tropical dry forest to shrub and grass. Tropical dry forests are important for fodder, timber and fuel and because the trees are thinly distributed over grass they are also important for wildlife and for grazing. Tropical shrubland occurs when the climate is even drier and, although this zone does not support forest as such, it still may contain scattered trees.

Subtropical forest

The subtropical domain is defined by FAO (2001a) as areas having mean monthly temperatures of over 10°C for more than 8 months a year. Subtropical forests show some seasonal variation in temperature and day length and the two distinct types of subtropical forest, subtropical humid and subtropical dry, are distinguished by seasonal distribution in rainfall and humidity. Both of these forest types are close to the sea.

Subtropical humid forest

Subtropical humid forests are located on or near to eastern seaboards. They are uniformly warm and humid throughout the year without any pronounced dry season. The major occurrences in the northern hemisphere are in south-east USA and south-east China. In the southern hemisphere they occur in the east of South America and Australia. At their best, these forests can be classified as subtropical rainforests where they have a similar structure to tropical rainforests. They are, however, less complex, less biodiverse, less dense, with fewer tree species and smaller trees with smaller and more waterproof leaves.

In south-east USA the angiosperm species are *Quercus* (evergreen oaks), *Magnolia* (magnolia), *Carya* (hickory), *Liquidamber* (sweet gum), *Acer* (maple), *Ulmus* (elm), *Fraxinus* (ash), *Populus* (poplar), *Platanus* (sycamore) and *Cornus* (dogwood). The conifers include *Pinus taeda*, *Pinus echinata*, *Pinus elliottii* and *Taxodium distichum* (bald cypress). Extensive plantations of *Pinus taeda* and *Pinus elliottii* have been established in the area. In south-east China the forests are a mixture of evergreens and deciduous species. The forests are rich in oaks, laurel (*Cyclobalanopsis*), *Castanopsis* and conifers (*Pinus massoniana*, *Pinus taiwanenesis* and *Cunninghamia lanceolata*), but there are many other species. The extensive bamboo (*Phyllostachys*) forests of China are part of the subtropical humid forest zone. In southern Japan the species are mainly angiosperms (such as *Castanopsis*, *Cyclobalanopsis* and *Machilus*), but conifers (*Podocarpus*, *Tsuga*, *Abies* and *Pinus densiflora*) are also represented. *Torreya*, which is a gymnosperm but not a conifer, is also present.

The subtropical humid forests of Brazil have been heavily exploited for timber and cleared for agriculture and grazing. Grasslands now dominate the region. The conifer *Araucaria angustifolia* is a major constituent of any remaining forest. In eastern Australia the forests are predominantly eucalypts (such as *Eucalyptus grandis* and *Eucalyptus pilularis*) or closely related members of the *Myrtaceae*, and there are many species. In the absence of fire and on better soils, these forests become subtropical rainforests of similar but simpler structure to the northern Australian tropical rainforests. The FAO classification of ecological zones places the North Island of New Zealand as subtropical humid. Local knowledge, however, would suggest that it is warm temperate. In the North Island of New Zealand the forests are a mixture of conifers (*Agathis*, *Podocarpus*, *Dacrycarpus*, *Dacrydium*, *Phyllocladus*, *Prumnopitys*) and evergreen angiosperms (*Weinmannia*, *Ackama*, *Metrosideros*, *Knightia*, *Elaeocarpus*, *Laurelia*, *Beilschmiedia*, *Litsea*, *Nestegis*).

Subtropical dry forest

Subtropical dry forests occur exclusively on western seaboards where the climate is characterized by a 'Mediterranean-type climate' of cool wet winters and hot dry summers. They are also further from the equator than what might initially be considered to be subtropical latitudes. There are occurrences in south-west Australia, Chile, western USA and the western Mediterranean (southern Spain, southern France, Italy, Greece, North Africa and the Mediterranean islands). The idea that the forests of Italy, southern France and southern Spain are subtropical would surprise many people in the region, especially during their winter. However, the effect of the warm ocean current adjacent to the Atlantic seaboard of Europe is remarkable. Toronto in Canada, which is not far from the boreal forest and has very intense winters, is on the same latitude (43.5° North) as Monaco on the Mediterranean Sea.

In the Mediterranean, the forest is usually olive (*Olea europaea*) or oak (*Quercus ilex*). In the USA, this forest type occupies parts of the coastal areas and plains of California and southern Oregon. Coastal fog is common and important in determining forest type and ecology. For example, in the north where the subtropical dry forests meet the temperate oceanic forests, *Sequoia sempervirens* (Californian redwood) occupies the seaward slopes together with *Pseudotsuga menziesii* (Douglas fir), *Thuja plicata* (western red cedar) and *Tsuga heterophylla* (western hemlock). Further south are *Pinus* and *Cupressus* (cypress) on the coast and *Quercus*, *Pseudotsuga menziesii* and *Arbutus menziesii* (madrone) are further inland. Most of the lowland areas in this region have been converted to urban use or irrigated agriculture. At its drier extremities the forest is replaced by chaparral shrub land. Fire weather can be very severe and many of the forest types have been fashioned by fire. Even though this region is classified as a dry type on the basis of temperature and rainfall, it supports the tallest tree species in the world (*Sequoia sempervirens*) and the most successful conifer plantation species in the southern hemisphere (*Pinus radiata*). *Pinus radiata*, however, has a very restricted distribution in its native habitat. In south-west Australia, *Eucalyptus diversicolor* (karri) occurs on the better soils where the rainfall is adequate. Karri is a very tall tree and this demonstrates, along with *Sequoia sempervirens* in California, that the subtropical dry forest zone can support highly productive forests. (These tall trees occur at the very wet end of the subtropical dry climatic zone and perhaps are out of place in the FAO classification.) On the poorer soils, *Eucalyptus marginata* (jarrah), *Eucalyptus calophylla* (marri) and *Eucalyptus gomphocephala* (tuart) are the major species. In Chile, as in the USA, the subtropical dry forest lies north to south on the west coast and is adjacent to, but at lower latitudes than, temperate oceanic forest. The influence of the sea is important. The climax dry forest of *Cryptocarya*, *Lithraea*, *Peumus*, *Quillaja* and *Beilschmiedia* has largely been degraded and replaced by thorn shrubs or converted to agriculture. Where rainfall is higher, *Nothofagus* and *Araucaria araucana* (monkey puzzle pine) are found.

Temperate forest

Temperate forests are further from the equator than tropical and subtropical forests and are distinguished by marked differences in temperature and day length between the seasons. The domain is defined as having mean temperatures over 10°C for 4–8 months. Temperate forests are divided into temperate oceanic and temperate continental types. Temperate oceanic forests are influenced by proximity to the sea and do not have the extremes of temperature experienced by their continental counterpart. Temperate continental forest occurs only in the northern hemisphere where large landmasses dominate the temperate latitudes. Temperate oceanic forests at their best are cool temperate rainforests that can rival tropical rainforests for grandeur and productivity. Tropical rainforests are productive because of high temperatures and abundant water. However, the amount of radiation intercepted by tropical rainforests is limited by high humidity in the atmosphere and by cloud cover. Also the day length hardly changes in the tropics and warm night temperatures promote respiration, which reduces net photosynthesis. In the well-watered oceanic regions of the temperate zone, days are long during the growing season and cool night temperatures keep respiration in check. Examples of grand and productive temperate oceanic forests are the coniferous rainforests of the Pacific North-west of the USA and the eucalypt forests of the wetter parts of Victoria and Tasmania in Australia. The temperate forests have a lesser number of species and are less layered than tropical forests. Sometimes the forests are dominated by only a few species, even just one.

Species composition differs between the northern and southern hemispheres. In the northern hemisphere, temperate oceanic forest occupies Western Europe, the north of Japan, and the Pacific North-west of the USA and southern British Columbia. Temperate continental forest occupies the most of eastern USA and a large belt of forest extending from Western Europe across Asia below the boreal forest. The forests are characterized by a mixture of angiosperms (usually deciduous) and conifers. The angiosperms include *Quercus*, *Fagus* (beech), *Fraxinus*, *Acer*, *Carya*, *Ulmus*, *Juglans* (walnut), *Populus*, *Salix*, *Tilia* (lime) and *Betula* (birch) and the conifers include *Picea* (spruce) and *Pinus*. The species differ between the continents, although many of the genera are common. *Thuya plicata* (western red cedar), *Tsuga heterophylla* (western hemlock) and *Pseudotsuga menziessii* occur in the oceanic forests in the west of the USA and *Quercus*, *Carpinus betulus* (hornbeam) and *Fagus sylvatica* are prominent in the oceanic forests of Western Europe. Temperate forests cover a large range in water availability, soils and temperature and the climate can be very variable. In Europe and the USA much of the temperate forest has been cleared.

In the southern hemisphere the temperate oceanic forests of New Zealand and Chile have some similarities, which reflect their common Gondwanan origins. The angiosperm genus *Nothofagus* (southern beech) is the main constituent in both countries and both have similar conifer genera (e.g. *Podocarpus* and *Dacrydium*). In Australia, fire has fashioned tall eucalypt forest (such as *Eucalyptus regnans*, *Eucalyptus globulus*, *Eucalyptus obliqua* and *Eucalyptus viminalis*). In the absence of fire on wet sites, rainforest species such as *Atherosperma moschatum* (sassafras), *Nothofagus cunninghamii* (myrtle) and *Acacia melanoxylon* (blackwood) can establish.

Boreal coniferous forest and boreal tundra woodland

The boreal domain is defined as requiring no more than 3 months over 10°C. Boreal forest forms a large belt of almost continuous forest across Eurasia and Canada. It occupies the domain between the temperate and the polar. There is no equivalent in the southern hemisphere because there are no landmasses at the latitudes that support boreal forest in the northern hemisphere. These forests are sometimes called cool coniferous forests or taiga. They are dominated by *Picea*, *Abies*, *Pinus* and *Larix* (larch), but the angiosperms *Salix*, *Betula*, *Populus tremuloides* (aspen) and *Alnus* (alder) recolonize areas disturbed by fire, wind and human activity. Trees become progressively smaller from south to north as the climate becomes colder, the growing season becomes shorter and boreal coniferous forest moves into boreal tundra woodland. At the northern limit the trees are stunted and sparse, occurring in scattered groups on higher ground until the trees give way completely to tundra. A similar sequence occurs as treeline is approached with increasing altitude, but this occurs over a much shorter distance. In North America the tree species approaching the tundra are *Picea glauca*, *Picea mariana*, *Abies balsamea*, *Pinus banksiana* and *Larix laricina*. In Eurasia, *Picea abies* and *Picea obovata* are the western species approaching the tundra and *Abies sibirica* and *Pinus sibirica* are the eastern species (Beazley, 1981). *Larix* species are also prominent (Osawa, 2010).

Mountain forest

There are extensive areas of mountain forests. Mountain forests usually are the last to be cleared and often the forests are restricted to the mountains in regions that have had a history of human activity. Mountain forests cover all of the domains from tropical to boreal, but they are treated together here because their climate is different, and sometimes very different, from that of the lowland around them. Temperature becomes less and rainfall may increase markedly with increasing altitude. Consequently, mountain forests tend to be cooler types and sometimes wetter types than the domain in which they sit. Tropical rainforest at altitude is sometimes covered in cloud for almost all of the time, in which case they are referred to as tropical montane cloud forests (Bruijnzeel *et al*., 2010).

Africa

The Atlas Mountains in Tunisia, Algeria and Morocco reach up to 4165 metres and have a humid climate. They contain mainly *Quercus* and *Pinus* (*Pinus pinaster* or *Pinus halepensis*) on the lower slopes and *Cedrus atlantica* (atlantic cedar) and *Juniperus thurifera* at higher altitudes. The tropical mountains of Cameroon, Ethiopia, Kenya and the Kivu ridge support a great variety of distinctive vegetation types, including bamboo (*Arundinaria alpina*) at the higher altitudes. In Madagascar, large areas of secondary grassland have replaced the original montane vegetation. In South Africa, the highveld reaches 3000 metres and *Podocarpus* and *Apodytes* are found.

Asia

Treeline in the Himalayas is at about 4000 metres. The tropical lowland forest to the south of the Himalayas changes to an evergreen forest that may contain *Pinus roxburghii* (chir pine), above which is evergreen *Quercus* forest and, higher still, a coniferous forest of *Abies* and *Tsuga*. Montane rainforests occur in Myanmar, Malaysia, Indonesia and New Guinea and may contain some tropical conifers (*Podocarpus*, *Libocedrus*, *Araucaria*, *Phyllocladus*) at altitude. The mountains of the Arabian Peninsula are the only areas of the region where forest grows and, as altitude increases, *Acacia* and *Commiphora* are replaced by *Olea* and *Podocarpus* and then by *Juniperus procera*. There are extensive areas of subtropical mountain forests from the Mediterranean through to southern China. The Mediterranean forests have been significantly degraded and contain considerable areas of shrub and grasslands, but *Quercus*, *Abies cilicica*, *Cedrus libani* (Lebanese cedar) and *Pinus nigra* also occur. The mountains bordering the Caspian and Black Seas have well-developed forests of *Fagus*, *Carpinus*, *Acer* and *Quercus*. The northern Himalayas contain *Quercus*, *Pinus*, *Cedrus deodara* (deodar), *Picea*, *Abies*, *Juniperus*, *Betula* and *Rhododendron*. The subtropical mountain forests of China are dominated by *Abies*, *Picea*, *Pinus*, *Betula*, *Cupressus*, *Tsuga*, *Cunninghamia lanceolata* and with *Chamaecyparis* in Taiwan. The subtropical mountain forests of Asia are very diverse and the species list given here is by no means complete. There is a vast area of temperate mountain forest in Asia, to the north of the subtropical zone. *Pinus*, *Larix*, *Picea*, *Abies*, *Betula*, *Fraxinus*, *Populus*, *Acer*, *Tilia* and *Tsuga* are represented.

North and Central America

The tropical mountains of Central America contain temperate species such as *Quercus*, *Acer* and *Salix*, but *Pinus* is also found. On wetter sites, *Lauraceae* is a prominent family. The subtropical parts of the Cascade Mountains, the Sierra Nevada and the Rocky Mountains contain *Pinus*, *Picea*, *Abies*, *Quercus*, *Populus tremuloides*, *Pseudotsuga menziesii*, *Tsuga* and the giant *Sequoia giganteum*. The temperate forests of the Pacific Coast Mountains are very productive and grand, and are dominated by *Tsuga heterophylla* and *Abies amabilis* (silver fir). *Pinus*, *Picea*, *Abies*, *Populus tremuloides* and *Pseudotsuga menziesii* are found in the temperate forests of the Rocky Mountains and species of *Fagus*, *Acer*, *Ulmus*, *Quercus*, *Betula*, *Picea*, *Pinus* and *Abies* in the Appalachians. Forests at higher elevations in the boreal zone contain *Pinus*, *Betula*, *Picea*, *Abies* and *Populus*.

Europe

Europe has mountains in the temperate and boreal domains. In the temperate domain, beech forests with *Picea*, *Abies*, *Fraxinus*, *Acer* and *Ulmus* occupy the lower elevations and *Picea* and *Abies* the higher elevations. In the boreal domain the mountain forests contain mainly *Betula*, *Pinus*, *Picea*, *Abies* and *Larix*.

Australia and New Zealand

In Australia and New Zealand, mountain forests are mostly confined to the temperate domain. In south-east Australia (which includes Tasmania), the higher elevation forests contain tall eucalypt forests where it is wet enough. The main species are *Eucalyptus delegatensis*, *Eucalyptus viminalis*, *Eucalyptus regnans* and *Eucalyptus nitens*. *Eucalyptus pauciflora* is a treeline species. Cool temperate rainforest containing *Atherosperma moschatum*, *Nothofagus cunninghamii* and *Acacia melanoxylon* is also represented. In New Zealand the montane forests are mainly *Nothofagus*, but conifers (such as *Podocarpus* and *Libocedrus*) are also significant.

South America

In South America the montane forests follow the Andes for virtually the whole length of the continent. Tropical mountain forests are to be found in Colombia, Venezuela, Peru and Bolivia, and they contain distinctive highland elements of the tropical forest on the adjacent lower country. There are many species. In the subtropical and temperate montane forests, the major genus is *Nothofagus*.

Mangrove forest

Mangroves occupy the intertidal zones of inlets and estuaries on tropical and subtropical coastlines (Spalding *et al*., 2010). They are a taxonomically diverse group, most belonging to four genera: *Bruguiera* and *Sonneratia*, and particularly *Avicennia* and *Rhizophora*. Mangroves are specifically adapted to survive and grow in the daunting marine intertidal environment. They have to be able to survive in a soil that contains no airspace and therefore almost no oxygen. They need to be able to absorb water and desalinize it before presenting it to the vital metabolic sites. They need to be able to persist in a very hot and desiccating environment when they are exposed at low tide.

Mangroves provide oxygen to their roots by having a variety of aerial roots. Air enters the aerial root through pores on the surface (called lenticels), which are connected to the root tissues below the water surface by a network of cells with a lot of airspace (called aerenchyma). *Rhizophora* has stilt roots, originating from the main stem well above the water line. *Avicennia* has pneumatophores, emerging vertically from a radial root close to but below the soil surface.

Mangroves desalinate water by a combination of excluding salt at the root surface, excreting salt through the leaves, accumulating salt in sacrificial leaves, depositing salt in metabolically less important tissue (such as in the non-functional components of the bark) and, at the cellular level, by depositing salt in the vacuole away from the sensitive metabolic sites in the cytoplasm. There is an energy cost in absorbing and transpiring fresh water extracted from salt water and consequently mangrove forests are not as productive as adjacent tropical land forests. Mangrove species are a part of a marine forest ecosystem that can support epiphytes, insects, birds, reptiles, amphibians, mammals, decomposing microorganisms and a broad array of marine organisms, including crabs and fish. Mangrove ecosystems have been an important source of construction timber, fuelwood, fodder, food and medicines as well as a habitat for shrimps and fish (Saint-Paul and Schneider, 2010; Marschke, 2012). Mangrove ecosystems are also important in arresting coastal erosion (Hogarth, 1999).

Planted forest

FAO defines planted forest as trees established through planting and/or through deliberate seeding of native or introduced species (2010). A 'forest plantation' may be more narrowly defined as planted forest managed specifically, and often intensively, for a productive function, mainly timber. Plantations are usually (though not exclusively) of one species (monocultures) in groups of the same age (even-aged). Some argue that plantations should not be regarded as forests at all but rather as an extension of cropped agriculture. However, because plantations are trees growing over a rotation length of many years and supporting a more complex ecosystem with a wider range of community values than agricultural monocultures, most people regard them as forests. Certainly FAO includes plantations as forests when compiling their global statistics on forest areas.

Plantations have been established in both temperate and tropical areas. Natural monocultures are common in temperate forests but rare in the tropics. This suggests that planted monocultures (plantations) would be more suited to temperate regions than the tropics. This does not necessarily mean that plantations cannot be established in the tropics; genus *Eucalyptus*, *Acacia* and *Tectona grandis* (teak) have been very successful. It just means it is a little trickier and more care needs to be taken in species selection and silviculture. Indeed, much of the current plantation expansion is occurring in tropical areas (see Chapter 9). Forest plantations will, in general, be more productive in warmer, wetter areas. A successful plantation species has to grow fast, have adequate wood properties and be resistant to disease when grown as a monoculture. This restricts the number of suitable candidates enormously and is the reason why local species occurring in mixed forests are often unsuitable. The most successful plantation species are pioneer species. Pioneer species are the first trees to establish on bare ground caused by a disturbance such as fire, wind, road construction and deforestation. Pioneers grow under full sunlight and grow fast enough to out-compete weeds. Physiologists call pioneers 'sun trees' and trees that germinate and grow under shade, 'shade trees'. Sun trees have fast rates of photosynthesis at high light levels and so grow rapidly when there is plenty of light (Fig. 2.4). Shade trees have much slower rates of photosynthesis at high levels of light but are more efficient at photosynthesis at low levels of light. Shade trees are therefore better adapted to persist under the low light conditions of the forest understory. Most prominent high-quality furniture species are shade trees and attempts to establish them as plantations have been spectacularly unsuccessful. The mahogany (*Swietenia macrophylla*) plantations of Fiji and teak (*Tectona grandis*) plantations of South-east Asia are exceptions. Even though a great number of species have been planted in plantations, it is likely that large-scale plantation enterprises will be limited to perhaps 20 pioneer species worldwide. Kanninen (2010) lists the six most commonly planted genera in order as *Pinus*, *Cunninghamia*, *Eucalyptus*, *Populus*, *Larix* and *Acacia*. Conifers comprise 53% and non-conifers 47% (Carle and Holmgren, 2008). *Hevea* and *Tectona* are also important plantation species (FAO, 2001a).

There is a good argument for considering local native species first if they are suitable for the purpose. However, suitable native species may not exist because of the physiological constraints mentioned above and in this case an introduced species (exotic) could be the best choice. Exotics often grow faster in their introduced environment than their home environment. *Pinus radiata* (radiata pine) is a good example. It is the dominant plantation conifer in the southern hemisphere, while of little consequence in its home environment of California and adjacent islands, where it is an insignificant relict tree under threat. The reason for its success outside of its native range has been a matter of great debate. When genus *Eucalyptus* is planted outside Australia, it often grows faster and carries more leaf area. Eucalypts outside Australia no longer co-exist with the plethora of fungi and leaf eating insects that occur in Australia. Clearly planting exotics comes with some risk and this needs to be recognized and managed. Another risk associated with planting pioneer species is that they are very 'weedy' and can establish and dominate areas where they are not welcome.

Asia's planted forests are mainly in China, India, Japan, Thailand, Vietnam and Indonesia. The principal species in China are *Cunninghamia lanceolata*, *Pinus massoniana*, *P. koraiensis*, *P. tabulaeformis*, *P. elliottii*, *P. taeda*, *Eucalyptus* spp., *Populus* spp. and *Larix* spp. In India the major plantation genera are *Eucalyptus* and *Acacia* (*A. nilotica*, *A. catechu*, *A. tortilis* and *A. leucophloia*). In Japan, the major plantation species is *Cryptomeria japonica* (sugi), but *Chamaecyparis obtusa*, *Pinus densiflora*, *P. thunbergii* and *Larix kaempferi* are also represented. The major plantation trees in South-east Asia are *Tectona grandis*, *Hevea brasiliensis*, *Eucalyptus* spp. and *Acacia* spp. (*Acacia auriculiformis* and *A. mangium*). In Europe

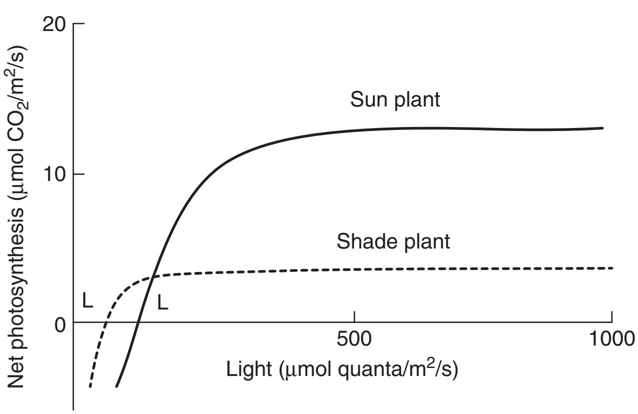

Fig. 2.4. A typical relationship between net photosynthesis and light (photon irradiance) for single unshaded leaves of sun plants and shade plants. L is the light compensation point. (From Beadle and Sands, 2004.)

the plantation genera are mainly *Picea* and *Quercus*. The USA has extensive plantations of mainly *Pinus taeda* in the south-east. In South America the main plantation trees are eucalypts and eucalypt hybrids (e.g. *E. grandis*, *E. urophylla*, *E. deglupta*, *E. globulus*) and pines (e.g. *Pinus caribaea* in tropical Brazil and *Pinus radiata* in temperate Chile). *Eucalyptus*, *Acacia* and *Pinus* are the dominant genera in Africa and Oceania (Turnbull, 2002).

Management of plantations can be intense, with very high productivity. Eucalypt plantations in Brazil can exceed a mean annual increment of 50 cubic metres per hectare per year. For comparison, the mean annual increment of the world's forests on average is about 2 cubic metres per hectare per year. Not all plantations are managed intensively and mixed species and natural regeneration are other options for consideration. There are considerable areas of plantations that have been mismanaged, or more accurately not managed at all, and consequently are over-stocked or have failed.

How Much Forest Is There?

The World Resources Institute and the United Nations Food and Agriculture Organization (FAO) both provide objective data as best they can. The distribution of the world's forest according to the FAO Global Forest Resources Assessment 2010 (FAO, 2010) is summarized in Tables 2.2–2.5. These data are obtained from within-country reporting supported by remote sensing and geographic information systems. The extent and accuracy of within-country reporting is not always optimal and this compromises the reliability of the data to some extent. The definition of forest in these tables is land with a tree cover of more than 10%, an area of more than 0.5 hectares, a minimum height of 5 metres at maturity and not predominantly used for agricultural purposes. The net rate of forest loss, although still alarming, appears to be slowing down due to both a reduced rate of deforestation and an increase in the amount of planted forest (Table 2.2).

Deforestation is largely in the tropics (Table 2.3) and gains in forest area, mainly through plantation establishment, are dominated by China (Table 2.4). Indeed China has recorded, over the period 1990–2010, a net gain of forest almost equivalent to that lost by Brazil, the number one deforesting nation. FAO treats the Russian Federation as part of Europe. However, for the purpose of discussion here, Europe is considered separately from the Russian Federation. This being the case, South America has the most forest (21% of world forest area), followed closely by the Russian Federation (20%), with North America and Africa equal third (17%). Asia is close behind at 15%, followed by Europe and Oceania (both 5%), with Central America and the Caribbean contributing less than 1% (Table 2.5).

South America (along with the Russian Federation) has the highest percent forest cover (49%; Table 2.5). Most South American forest is

Table 2.2. Gains (+) and losses (–) in global forest area (millions of hectares/year) over the periods 1990–2000 and 2000–2010. (Compiled from data given in FAO, 2010; *Natural forest expansion calculated by difference.)

	1990–2000	2000–2010
Deforestation and natural disasters	–16.0	–13.0
Afforestation (planting forests on non-forested land)	+3.6	+4.9
Natural forest expansion*	+4.1	+2.9
Net forest loss	–8.3	–5.2

Table 2.3. Five countries with largest annual net loss of forest area, 1990–2010. (Compiled from data given in FAO, 2010.)

Country	Net loss (1000 ha/year)
Brazil	2766
Indonesia	1206
Nigeria	410
Tanzania	403
Myanmar	373

Table 2.4. Five countries with largest annual net gain of forest area, 1990–2010. (Compiled from data given in FAO, 2010.)

Country	Net gain (1000 ha/year)
China	2486
USA	385
India	225
Vietnam	222
Spain	218

Table 2.5. Total forest and planted forest areas in 2010 and net annual gains or losses in forest area 1990–2010. (Compiled from data given in FAO, 2010.)

Region	Forest area (million ha)	% land area	% of global forest area	Net gains (+) and losses (–) (million ha/year)	Planted forest (million ha)
South America	864	49	21	−4.11	14
Africa	674	23	17	−3.74	15
Asia	593	19	15	+0.82	123
Central America and Caribbean	27	36	<1	−0.27	1
North America	679	33	17	+0.09	36
Russian Federation	809	49	20	+0.01	17
Europe	196	34	5	+0.77	53
Oceania	191	23	5	−0.37	4
World	4033	31	100	−6.8	264

tropical (96%; FAO, 2001b). South America contains almost 60% of the world's tropical forests, dominated by the vast expanse of the Amazonian forests. Some South American countries have very high forest cover. For example, French Guiana and Suriname have 98% and 95% forest cover respectively. By contrast, Uruguay and Argentina have 10% and 11% forest cover. South America is the most deforesting continent (net 4.2 million ha/year between 1990 and 2000, and 4.0 between 2000 and 2010). This is largely due to Brazil, the most deforesting country on Earth (net loss of 2.9 million ha/year between 1990 and 2000 and 2.6 between 2000 and 2010). Argentina, Bolivia, Colombia, Ecuador, Paraguay, Peru and Venezuela all had significant net losses in forest area. Chile and Uruguay were the only South American countries to increase their forest areas between 1990 and 2010, mainly due to plantation establishment. South America has 14 million ha of planted forest (Brazil has 7.4 million ha; Table 2.6), much of which is highly productive because of favourable climate, suitable species and intensive management.

Africa is the second most deforesting continent (net 4.0 million ha/year between 1990 and 2000, and 3.4 between 2000 and 2010). Nigeria, Tanzania, the Democratic Republic of the Congo, Zimbabwe and Sudan accounted for a net forest loss of 1.8 million ha/year between 1990 and 2010. Almost all forest in Africa (98%) is tropical. Africa has 24% of the world's tropical rainforest (FAO, 2001b) concentrated in west equatorial Africa, but drier forest types predominate. Africa has almost

Table 2.6. Countries/regions together having more than 80% of the world's planted forest area in 2010. (Compiled from data given in FAO, 2010.)

Country	Planted area (million ha)	% of world planted area
China	77.2	29.2
Europe	52.3	19.8
USA	25.4	9.6
Russian Federation	17.0	6.4
Japan	10.3	3.9
India	10.2	3.9
Canada	9.0	3.4
Brazil	7.4	2.8
Sudan	6.1	2.3
Total	**214.9**	**81.4**
World	264	100

80% of the world's tropical forests that are not rainforests. Senegal and Gabon have 88% and 85% forest cover respectively, whereas Algeria and Niger have just 1%. Sudan and South Africa have 6.1 and 1.8 million ha respectively of planted forest.

Asia has 61% tropical, 23% subtropical, 14% temperate and 2% boreal forest (FAO, 2001b). Asia displays considerable variability in its forest area dynamics. This variability is demonstrated by its having had an overall net gain in forest area over the period 1990 to 2010, but also having the second (Indonesia) and fifth (Myanmar) most deforesting countries over this period (Table 2.3). China recorded a huge gain of 2.5 million ha/year over the period, with India and Vietnam also making important gains (Table 2.4). Asia has the most planted forest of any region, mainly due to China but Japan and India also have extensive areas of planted forests (Tables 2.5 and 2.6).

FAO considers North America to be Canada, USA and Mexico (also Greenland and Saint Pierre and Miquelon). This covers a wide latitudinal range and consequently a wide range in forest types. Canada has mainly boreal forest, the USA mainly temperate forest and Mexico mainly subtropical forest. Canada and the USA have about the same area of forests (310 and 304 million ha) and much the same percent forest cover (34% and 33%). Canada recorded no change in forest area between 1990 and 2010, but the USA recorded an increase of 385,000 ha/year, second only to China. Mexico, on the other hand, was a net deforester (275,000 ha/year) over the period (Table 2.3).

The Russian Federation has almost all boreal forest and had a small net gain in forest area over the period 1990–2010. The Federation has 17 million ha of relatively low productivity planted forest. Europe (excluding the Russian Federation) reported net gains in forest area over the period 1990–2010, with no individual country reporting anything other than a trivial loss. Finland (73%) and Sweden (69%) have high forest cover. Ireland (11%), the Netherlands (11%) and the United Kingdom (12%) have relatively low forest cover. Iceland has no significant forest cover. Europe has large areas of mainly low productivity planted forests (53 million ha), second only to China.

Oceania has 5% of world forest area and Australia has 78% of the forest area in the region. Oceania has 62% tropical forest, 30% subtropical and 8% temperate. Drier forest types predominate due to the large contribution of Australia (although Australia has wetter tropical and temperate forest types along the east coast and in Tasmania). FAO (2010) has recorded a large rate of deforestation in Australia over the period 2005–2010 (924,000 ha/year), but this is attributed to fire and drought rather than land clearing. The satellite imagery used by FAO assesses leaf area and the loss of leaf area through fire and drought caused previously classified forest to no longer meet the definition. The declassified forest most likely will recover and a significant reforestation event is to be expected in the future to compensate. Some of the Pacific Islands have high percentages of forest area. For example, The Federated States of Micronesia is 92% forested. Papua New Guinea and the Solomon Islands have relatively high rates of deforestation. New Zealand has over 20% of its forest area (7% of total land area) as fast-growing intensively managed forest plantations of mainly *Pinus radiata*.

Forest productivity is determined largely by temperature and water availability, as discussed earlier in this chapter. As a result, forests in warmer and wetter areas (e.g. tropical rainforests) should be more productive than forests in cooler (e.g. boreal) areas. This is demonstrated in Table 2.7 by comparing South America (98% tropical forest) with the Russian Federation (almost exclusively boreal forest). South America and the Russian Federation have similar forest areas (Table 2.5), but South America has three times greater biomass density (247 t/ha) than the Russian Federation (80 t/ha). This difference, however, is less pronounced when looking at total forest carbon because of a greater proportion of carbon in dead biomass and litter and most particularly soil in the cooler boreal

Table 2.7. Live biomass and carbon in forests from various regions in 2010. (Derived from FAO, 2010; excludes Central America and Caribbean.)

Region	Live biomass (t/ha)	Live biomass (% world)	Carbon in biomass (t/ha)	Carbon in dead wood, litter and soil (t/ha)	Total carbon (t/ha)
South America	247	36	118	99	217
Africa	176	20	83	63	146
Asia	125	12	60	65	125
North America	113	13	55	97	152
Russian Federation	80	10	40	117	157
Europe	131	4	64	115	179
Oceania	111	4	55	59	113
World	149	100	72	90	162

region. Indeed, only South America and Africa have a greater amount of carbon in live biomass than in dead wood, litter and soil. Globally, there is a greater amount of carbon in dead wood, litter and soil than in live biomass. The importance of carbon held in forests will be discussed in more detail in Chapter 8.

Planted forests occupy 6.6% of world total forest area, having increased by nearly 5 million ha/year since 2000 (FAO, 2010). FAO (2010) predicts a planted forest area of 300 million ha by 2020 (7.4% of world total forest area). China, the Russian Federation, the USA, Japan and India have collectively more than half of the world's planted forest. China alone has almost 30%. The area of planted forests shown in Tables 2.5 and 2.6 do not reflect plantation productivity. Planted forests in the cool temperate and boreal zones are of relatively low productivity. By contrast, forest plantations in, for example, South America, South Africa, Australia, New Zealand, South-east Asia and south-east USA have warmer growing temperatures and therefore are very productive. For example, Chile, Uruguay, Vietnam, Malaysia, Thailand, Indonesia, South Africa, Australia and New Zealand do not make the list in Table 2.6, but support highly productive plantations managed primarily for wood production. The proportion of plantation forest to total forest is high in some countries (e.g. over 20% in New Zealand). Although world plantations occupy less than 7% of total forest area, they probably supply at least 50% of overall wood production and this proportion is increasing (see Carle and Holmgren, 2008). As a result, plantations reduce the pressure on native forests to supply wood. Plantations for wood production are further discussed in Chapter 9.

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3 The Environmental Value of Forests

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The Value of Forests

The value of forests means different things to different people. People may value forests for a range of reasons or may give prominence to one overriding value. People may differ over the values they place on forests and this can cause conflict. Likewise people may place different values on different types of forest. At the most fundamental level, forest-dwelling communities value forests for their very survival. Some people place negative values on forests. Agriculturalists from ancient times to the present have seen forests as a barrier to development, a harbourer of animals that prey on livestock and a haven for plant pests and diseases. Urban developers often consider forests to be a costly nuisance. People who build their homes close to or in the forest may face a serious fire risk, albeit choosing to take this risk. Falling trees and limbs can cause damage to person and property. Tree roots can infiltrate drains and sewers and damage building foundations. Some find forests to be dark and claustrophobic. However, the overriding majority of people value forests and consider they provide a net positive benefit.

The benefits of forests may be tangible, such as the forest products used by humans. These include wood used for construction and paper production; wood used for fuel (energy); and a wide range of non-wood forest products such as food, fodder, pharmaceuticals, dyes, tannins, cosmetics, essential oils, garden plants and resins. Tangible benefits are relatively easy to subject to economic analysis. Less tangible benefits are the environmental and social benefits of forests and the ecological services they provide. These include conservation of soil, water and biodiversity; recreation and amenity; aesthetic, cultural and religious values; protection from natural hazards; and climate amelioration. These less tangible benefits are not so easy to subject to economic analysis, although natural resource economists are eagerly pursuing ways of doing so. This chapter will deal with environmental benefits of forests. Following chapters will deal with forest products.

Water Conservation

Water quantity

The hydrologic cycle is shown at the global level in Fig. 3.1 and at the catchment (watershed) level in Fig. 3.2. Atmospheric water condensed in clouds falls as rain mostly over the oceans (79%), but also over the land (21%) where it enters the soil to provide water for plants, runs off to streams over the surface or enters the groundwater. Some of the water from groundwater and streams finds its way back into the oceans. Water evaporates back to the atmosphere mainly from the ocean (87%), but also from the land (13%) either directly from the land surface or via plants in the process of transpiration (Fig. 3.1). Of the total volume of water (approximately 1.4 billion km^3), only 2.5% is fresh and for plants, otherwise running off to streams over the surface or entering the groundwater. Most of this (approx. 70%) is tied up in polar and montane ice. Only about 0.05% of the fresh water is stored in the soil and available to plants. Solar energy acts as a giant still to ensure that fresh water is always being regenerated. Each year about 575,000 km^3 is evaporated from land and oceans into the atmosphere (Fig. 3.1). If fresh water was evenly distributed over the Earth, there would be no shortages to plants and animals. However, distribution is not equal and

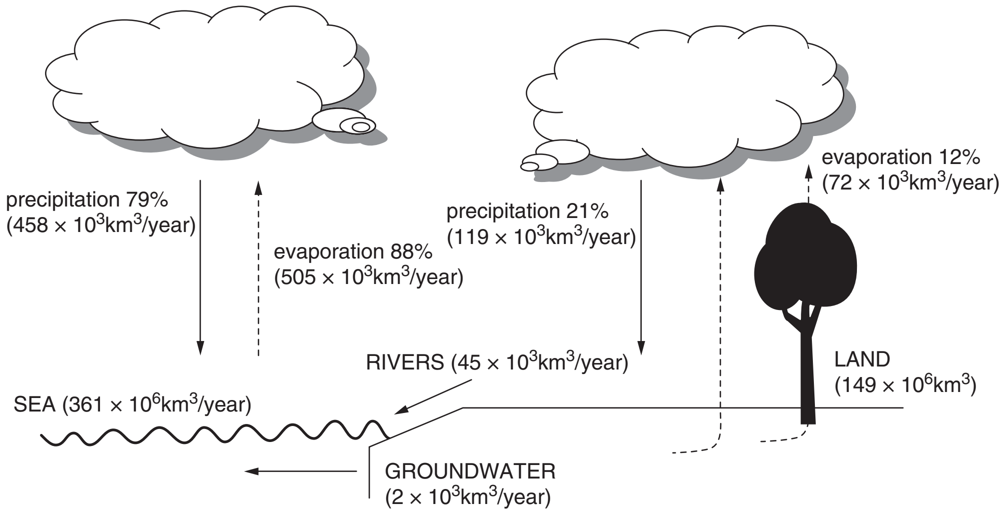

Fig. 3.1. Global hydrologic cycle. (Constructed from data of UNESCO, 1978.)

in certain parts of the world fresh water is the major limiting resource to plant and animal life.

Figure 3.2 is an idealized land surface in a forested catchment sloping down to a stream. The water balance is determined by accounting for all of the inputs (precipitation), outputs (evaporation and streamflow) and storage (soil water and groundwater):

$$Q = P - (E + \Delta S + \Delta G) \qquad (3.1)$$

where Q = water yield (streamflow); P = precipitation reaching the soil plus litter surface; E = evaporation of water from soil and litter, plus transpiration from leaves of water absorbed through the roots, plus evaporation of water intercepted by the canopy; ΔS = change in soil water storage; ΔG = change in groundwater storage.

Rainfall intensity and duration is very uneven over scales of minutes to millennia. This results in droughts, rains and fluctuations in streamflow. It is the extreme events rather than the average that often creates most interest.

The water table is the surface that separates a zone of unsaturated soil above from saturated soil below. The unsaturated soil between the water table and the land surface contains air in its larger pores and water in its smaller pores. The force of adhesion of water to the pore walls increases as pore size diminishes. Consequently, the smaller pores can hold water but the larger pores will drain to the water table. Plant roots require air to function and are confined to unsaturated soil. Plants, through the process of transpiration (evaporation of water from the leaf surface), can exert enough pull on the water held in the small pores to break the forces of adhesion and reduce the water content of the soil. Rainfall infiltrating the soil will replenish the water in the small pores until all of the small pores capable of holding water against drainage are full. The soil can hold no further water unless water is entering the soil at a faster rate than it can drain. Soil scientists say that soil in this condition is at ‘field capacity’. The amount of water that a soil can hold at field capacity depends on its depth to the water table (or a water impeding layer): the deeper the soil, the more water it will hold. The amount of water held at field capacity also depends on the texture of the soil: fine-textured soils (clay soils) have relatively more small pores and therefore can hold more water than coarse-textured soils (sandy soils), which have relatively fewer small pores. However, the rate at which water can enter the soil (the infiltration rate) is greater in sandy soils than clay soils. Saturated soil, the soil below the water table, has its entire pore space filled with water and the water in the saturated zone is called groundwater.

Precipitation may be snow, sleet or hail, but predominantly is rain. Rain falling in a forested catchment may fall directly to the ground or be hung up in the canopy. Anybody who takes shelter under a tree during rain can attest to the fact that

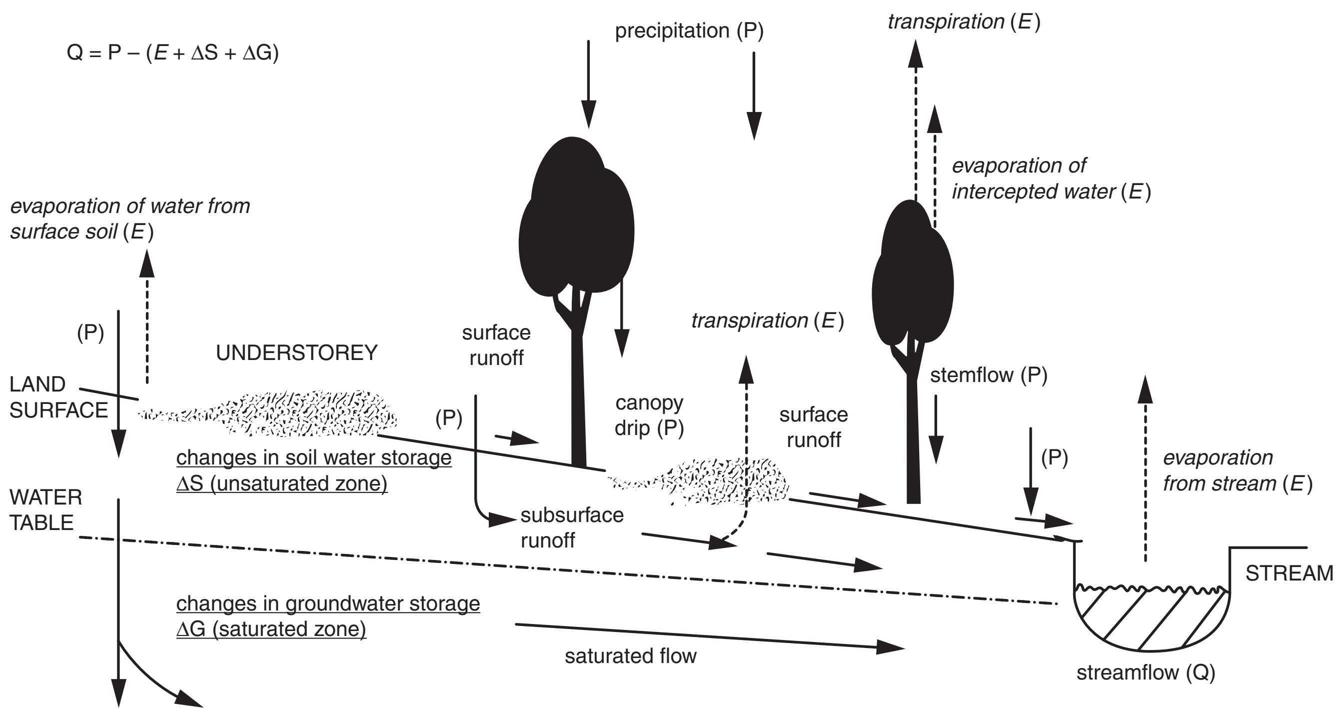

Fig. 3.2. Hydrologic cycle at the catchment level. Inputs are in plain type, outputs in italics and changes in storage underlined.

initially the canopy provides good shelter. After a while, however, the canopy can intercept no further rain and water starts to drip from the leaves and flow down the stem. The amount of water intercepted by the leaves and that does not reach the ground can be substantial in forests. The precipitation reaching the ground surface (directly, by stem flow or by canopy drip) will enter the soil and will either add to the amount of water stored in the unsaturated soil or will flow (runoff) to groundwater and streams. The amount of runoff depends on slope, vegetation type, soil depth and texture, the amount of water already in the soil and, most importantly, the duration and intensity of the rain. Most flow to streams occurs as saturated flow from the groundwater or over the surface of an impermeable subsurface layer, but flow can also occur over the soil surface (overland flow) or even in the unsaturated subsurface under certain circumstances. Flow to streams at the expense of increasing soil water storage is favoured by intense rainfall, steep slopes and bare ground (no litter or soil humus). As the soil becomes wetter from prolonged rainfall and exceeds field capacity, the soil can no longer store water. In such circumstances all of the water will flow to streams or groundwater. If rainfall is entering the soil at a faster rate than it is draining from the soil profile, the groundwater may be recharged at such a rate that the water table may rise to the soil surface and overland flow may occur. Also, overland flow may occur as a result of intense rain on soils with low infiltration rates or over impermeable surfaces such as rocks.

Water is returned to the atmosphere by evapotranspiration, which is the sum total of water evaporating directly from the soil surface, water taken up by plants from the soil through their roots and transpired through their leaves, and the direct evaporation of rain intercepted by the canopy. The water yield of a catchment depends on vegetation type. For many forested catchments, the additions and subtractions to soil water storage and groundwater storage averaged over a year balance out. Consequently, the impact of ΔS and ΔG in equation 3.1 is small and water yield is mostly determined by P and E.

Forested catchments usually have lower water yields than grassed, cultivated or otherwise disturbed catchments. This is because the amount of intercepted water is greater in forests and therefore less precipitation reaches the ground. Forests often transpire greater amounts of soil water as well. Forest trees have deep roots and can access water deeper in the soil. Different types of forest can produce different water yields. In general, evergreen forests (conifer and angiosperm) have canopies that intercept more water than deciduous angiosperm forests and therefore produce lower water yields. This happens because deciduous trees are without leaves to intercept and transpire water for several months in the year. Also water yield can depend on the stage of development of the forest: if the forest (including understorey) increases the size of its canopy, then the amount of both intercepted and transpired water will increase and the water yield will be reduced. Thinning and selective logging (removing a few trees) often has little effect on water yield because the residual vegetation can quickly increase its transpiring leaf area and resume near original values of transpiration and interception.

Clearfelling a forest will increase water yield and if the site is deforested and transformed to another land use such as agriculture, the increase in water yield can be permanent. If the site is allowed to regenerate to forest, water yield ultimately will decrease back to forested levels. However, in some forests, the regeneration following clearfelling (or a wildfire) is so vigorous that it will reduce water yields below that of the pre-harvest forest and then slowly increase to pre-harvest levels over perhaps decades. This is the case for *Eucalyptus regnans* forests in Australia (Vertessy *et al.,* 2001). Forest plantations established on cleared land may initially increase water yield if weeds are controlled, but ultimately should reduce water yield. Any effect of clearing or replanting on water yield will depend on the area of disturbance involved. If the area in any year is small relative to the area of the catchment, the effect on water yield will be correspondingly small. If, on the other hand, a significant proportion of a catchment is cleared for agriculture or grazing, the increase in water yield can be substantial. Sometimes a wildfire will remove most, if not the entire, transpiring canopy in a catchment. Under these circumstances the increase in streamflow (and more particularly the decrease in water quality) can be substantial. Wildfires can also make soil surfaces water repellent, thereby reducing soil infiltration rates.

The fact that forested catchments have reduced water yields has been a source of controversy in catchment management, particularly when contemplating establishing tree plantations in areas where water is in short supply and in competition with other land uses (e.g. in India, South Africa and Australia). The impact of plantations will depend on circumstances as two Australian examples serve to show. The city of Perth in Australia extracts groundwater from an area shared with 22,000 ha of un-thinned *Pinus pinaster* plantations. Under current drought conditions there is no groundwater recharge under the plantations and the government is considering replacing them with a less consumptive land use. By contrast, the Murray–Darling Basin in Australia is large with challenging and controversial opinions on how the limited amount of water should be shared among environmental flows, irrigated agriculture and other dryland uses, including plantation establishment (Murray–Darling Basin Authority, 2010). Plantations are responsible for just 2.5% of consumptive water use in the basin and as such their impact is almost negligible. However, if a relatively large area of plantation were to be established in sub-catchments within this basin, the impact on adjacent farmers sharing the water could be substantial.

Streamflow can vary enormously throughout a year, from no flow to full flood, with slope, soil type and land management practices having important effects. Streamflow can also vary diurnally (greater at night than in the day), reflecting the greater water use by vegetation near streams during the day. If soil infiltration rates are slow owing to steep slopes, shallow soils of fine texture, soil compaction or the creation of impermeable surfaces (e.g. roads), runoff to streams may be accelerated to the extent that infiltration to the water table is diminished. This may reduce streamflow during the dry season. The impact of deforestation on flooding has often been exaggerated. Floods are caused by excessive rainfall and under these conditions all other hydrologic variables are swamped into relative insignificance. Because streamflow is less in forests, deforestation may cause a flood to start a little earlier and last a little longer. Also sedimentation to streams resulting from deforestation may reduce stream capacity and promote flooding. For these reasons deforestation on highlands is often blamed for causing floods on the lowland. This may or may not be true, depending on circumstances. Land management on the lowlands also plays a part: greater flood plain occupancy, greater channel constriction, more roads, more ditches and more non-absorbing surfaces will all contribute to lowland flooding. Reforestation of catchment uplands has several beneficial effects, but large-scale flood mitigation is not one of them. In general, forest cover in upland catchments will not prevent floods and deforestation of upland catchments is not the primary cause of floods.

If forests (deep-rooted with high evaporation) are replaced with pasture species (shallow rooted with lesser evaporation), then over time (perhaps many decades) the groundwater levels may rise. If the rising groundwater collects salts from the soil, the rooting zone of plants can become saline and salt may be exposed where the water table breaches the soil surface at lower parts of the catchment. For example, large areas of soils in some semi-arid parts of the world have become unproductive because of soil salinity induced by clearing of forest. Replanting of forests can reverse this effect, but the process takes a long time. Finding suitable species that are both copious transpirers and salt tolerant is a challenge.

Water quality

A well-managed forest with intact understorey and well-developed litter and humus layers usually acts as a filter and produces better quality water with less turbidity and sediment than a catchment with an alternative land use. This will be discussed further in the next section on soil erosion. Wildfires can cause immediate and extreme deterioration in water quality. A case study from Canberra in Australia ably demonstrates the factors involved in water quality. The water supply to the city of Canberra is provided from two catchments. One is forested and the water requires no treatment. The other has a component of agriculture and grazing in the catchment and the water requires treatment for domestic consumption. However, in 2003, the forested catchment was extensively burnt and the water quality deteriorated markedly.

Soil Conservation

The conservation of soil can be considered in two complementary ways. The first of these is to maintain the fertility of the soil on a site and the other is to stop the loss (erosion) of soil from the site. Most of the land cleared in the past for agriculture and for urban development was on the better soils that would have originally supported forests. However, forests can also exist on quite poor soils (e.g. boreal forests and forests on sand dunes) and on quite steep slopes. Consequently, there has developed a culture that agriculture should have the first pick of soils and forestry should be left with the residue. This does not always make economic or environmental sense. Usually forests have better soils than adjacent non-forested areas on the same soil type. Young (1997) reviewed the evidence for this. Forests better preserve carbon and nutrients than non-forest soils and forest soils also tend to have better physical properties. It follows that reforestation of non-forested areas has the capacity to improve the soil and deforestation has the capacity to degrade soil. Deforestation, particularly in the tropics, can remove a significant amount of carbon and nutrients from the site. However, forest harvesting, as distinct from deforestation, does not appear to cause significant productivity loss in 'natural' forests (Attiwill and Weston, 2001). Forested areas usually suffer less soil erosion. Soil erosion is the process by which soil is removed from a site by agents such as ice and snow, but mainly by water, wind or human disturbance. Soil erosion clearly reduces the fertility, productivity and utility of the soil at the site from which it has eroded. The eroded soil is deposited elsewhere as sediments, which may be either a benefit or a nuisance.

Soil fertility

Forest ecosystems and nutrient cycling

Forests are bio-systems where radiant energy of the sun captured in organic compounds by photosynthesis is the main energy source for living things. The captured radiant energy flows through forest ecosystems as organic matter and is lost again as heat during metabolic reactions. While energy enters the system and is eventually lost, the elements to construct living things are finite in the biosphere and are continuously used and reused, or cycled. Because forests account for 50% of all terrestrial photosynthesis, they are central to the cycling of carbon in the biosphere and to nutrient cycling at a regional level (Malhi, 2012).

As trees grow and their structures are renewed, plant residues such as branches, leaves, bark and fruits accumulate on the forest floor and roots die and release organic matter into soil. These organic materials serve as an energy source for the decomposer community. In forest ecosystems only about 1.5 to 5 per cent of primary production is consumed by herbivores, leaving the bulk of organic materials to be consumed by organisms living in litter and surface soil. This interacting web of biota ranges from the relatively large earthworms and arthropods that mix detritus between soil layers and break it in to smaller pieces, through to fungal and bacterial microbes that mineralize organic matter, releasing CO_2 to the atmosphere and inorganic nutrients in to the soil. Nutrients that were once bound in plant and animal structures become available again for plant uptake. This is the process of nutrient cycling, which, over decades, centuries and millennia, acts to concentrate carbon and nutrients in the forest floor and surface soil. The net result of forest growth is the accumulation of carbon and nutrients in litter and surface soil. Much of the annual demand for nutrients is met by tree internal cycling of nutrients, such as withdrawal of nutrients prior to leaf fall, and from nutrients released again from litter and soil organic matter (Attiwill and Adams, 1993). Consequently, a large proportion of the annual demand for nutrients is drawn from nutrient cycling rather than uptake from the soil (Fig. 3.3). Forests live on their past accumulation of nutrients.

The process of nutrient cycling involves the crucial step whereby organic matter is decomposed by the microbial component of the soil biota, which is responsible for over 90 per cent of decomposition and mineralization. As decomposition proceeds, litter is broken into smaller pieces by soil fauna and organic matter derived from microbes is mixed intimately with the soil mineral component in the process of humus formation. Typically the humus formed dominates the soil organic matter pool and contributes to many of the environmental values of soil. Carbon locked in the organic–mineral complexes is called humus and is resident in soil for decades, centuries and millennia, so that most organic matter in soil is old and important in carbon storage. Because it is resistant to decay, humus also contributes significantly to the formation of stable soil aggregates, which increase the diffusion of water and air through soil and form an ion-exchange surface that holds nutrients.

Differences between soils under forests and under agriculture

The accumulation of organic matter on and in forest soils distinguishes them from agricultural soils.

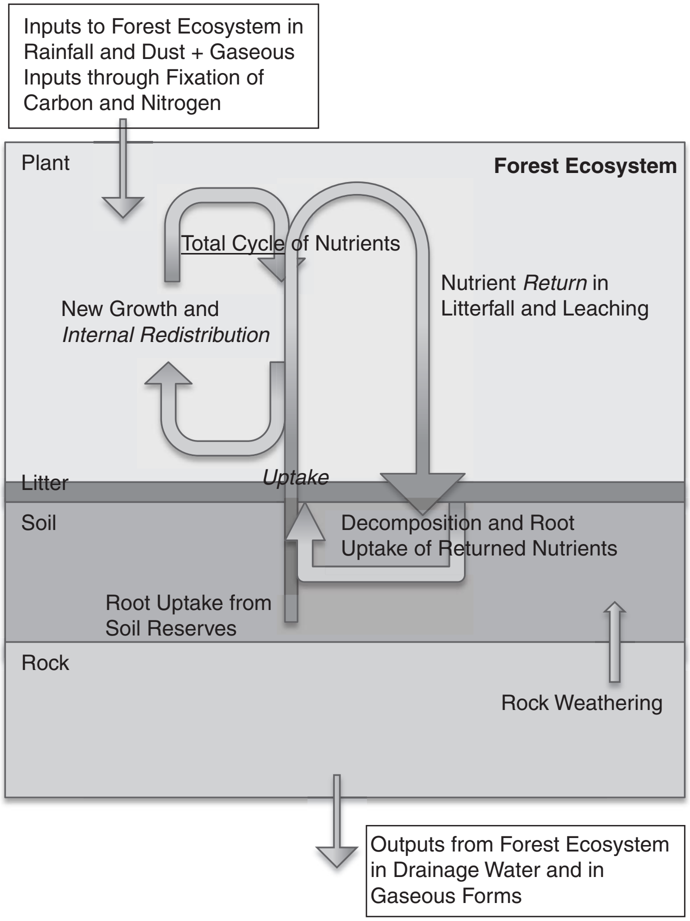

Fig. 3.3. A model of nutrient cycling in a forest ecosystem. The three main nutrient cycles are shown in italics (*Return*, *Internal Redistribution*, *Uptake*). The 'Total Cycle' of nutrients is the sum of all fluxes between plant and soil plus the amount needed for new growth. (Adapted from Attiwill and Leeper, 1987; Attiwill and Adams, 1993.)

Soils of unmanaged forests are rarely disturbed in comparison with agricultural soils, where product removal limits the addition of organic residues to the soil. Agriculture in many parts of the world seeks to maximize inputs of organic residues to soil to maintain the benefits of increased microbial activity and better soil porosity and nutrient holding capacity. Apart from direct benefits realized in higher yielding crops, residues will also deliver carbon into organic matter, which remains in soil for centuries and millennia. The potential benefit of organic enrichment of agricultural soils is evidenced by the activities of pre-Columbian inhabitants of the Amazon basin, who created fertile agricultural soils from relatively infertile and highly weathered former tropical forest soils. Known as terra preta, these anthropogenic soils are rich in organic matter and include charcoal particles. They demonstrate that organic materials incorporated into soil by humans can create sustainable soils for agriculture while increasing long-term carbon sequestration in soil (Glaser and Birk, 2012). Because it is a significant component of carbon stored in the terrestrial biosphere that is exchangeable with the atmospheric pool of carbon, maintaining and building soil organic matter may be crucial in our efforts to limit the rise in atmospheric CO_2 concentrations (Stockmann *et al.*, 2013). Ultimately though, all soil organic carbon is subject to decomposition and is released back to the atmosphere.

In many parts of the biosphere, the distribution of ecosystems is determined largely by temperature regime and the availability of water (Chapter 2). Soil fertility is a consequence of ecosystem productivity and nutrient cycling, rather than a key determinant of the distribution of vegetation types. The occurrence of complex rainforests on pure white sands is good evidence of the importance of nutrient cycling in supplying nutrients for growth, rather than direct uptake from soil. This point is often overlooked in judging the suitability of forested lands for conversion to agriculture. Once cleared of forest, the suitability of the site for agriculture will depend more on soil features such as texture, porosity, structural stability and nutrient holding capacity than on the stature of the forests that once grew there. Tropical ecosystems have a greater proportion of nutrients in living biomass than temperate soils (see Table 2.7, Chapter 2) and consequently deforestation (felling plus burning) can result in a relatively infertile soil subject to leaching and unsatisfactory for agriculture. In agricultural systems, nutrients held on soil particles determine the ability of the soil to store nutrients for plant uptake. Removals of nutrients in crops and other products must be made good with fertilizers. Nitrogen and phosphorus fertilizers are the most common and these have been applied at rates and in places that threaten other environmental values. Indeed, the industrial manufacture of nitrogen fertilizers has increased reactive nitrogen in the biosphere to a point where rising soil emissions of nitrous oxide (N_2O), a powerful greenhouse gas, is a major concern (Fujimaki *et al.*, 2009). Soil properties in agricultural and forest soils are contrasted in Table 3.1.

Soil erosion

The development of soil is a balance between the rate at which parent material is broken down to form new soil and the rate at which soil is removed by erosion. Topsoils are produced at a rate of 0.5–2.0 t/ha/year and soil loss under the best practice of cultivated agriculture is also 0.5–2.0 t/ha/year, which means that there is no net loss or gain of soil. Soil loss under poorly managed agriculture (and forestry) often will exceed the rate of soil development and there will be a net loss. Zimbabwe would require US$1.5 billion of fertilizers each year to compensate for natural nutrient loss from soil erosion. The USA loses US$18 billion per year

Table 3.1. Generalized listing of contrasting agricultural and forest soil properties and the main consequences of the differences.

Soil property	Agriculture	Forestry	Main consequences for forests versus agriculture
Standing litter layer	Absent or low in mass (<0.5 t/ha)	Up to 50 t/ha or more	Physically protects soil surface from erosion Acts as mulch to conserve soil moisture Storehouse of carbon
Annual litter inputs to soil surface	Limited by crop removal and grazing removal	Ongoing in natural systems Litter removed in some forests May be interrupted with forest operations or final harvest in wood production forests	Maintains production of a range of organic decomposition products in soil More decomposable soil organic matter in forests compared with agriculture
Surface soil organic matter	Dominated by finely divided, old and very stable humus	A mix of freshly added and fragmented organic matter, decomposable organic fractions and old and very stable humus	Due to greater abundance of organic food sources, a higher biomass of soil biota in forests compared with agriculture Storehouse of carbon
Soil softness and permeability to air and water	Tending to compacted soils from loss of coarse organic matter fractions and from either or both of farm machinery and hard-hooved animals	In natural systems soil root channels are maintained and soil peds are not subject to compaction Increasing intensity of forest management will tend more to compaction from machinery passes	Management operations, even in intensively managed forests, will have less impact compared with the more frequent operations under agriculture

in fertilizer nutrients to soil erosion (National Research Council, 1993). In relatively undisturbed forests on moderate or less slopes, the rate of soil development can exceed the rate of soil loss from erosion. Generally speaking, soils are developed under forests and lost under agriculture. Because topsoils are lost under intensive agriculture, productivity is reduced unless fertilizers are used. Otherwise more forests are cleared to compensate for lost productivity. This compounds the problem by increasing the contamination of ground and surface waters and increasing the overall rate of erosion by clearing more forest and exposing more land.

Any event that exposes bare mineral soil has the potential to promote soil erosion by both water and wind. Such events include fire, overgrazing, drought, pestilence (e.g. swarms of locusts), disease, deforestation, forest degradation, soil cultivation, weed control, road construction, forest harvesting operations, earth works and urban development. It follows that the key to controlling soil erosion is to avoid exposing mineral soil or to keep the time interval during which the soil is exposed as short as possible. Tying the soil together with a network of plant roots and promoting a protective cover of litter and humus on the soil surface as soon as possible after any disturbance can achieve this. The vegetative cover need not necessarily be forest, although the reduced runoff in forested catchments would provide an advantage. It follows that deforestation will promote erosion for the time the soil is exposed but erosion will be arrested when the site is revegetated by reforestation or by some other land use that provides a complete vegetative cover with a complex web of roots. If forest is replaced by cultivated agriculture, the potential for soil erosion by both water and wind is increased.

Erosion by water

The factors determining soil erosion by water are described by the Universal Soil Loss Equation (Wischmeier and Smith, 1965)

$$A = RKLSCP \quad (3.2)$$

where A is the mass of soil lost per unit area, R is the rainfall factor, K is the soil erodibility factor, L is the length of slope factor, S is the slope gradient factor, C is the cropping management factor and P is a factor related to erosion control practices. Qualitatively this means that soil erosion by water is maximized when rain is prolonged and intense on erodible soils on long steep slopes that have no vegetative cover and where no attempts have been made to try to manage the problem.

There are various factors that make intensive agriculture particularly vulnerable to erosion by water: large areas of monocultures are often planted with little regard to the configuration of the terrain; there are extended periods in which the cultivated soil has little or no vegetative cover at all; heavy machinery exposes, compacts and reduces the water infiltration rate of soil; and roads provide paths for the runoff of water. Erosion can be significantly reduced by using minimum tillage, mulching, conserving crop residues, rotational cropping, mixed cropping and contour strip cropping. Row crops usually are most profitable in the short term but offer the least resistance to soil erosion. The reason that forests are effective at controlling soil erosion by water is a combination of several factors: forests have less surface runoff of water to streams; the surface of forest soils are generally covered by a protective layer of humus and litter; forests and their understorey form a complex root network that is effective in holding the soil together; and forests are often in remote areas and relatively protected from human disturbance. However, when forests are disturbed, particularly on steep country, the potential for soil erosion by water is substantial. The soils most vulnerable to erosion by water are poorly aggregated fine-textured soils where the resistance to particle detachment by water is low and where water infiltration rates also are low. Sometimes the protective effect of vegetation is not sufficient to arrest erosion by water. On the very steep upper slopes of young and recently uplifted mountain ranges, such as the Himalayas and the New Zealand Alps, extensive soil erosion is inevitable and a fact of life. No management intervention can stop it. However, in most instances the management of vegetative cover is the key to arresting or slowing down soil erosion from water. The interacting effects of rainfall intensity, slope and ground cover are demonstrated in an agricultural system in Nigeria (Table 3.2). Soil loss increased with annual rainfall and with slope. Soil loss was greatest on the bare fallow plot. However, when maize was grown with a protective mulch, soil loss was zero, even on the steepest slope.

A mixture of different roots is more effective at reducing soil loss than roots from a single species alone and the role of the understorey in arresting soil erosion is substantial. Forests are most effective in erosion control when they have a well-developed understorey with a complex network of roots, leaf litter and humic horizons. The key factor in the relative efficiency of different land uses is the degree of intactness and completeness of the soil litter and humus layer, the complexity of the root web and the lack of disturbance in the system. This is well demonstrated by the range of land uses shown in Table 3.3.

Litter has been removed from some forests (for example, Portugal) for centuries. This has gradually but relentlessly reduced the fertility of the soil as well as increased the risk of soil erosion. Similarly, collecting leaf litter for fuel under plantations in Nepal and collecting leaves under mahogany and teak plantations in the Philippines for producing mosquito repellents, chicken feed and fertilizers exposes the soil to the risk of soil erosion unless special care is taken. Care needs to be exercised to reduce soil erosion in forest operations. Residue retention between rotations of plantations not only conserves nutrients on the site but also reduces the potential for soil erosion. Cultivation and weed control are standard practices in plantation establishment, but this comes at the risk of soil erosion, which needs to be taken into account in steep terrain in areas of high rainfall. The practice of sowing a legume crop as soon as possible on the cleared land prior to plantation establishment, such as is practised in New Zealand, helps to reduce soil erosion as well as improve nitrogen nutrition. Soil conservation techniques such as contour ploughing, minimum tillage, cover crops, multiple cropping, mulching, terracing and building structures to control water flow can reduce soil erosion from water. For example, thousands of years ago, the Incas in South America constructed intricate terraces on the steep slopes of the Andes to intercept rainfall and prevent erosion. Today, intricate terraces support rice culture in Bali. This again demonstrates that erosion on steep slopes can be controlled without forests. Forest harvesting operations compact, deform, disperse and expose mineral soil. Soil erosion and sedimentation to streams can be substantial if steps are not taken to arrest this. The provision of untouched buffer strips around streams as sediment traps is a common requirement in logging codes of practice worldwide. Road construction is another forest operation that has the potential to cause significant erosion. Fire over a catchment can cause substantial erosion because it exposes mineral soil. Fire can eliminate the protective soil litter, destroy humus and soil organic matter, kill the roots and destroy soil structure. It can also increase runoff of water after heavy rain and this will further increase erosion of the exposed soil.

Soil erosion by water can be from the soil surface (sheet erosion, gully erosion and stream erosion) or subsurface (tunnelling). Sometimes soil erosion on steep slopes can be very deep-seated and whole hillsides plus vegetation detach (mass wasting or landslides). The presence or absence of forests has little influence over the occurrence of deep-seated landslides. Erosion by water may be uniform and hardly noticeable. For example, sheet erosion may slowly but steadily remove layer after layer of soil until there is little left. More often, however, erosion by water is intermittent and uneven over the landscape and occurs in short bursts at times of intense rainfall on patches of ground with sparse or no vegetative cover. Surface erosion is potentially greater in the tropics than the temperate zone

Table 3.2. Soil loss (t/ha) during higher and lower rainfall years from different maize cultivation practices in Nigeria. (Derived from Lal, 1997.)

	Slope (%)		
Treatment	1	5	15
Higher rainfall year (781 mm)			
Bare fallow	7.5	80.4	155.3
Maize without mulch	1.2	8.2	23.6
Maize with mulch	0.0	0.0	0.0
Lower rainfall year (416 mm)			
Bare fallow	3.7	75.8	73.9
Maize without mulch	0.4	2.8	17.1
Maize with mulch	0.0	0.0	0.0

Table 3.3. The effect of forest type and ground surface cover on soil loss in the tropics. (Abridged from Hamilton and Pearce, 1987.)

Forest type and ground surface cover	Soil loss (t/ha/year)
Mixed species uneven-aged forest	0.30
Forest plantations, undisturbed	0.58
Tree crops with cover crop or mulch	0.75
Shifting cultivation, cropping period	2.78
Tree crops, clean weeded	47.60
Forest plantations, burned or litter removed	53.40

because rain is more frequent and intense, there is less litter on the soil surface, the soil has thinner humic horizons and there is less ground vegetation. As a result, logging operations in wet tropical forests are very sensitive to soil erosion, particularly on steep slopes.

Sites eroded by water can be rehabilitated by covering the soil surface with vegetation, litter and root system networks as soon as possible. Trees have a major role in rehabilitation because they are deep rooted and have strong roots. However, trees alone are not a panacea and should be used in conjunction with grasses, herbaceous species and shrubs in order to achieve a complex web of roots. Vetiver grass (*Vetiveria zizanioides*) grown in the tropics as a narrow dense hedge along the contours can be very effective at reducing erosion. Tree roots can assist in stabilizing areas prone to shallow slips and in preventing stream bank erosion. One of the many benefits of trees in agroforestry systems is erosion control. Rows of trees planted along the contours in agroforestry systems can trap soil moving down hill.

Erosion by wind

Soil erosion in dry country can be by water following intense rainfall, but erosion by wind is more common. Wind erosion is more uniformly spread over the landscape than water erosion and its consequences can be both spectacular and disastrous. For example, Leo Tolstoy witnessed the 'black storms' in the Ukraine in 1891, which caused crop failures resulting in entire villages starving to death. In the USA the natural vegetation of the prairies was removed and replaced by poorly managed agriculture on sub-marginal cultivated farmland. The resulting dust storms in the 1930s lasted for days, blocked out the sun, ruined machinery, inundated buildings and mechanically abraded plants, animals and structures. In dry country, vegetation cover is more fragile and recovers less well after damage. Droughts are often prolonged (and when the rains come they may be intense). The key to arresting soil erosion in dry areas is to maintain or improve the productivity of the soil so that the vegetation provides a more or less complete cover for all of the year and is protected as far as possible from the ravages of drought. This can be achieved by avoiding overgrazing, minimum tillage, not cultivating poor soils, managing the soil to increase its fertility and water holding capacity, mulching, conserving soil organic matter, water harvesting, avoiding soil salinity, avoiding fire and by constructing windbreaks and soil barriers. Annual grasses 'hay off' and die and the soil is vulnerable to erosion during this period. Trees and other perennials (in combination with grasses) have an advantage in controlling soil erosion in dry country because they are deep rooted and long lasting. Examples of the use of trees to combat soil erosion from wind include: extensive plantings in the African Sahel to slow down the desertification of overgrazed land; establishing the 6000-km long 'Green Great Wall' to protect Beijing from the advancing wind-eroded soils of the loess plateau; and stabilization of advancing coastal sand dunes (in conjunction with coastal grasses) in many parts of the world (McKelvey, 1999).

Sedimentation

Eroded soil is either washed or blown to other locations, where it is deposited as sediments. Sedimentation is a mixed blessing, but the net effect is decidedly negative. Even before the soil is deposited as sediment, it can have negative effects. Eroded soil carried in streams reduces the quality of the water for human and animal consumption by increasing the turbidity of the water and by carrying harmful substances such as insecticides, herbicides, fungicides, excess nutrients (particularly nitrogen and phosphorus) and industrial wastes. The reduction in water quality can harm or kill aquatic life and can limit its use in irrigation and industry. Wind-blown soil reduces visibility and endangers health, and water-borne sediments can raise the level of river beds and reservoir beds so that adjoining areas are subject to flooding. Groundwater levels can rise and wide areas can become waterlogged, developing into marshes. Reservoir capacities are reduced and the life of hydroelectric turbines and water pumps is also reduced. Water flows to industry and agriculture are impeded and irrigation canals become clogged and ineffective. Sometimes good soil is deposited where it is useful for agriculture, such as in the fertile flood plains of river systems (e.g. the Nile, Tigris/Euphrates, Ganges and Yangtze Rivers) whose continued productivity depends on erosion. However, very large amounts of eroded soil are deposited on stream and reservoir beds and in the oceans, where it can be of no agricultural significance. The ancient civilizations on the fertile floodplain of the Tigris/Euphrates River developed on sediments from erosion, but ultimately failed because they were overwhelmed by excess sediment (see Chapter 1).

The amount of soil eroded and deposited as sediments can be enormous. More than 1 billion hectares of the land surface of the Earth are experiencing serious soil degradation as a result of water erosion (Oldeman *et al.*, 1991). The current global rate of soil loss is of the order of 75 billion tonnes per year (Pimental *et al.*, 1995), of which about 50% is human-induced. The world's rivers deliver about 20% (15 billion tonnes) of sediment to the ocean each year (Walling and Webb, 1996) and many more billions of tonnes settle on stream bottoms and/or silt up reservoirs behind dams. For example, China loses more than 2 billion tonnes of soil each year, most of which is deposited in the Yangtze River. The annual sediment yield from the upper Yangtze River basin alone is 0.5 billion tonnes (Dingzhong and Ying, 1996). It takes 3.5 billion cubic metres of water to flush 100 million tonnes of soil deposited in the Yangtze River to the ocean. This water could be used for more productive purposes (National Research Council, 1993). Erosion of highly erodible rocks and soils on steep slopes in areas of high rainfall can be spectacularly high. The annual sediment yield from a schist basin in a high rainfall area of the New Zealand Alps is nearly 30,000 tonnes per square kilometre (Hicks *et al.*, 1996), while each year 500,000 cubic metres of gravel is removed from the Waimakariri River in New Zealand for flood mitigation. The Netherlands flood because of sediment arriving from other countries upstream on the Rhine.

Upstream erosion causes downstream sedimentation and therefore better upland watershed management will assist in controlling downstream sedimentation. If natural erosion rates are not extreme, undisturbed forests with intact understoreys will reduce erosion and sedimentation to streams. Disturbing (e.g. logging) or removing forests may increase erosion and therefore sedimentation to streams. Greer *et al.* (1996) found that suspended sediment concentrations in the Segama River catchment in Sabah were elevated as a result of the mosaic of forest patches at various stages of recovery from logging. They remained lower, however, than in the lower catchment, which contained commercial oil palm plantations, agriculture and degraded forest. Rapid regrowth of secondary vegetation following logging caused sediment loads to decrease to near undisturbed levels within 3 years. Forest establishment may decrease sedimentation if it replaces poor land use. For example, Dano (1990) showed that no-burning and reforestation increased water yield (9.5% and 11.5% respectively) and decreased sediment yield (59% and 72% respectively) compared with annually burnt *Imperata* grassland in the Philippines. Protecting stream banks and drainage lines during forest harvesting by leaving undisturbed vegetation (buffer strips) will reduce sedimentation.

Climate change and soil environmental values

Both climate change and population growth are creating conditions that favour fire. The frequency and intensity of forest fire varies over time and are often the result of chance factors such as the coincidence of ignition source, fuel availability and fuel dryness. Although fire is a ubiquitous natural process in forests, recent unprecedented heat and dry weather has forced forest managers to increase fuel reduction burning to reduce the risk of uncontrollable wildfires, so that climate change has already become a key driver of forest management in the USA and in Australia (Price and Bradstock, 2012; Stephens *et al.*, 2012). Over the last two decades, the temperate forests in these two countries have experienced an alarming increase in fires that threaten people and houses. Forest burning, estimated at about 1% of forests annually, already contributes about 15% of global fire-driven CO_2 emissions to the atmosphere. It seems this will increase in the future through greater areas burnt in planned and unplanned fires.

Climate change, through increased forest fire, will influence the environmental role of forests in the carbon cycle, and the storage of carbon in forest biomass and soil. As discussed in Chapter 8, the potential impacts are high because forests annually cycle about 10% of atmospheric CO_2 while sequestering about 80% of terrestrial biomass carbon and about 40% of below-ground carbon. Fire oxidizes organically bound carbon to release CO_2 and modifies forest organic matter to produce a wide range of charred and partially oxidized materials that are more long-lived than non-fire modified fuels and organic matter. The larger particles of these pyrogenic products are deposited on the forest floor as charcoal, while the smaller soot particles are dispersed aerially (Forbes *et al.*, 2006).

Charred organic matter is more resistant to decomposition and lives longer in soil than unburnt soil organic matter. In terms of the overall forest–atmosphere carbon balance, the extent to which charcoal longevity counteracts the CO_2 emissions in the burn or accelerated decomposition in the fire-blackened soil is uncertain (Kuhlbusch and Crutzen, 1995; Krull *et al.,* 2008).

In both agriculture and forestry, biochar is emerging as a cheap and readily available amendment that increases soil fertility and water holding capacity, stimulates beneficial biological activity and increases soil carbon storage to mitigate climate change (Sohi *et al.*, 2010; Lehmann *et al.*, 2011). In sandy plantation forestry soils, biochar acts to hold pesticides from moving in to and polluting groundwater (Wang *et al.*, 2010). However, there is still some uncertainty about the potential contribution of biochar to terrestrial carbon storage. Several lines of investigation reveal that surface-applied biochar can be readily decomposed at high soil surface temperatures in tropical regions, requiring a subsurface application for longevity (Zimmermann *et al.*, 2012). Better definition of the different types of biochar, combined with studies of decomposition rates across a wider range of soil temperature and moisture conditions will help determine the best way to apply biochars to maximize sustainable management and carbon storage goals.

Conservation of Biodiversity

What is biodiversity?

'Biodiversity' is a contraction of 'biological diversity' and can be defined as the variability among all forms of life, including plants and animals as well as fungi, microbes and protistans (single-celled organisms) (Hunter and Gibbs, 2007). It can be considered at three levels: (a) genetic biodiversity, which considers the genetic variation within populations and species; (b) species biodiversity, which is essentially a count of the number of species present; and (c) ecological biodiversity, which is the variability within and between ecosystems. From a forest management perspective, genetic biodiversity is variation within a species, and tree-breeding programmes need to ensure that sufficient genetic diversity is conserved to protect the species against environmental variation and biological threats. Conservation management of species biodiversity is directed at identifying and managing threatened species and to reducing the rate of species extinctions. Conservation management of ecological biodiversity focuses on maintaining representative examples of intact ecosystems to safeguard the full range of biodiversity that occurs on this planet, including the ecosystem processes necessary to sustain this diversity.

The measurement of biodiversity is complex and never exact. Species and particularly ecosystems cannot be precisely defined, boundaries are often indistinct, while for most taxonomic groups we simply do not know what species are present. While our knowledge of vertebrate animals and plants is good, with more than 70% of species having been described, our knowledge of other taxonomic groups is poor. For example, perhaps only 30% of insects and less than 4% of nematodes are known to science, while our knowledge of fungi is even poorer (Scheffers *et al.*, 2012). Current estimates of the number of species on this planet, ignoring microbial diversity, range as high as 50 million, while only 1.8 million of these have been described. The challenge in improving our knowledge of global species diversity is that most undescribed species either occur in systems (e.g. soils and the ocean deeps) or countries (e.g. in the tropics) that are difficult to research, while most of these undescribed species are likely to be small and cryptic – for example, a recently discovered chameleon (reptile) living in forest floor litter in Madagascar (*Brookesia micra*) has an adult body size of less than 20 mm.

In general, biodiversity decreases with increasing latitude and altitude. Latitudinal gradients have been particularly well studied in Central and North America, where the number of tree species decreases from over 800 species in Central American forests (e.g. in Panama), to 250–350 species in the temperate forests of the USA, to fewer than 30 species in the boreal forests of Canada and Alaska. Birds and mammals show similar patterns, decreasing from more than 600 and 150 species respectively in tropical Central America to fewer than 150 and 50 species respectively in boreal forests. These latitudinal patterns are even more apparent at a local scale. For example, the number of tree species with a diameter of ≥10 cm in seven 1-hectare Amazonian tropical rainforest plots (latitude 0–12°S) ranged from 89 to 283. In contrast, in all of New Zealand (268,000 km^2, latitude 34–47°S), there are fewer than 200 temperate rainforest tree species with a diameter of ≥10 cm. The boreal forests that cover vast swathes of northern Canada (latitude 48–68°N) comprise perhaps as few as 20–30 tree species ≥10 cm diameter, with often less than five tree species present over extensive areas. Similar patterns occur along altitudinal gradients. For example, in Nepal, bird species richness decreases from 300–360 species below 1500 m elevation to less than five species above 6000 m elevation in the Himalayas, while mammal species richness decreases from 94 species below 500 m elevation to two species above 5000 m elevation. One of the consequences of these gradients is that lowland tropical areas typically have the greatest species richness of any area on the planet, terrestrial or marine.

Conservation biologists have identified 25 'biodiversity hotspots' that, while comprising only 1.4% of the Earth's land surface, contain as many as 44% of all species of vascular plants and 35% of all species of birds, mammals, reptiles and amphibians (Myers *et al.*, 2000). These hotspots are defined by both the presence of endemic species, that is species that only occur in that area, and the degree of threat that these areas face (e.g. from deforestation). Of the 25 hotspots, tropical rainforests are dominant in 15, while Mediterranean-type ecosystems are dominant in a further five. The leading tropical rainforest biodiversity hotspots are Madagascar, Philippines, Sundaland (Malaysia, Sumatra, Java and Borneo), Brazil's Atlantic forest and the Caribbean. However, human activities currently drive species to extinction at 100–1000 times the background rate, although the restriction of most biodiversity to megadiverse hotspots that are under immense pressure from rapidly expanding human populations suggests that future extinction rates could be much higher than this.

Why conserve biodiversity?

Many reasons have been proposed for why humans might want to conserve biodiversity, but these can be broken down into two broad groups. The first sees biodiversity conservation being important because the biodiversity is of direct benefit to us (this is often referred to as utilitarian values). In contrast, the second sees biodiversity as having value in and of itself and independent of humans (called intrinsic values) – all species have the right to exist. Some eco-philosophers have argued that there is a third group of reasons why biodiversity conservation is important (Norton, 1987). They suggest that the presence of wild places and wild species, whether we experience them first hand ourselves or vicariously via television or other media, provides us with a sense of identity or place, a reflective contrast to our busy modern lives or a deeper connection with the world that we are all inherently a part of – this might be akin to some form of spiritual value.

Fundamentally, humans, individually and collectively, operate out of self-interest in a competitive environment. It is therefore unlikely that the human race will look after biodiversity unless there is something in it for them. This may sound cynical but, from an evolutionary perspective, it is appropriate behaviour. If, for the case of argument, ethical, cultural, religious and philosophical considerations are put aside, it might be argued that the human race need only be concerned with those species that impact directly on their sustenance. Three cereals (wheat, maize and rice) represent about 50% of all human energy input. Twenty species of plants and five species of animals account for more than 90% of human sustenance and about 1000 species (less than 0.01% of all species) have some current economic value to humans (Solbrig *et al.*, 1994). It might be argued that, because the amount of biodiversity on the planet is so high (perhaps as much as 50 million species), the loss of some or even a significant portion of this will have little effect on the existence of humans on Earth, providing we look after these key species. However, this analysis, besides being heartless, is incorrect. Biodiversity is essential for a myriad of ecosystem services, including water provision and purification, nutrient cycling, pollination, carbon sequestration and climate regulation. Recent research has highlighted that biodiversity loss is having important impacts on primary production and decomposition, which in turn have major impacts on ecosystem services (Hooper *et al.*, 2012). It appears that the ecosystem consequences of species loss are likely to be as severe as other better-known factors impacting global ecosystems, such as climate change and pollution, and we do not yet know just how many species we are losing.

Clearly biodiversity provides the opportunity to widen the consumption base that humans exist on, but biodiversity provides far more than this for humanity. Besides producing wood (for construction and fuel) and food, forests produce a range of other economically valuable products such as fodder, dyes, tannins, cosmetics, essential oils, garden plants and resins. These are termed non-wood forest products and will be discussed in more detail in Chapter 5. Perhaps one of the most important products to come from forests is medicinal compounds. For example, aspirin, the best-selling medicine of all time, although now synthetically produced, is based on extracts originally derived from the bark of willow trees. There are more than 100 substances extracted from 90 species of plants used in medicines and about 5000 species of plants, many from forests, have been extensively investigated as sources for new drugs. The World Health Organization lists 21,000 names of plants that have been reported to have medicinal use, although very few of these have been scientifically tested (Groombridge, 1992). Many peoples have a long history using traditional medicines based on plants. Animals are also used for medicine. It is inevitable that more plants, animals and microorganisms will be found with medicinal and other uses, and some of these may well be from currently undescribed species. Forest plants, and particularly rainforest species, are rich in chemicals, particularly alkaloids, which they produce to protect themselves from disease or insect attack. These chemicals produce useful drugs now and will do so in the future, providing the species still exist. Forests may be very biodiverse, but there is considerable ignorance about what is actually there.

The conservation of biodiversity is intimately associated with the integrity of ecosystems. Forests are complex ecosystems that provide a wide range of values to humans as discussed in this and the next two chapters. There is evidence that some terrestrial ecosystems are dependent on a high diversity of plants, animals and microorganisms (Reaka-Kudla *et al.*, 1997). The integrity of these ecosystems depends on the involvement and interaction of biological entities at all levels. Loss of biodiversity threatens the integrity and functioning of the whole. It is not known whether there is an element of redundancy in this and whether all organisms are necessary for ecosystem stability. Certainly some ecosystems with lower biodiversity appear to be stable (Kimmins, 1992). Indeed, the relationship between levels of biodiversity and ecosystem stability and resilience is obscure (Kimmins, 1997). The question of how much biodiversity we can lose before the human race is threatened is unknown. This highlights the lack of knowledge in this area. Certainly it would be wise to err on the side of caution. It follows that one of the best ways to conserve biodiversity is to conserve intact ecosystems. Indeed, the main forms of management for conservation of biodiversity in forests are to reduce habitat destruction and fragmentation, to provide representative protected areas of sufficient size and arrangement, and to promote sustainable forest management based on ecological principles (Chapter 7). The provision of protected areas alone is not sufficient to conserve biodiversity. A range of sustainable forest management options are required (Lindenmayer and Franklin, 2002). The object of forest management should be to mimic as far as possible the natural disturbances in the ecosystem (Hunter, 1999). The precautionary principle of 'if you don't know the effect of a human intervention, then don't do it' has considerable merit because extinction is irreversible. This can be taken to unreasonable extremes, however, when used as an excuse to not manage at all, an approach that can have worse consequences.

Many humans instinctively believe that the welfare of all other species is intimately connected to their own welfare. This is often a gut feeling, but research into the complex web of interdependence of species within ecosystems strongly reinforces this. Humans also extend their self-interest to future generations in being concerned to hand the world on to their progeny in good condition. However, humans are capable of rising above self-interest and, on face-value at least, are concerned about the conservation of other species without any apparent expectation of a reciprocal benefit. The concept that all biological entities have an intrinsic value independent of human values is difficult to explain but is widely accepted. Ethics, culture, philosophy and religion all play a part in our relationship with other species. Certainly Buddhism and Taoism strongly advocate conservation of biodiversity. Indeed, Hamilton (1993) considered that it would not be the ecologists, engineers, economists or earth scientists who will save space ship earth, but rather the poets, priests, artists and philosophers. The concept of 'deep ecology', espoused in the 1980s (Tobias, 1985), at its most extreme says that all individual living things are sacred and that humans have a moral obligation to respect this irrespective of whether this is to their advantage or disadvantage. While this has some appeal, it must be said that it is most likely to be entertained by those humans who are already well fed, clothed and sheltered and plan to remain so. We eat our companion species, we use them for fuel and shelter, and plant and animal products dominate our living environment. Most humans would agree that it would be a betrayal of duty to be responsible for extinction of species. Even so, most humans welcomed the extinction of the smallpox virus and many would not be at all concerned with the demise of some invasive species that threaten us or even just annoy us. Also humans tend to place different values on different species: animals are generally favoured over plants and larger boutique animals (e.g. tigers and pandas) are favoured over less conspicuous animals such as undescribed insects. Another ethical issue is the use and abuse of genetically modified organisms. Genetically modified organisms contribute to biodiversity and potentially offer enormous economic advantages to the human race. However, once released they cannot be recalled and their impact on ecosystem composition and processes cannot be reliably predicted.

Threats to forest biodiversity

It is clear that biodiversity globally is in rapid decline and it has been suggested that within 240 years Earth may face the sixth mass extinction (Barnosky *et al.*, 2011). The *Millennium Ecosystem Assessment Report* (2005) has identified five key drivers of biodiversity change globally: habitat change, climate change, invasive species, over-exploitation and pollution. While pollution is less of a threat to forests globally, although it may be important locally, the other four factors are seriously impacting on both the extent and composition of forests throughout the world.

Habitat change and loss is without doubt the single biggest factor currently affecting the extent and composition of forests globally. Rates of deforestation across different forest biomes have been widely reviewed and are discussed in more detail in Chapter 6 of this book. While much of the focus in conservation biology has been on the retention of old-growth or primary forests, disturbed forests (e.g. as a result of past timber harvesting) can still retain value as many native species persist and these forests have the potential to regenerate back to a condition similar to that prior to disturbance. However, a recent comprehensive assessment of the effects of disturbance on tropical rainforests has clearly shown that biodiversity values were substantially lower in degraded forests than in intact tropical rainforests and that there is no substitute for maintaining primary tropical rainforest if we are to sustain tropical biodiversity (Gibson *et al.*, 2011). Notwithstanding this, of all the disturbed forest types, selection logged forests were the most similar to primary forest. But even for forests that are legally protected, the outlook is not good – a recent assessment of 60 representative protected tropical forest reserves (mostly larger than 10,000 ha; Laurance *et al.*, 2012) found that 80% showed some decline in reserve health and in half the decline was relatively serious. Reserve health was based on the status of a range of forest plant and animal guilds. The strongest predictors of reserve health were habitat disruption, hunting and forest-product exploitation, with environmental change (especially habitat loss) outside the reserve also being a key factor influencing reserve health.

Deforestation permanently removes the biodiverse forest and replaces it with a less biodiverse alternative land use. As a result, deforestation almost always reduces biodiversity. So too does forest degradation, although to a lesser extent if there is the opportunity for ecosystem recovery over time. Ecologically based forest management has the least impact, although will still reduce biodiversity. It then follows that forest management for timber production will be better for biodiversity if it substitutes for deforestation (Burgman and Lindenmayer, 1998).

While it is clear that climates are changing globally and that anthropogenic factors, especially increasing atmospheric CO_2 levels, are an important contributor to this, it is less clear what the current and potential future impacts of these changes will be on forest ecosystems. It has been suggested that increasing atmospheric CO_2 levels will result in increased tree productivity, although increased temperatures may also increase evapotranspiration, which could offset any gains arising through elevated CO_2 levels. While small changes in temperatures may not be that important for many of the world's forests, changes in rainfall patterns and especially the incidence of drought may be far more significant. There are increasing reports of drought-induced forest mortality events, and it has been suggested that even small changes in drought intensity could lead to forest mortality all over the world (Choat *et al.*, 2012). Changing climates are also resulting in changes in disturbance regimes. For example, recent outbreaks of mountain pine beetles in British Columbia have occurred further northwards than historically, while an unbroken sequence of warm summers since 1987 have been implicated as the cause of spruce mortality in Alaska, where in some areas over 90% of all spruce trees have been killed (Logan *et al.*, 2003). The impacts of climate change are further discussed in Chapter 8.

In some forest systems, especially on islands such as in New Zealand, invasive species seriously threaten forest biodiversity. Invasive species are species that have been introduced into an area in which they previously did not occur and have established in the wild and are having adverse environmental impacts. Humans have been moving plants and animals around ever since the time of the hunter-gatherers, but it has only really been since European colonial expansion and especially the rapid expansion of global trade that large numbers of species have been shifted to new locations. While the majority of species that are introduced to new locations never persist in their new environment, a small number do and of these an even smaller number go on to have adverse effects on a wide range of values, including food and fibre production and native biodiversity. It is these species that are of most concern in forest ecosystems worldwide. The impacts of forest pests on timber production are discussed briefly in Chapter 9; the focus here is on invasive species that impact biodiversity values.

There are numerous examples worldwide of the impacts of invasive species on biodiversity. One of the best documented examples is from New Zealand, where the indigenous vertebrate fauna (which is dominated by reptiles and birds) evolved in the absence of mammalian predators, with the main predators being owls and eagles. When rats were introduced in the 1700s and stoats and weasels in the 1880s, the birds were particularly vulnerable and one-third of the New Zealand avifauna became extinct, while many other species are now threatened with extinction. The Australian possum, introduced to New Zealand for fur, and various Northern Hemisphere ungulates (deer and goats, which were introduced for hunting), have also become invasive and have ravaged most of New Zealand's forests, with the possums destroying tree canopies, while ungulates prevent regeneration by browsing the understorey. As a result, New Zealand's indigenous forests are in serious decline. Another good example of a biological invader is the fungus *Endothia parasitica* that was introduced into the USA from Japan, Korea and China in the early 1900s and has now almost eliminated the American chestnut (*Castanea dentata*). There are also many examples all over the world of introduced weeds out-competing and endangering native plant species. For example, *Pueraria lobata* (Kudzu), introduced into the USA from China and Japan, now infests more than 2 million hectares of forest. However, the most destructive invasive species globally is *Homo sapiens*, who is ruthlessly efficient at competing for habitat and preying on other species.

Protection of forests against biotic agents (e.g. fungi, insects, vertebrate browsers) and abiotic agents (e.g. fire, storm) is an important responsibility of forest management. Forest protection is not considered in any detail in this book, but its critical importance is acknowledged. Further information can be found in Tainter and Baker (1996), Lundquist and Hamelin (2005), Wainhouse (2005) and Nair (2007).

Forest restoration

One method that is widely used to address forest degradation and loss is to re-establish new individuals of forest plants and animals through restoration. Restoration plantings are undertaken for a range of reasons, including to buffer remaining forest remnants, enhance connectivity between remnants, increase the total area of forest habitat, provide habitat for beneficial species (e.g. pest-control agents or pollinators) or to reintroduce locally extinct species (Hobbs, 1993). For vegetation, restoration usually involves planting or direct-seeding desired species. However, in many instances it may be sufficient to simply remove degrading factors such as grazing. So long as seed sources are in close proximity and the extant vegetation does not limit establishment, native species will re-establish naturally (Wilson, 1994); this latter approach has been termed minimum interference management or natural regeneration. A further approach to restoration that is showing some promise, especially in tropical countries, is to use timber plantations as both a source of income for rural communities and as a tool for facilitating the regeneration of tropical forests in previously degraded sites (Lamb *et al.*, 2005).

While relatively straightforward, there are a number of issues that need to be considered in implementing restoration that, if given proper attention at the outset, are likely to greatly increase restoration success. It is important be clear what factors have led to the degradation and to make sure that these have been addressed (Hobbs and Norton, 1996). For example, if the key degrading factor was grazing, then removing grazing pressure (e.g. by fencing out domestic livestock) may be sufficient to ensure restoration success. However, in other situations, degrading factors might be more difficult to reverse (e.g. soil compaction) and may require a more intensive approach than would otherwise be the case (e.g. ripping the soil prior to planting). In some situations, removing the initial degrading factor may create additional problems, which need to be addressed. For example, removal of grazing animals from sites that have a long history of fertilizer application more often than not results in the establishment of a rank sward of invasive grasses. In fact, in many forest environments, non-native grass control is one of the biggest challenges facing restoration (Thaxton *et al.*, 2012). Restoration therefore needs to address this through appropriate pre- and post-planting weed control (e.g. using herbicide or mulch) or through measures aimed at reducing soil nutrient levels (e.g. addition of bark chips or even scarifying the soil), in addition to controlling the original degrading factor.

Species choice is also an important consideration in restoration. While the restoration goal might be to re-establish rainforest, planting of mature rainforest species into pasture sites might not be appropriate in some situations (e.g. sites prone to frost) and a better approach would be to establish fast-growing seral species. The use of seral species in rainforest restoration is common in many forested regions and so long as a seed source is present, later canopy dominants usually readily establish (Reay and Norton, 1999). However, for some forest types (e.g. sclerophyll forests such as occur over much of Australia) and for rainforest in frost-free sites, planting directly into open sites works well, so long as there is adequate weed control. For example, in many areas of Australia, eucalypt species establish readily in pasture, whether planted for restoration purposes or as shelter belts, except where high soil nutrient and herbivorous insect levels result in defoliation or weeds are not controlled. The best guide to species choice is usually to see what is happening at sites where regeneration is occurring naturally.

Another important consideration in restoration is the origin of the plant material, with the usual convention being to source plants from sites close to the restoration sites. Some plant nurseries now specialise in eco-sourced plants to meet this need. In order to ensure a wide genetic base and fit planting stock, seed should be sourced from many healthy plants in the local area. Because of the risk of too narrow a genetic base in planting stock and the possibility that rapid climate change will drive local populations to extinction, some authors are now recommending ‘composite provenancing’ for restoration plantings, where most material is collected locally from genetically healthy stock, but some is collected at increasing distance from the site and perhaps 10–30% of material is collected much further afield (Sgrò *et al.*, 2010). Consideration of mycorrhizal fungal associations is also important. For many woody plants, mycorrhizal fungi are essential to ensure establishment success and rapid growth as they assist in nutrient uptake and provide some pathogen protection (Williams *et al.*, 2011). However, the correct mycorrhizae need to be present – with endotropic mycorrhizae favouring some plant groups and ectotrophic mycorrhizae other groups.

The timing of planting also has an important influence on restoration success. In temperate climates, the best time to establish restoration plantings is usually spring, after the last of the severe winter frosts but before summer soil moisture deficits develop. Similar considerations also apply in more arid climates, especially in relation to the timing of rainfall events (Sitters *et al.*, 2012). With direct seeding, sowing prior to winter might be required to ensure that seeds are properly scarified over the winter and can then germinate as soon as conditions become suitable in spring. A final factor for restoration success is to make sure that appropriate post-planting maintenance is undertaken. This involves ensuring that grazing animals continue to be excluded from the site: even one cow can destroy many thousands of dollars of plants and many hours of hard work in a very short period of time! Ongoing control of plant and animal pests is essential. Where restoration occurs on fertile soils with good soil moisture, ongoing control of grass and broad-leaved weeds is essential until plants are big enough to overtop and suppress them.

The actual approach adopted for restoration will depend on the local situation, especially the availability of seed sources and the nature of the site to be restored, as well as the resources (financial and labour) available to undertake the required work. Natural regeneration will work best at sites where seed sources are in close proximity, while the planting of nursery-raised seedlings is likely to be more appropriate at sites where local conditions limit the likelihood of natural regeneration (e.g. seed sources are distant). In some instances, a mix of approaches might be used.

Uniformity

The opposite of diversity is uniformity. Humans employ intensive monocultural systems for providing their food and some of these are tightly bred with a narrow range of genetic variation between individuals. The biodiversity among grazing animals is similarly restricted. Plantation monocultures are becoming increasingly important for the production of wood and the proportion of genetically confined 'improved tree breeds' and clonal material is increasing. Clearly biodiversity is reduced when biodiverse forests are cleared and replaced by alternative more uniform land uses. Also the intensity of these systems in terms of energy consumption and the use of pesticides and fertilizers cause concern when they promote adverse off-site effects. There is a growing desire among some foresters to move towards more diverse and less intensive forms of forest management. However, the counter argument is that intense uniform systems are so efficient at production that they require a smaller land base and relieve the pressure on the broader landscape (this is called land sparing). Also, depending on circumstances, there can be considerable biodiversity in monocultural tree plantations, certainly more than in agricultural monocultures. These matters will be considered further in Chapter 9.

Recreation, Amenity and Aesthetics

Most people recognize forests as scenic and beautiful places and are concerned that this aesthetic quality is safeguarded. For some it is enough just to know that the forests are there and they are satisfied with pictures on calendars and documentaries on television to demonstrate to them that this is so. Others go one step further and visit the forests but rarely venture further than the road or the immediate vicinity of the picnic ground. Still others go right into the forests for days or weeks and enjoy in full what the forest has to offer. People usually consider scenery as static, almost like photographs. Forests, however, are not static but are dynamic systems that are constantly changing. It is unrealistic and ecologically unsound to expect a forest manager to 'freeze in time' an appealing forest vista. It is impossible to do so. Also it does not necessarily follow that the most scenic forests are those in the best ecological condition and vice versa. For example, forests with many over-mature and dying trees may look untidy. However, the process of death, decay and rebirth is an integral part of a forest's growth and survival. Forests may pass through stages of more scenic and less scenic during their development. For example, forests in a regenerative phase with many small trees and few larger trees are generally considered to be less appealing than 'old growth' forests where there is a preponderance of large trees. Forests that have been cleared either by fire, wind or human disturbance may look rather ugly, but can subsequently develop into something quite attractive. Young plantations may look rigid and contrived, but older thinned plantations can be very appealing. Old growth forests with very large trees can be spectacular and awe-inspiring and to some they have a spiritual value. Religions through the ages have set aside reserves of trees that they consider have particular significance.

A responsibility of forest management is to reduce any adverse visual impacts. This requires attention to the visual impacts of forest roads (route, shape, cuts and fills), forest shapes (edges, lines), forest operations (felling, planting, residue management, soil exposure and erosion, windrows, burning, weeds) and species (selection and distribution). The design of forest landscapes to please and not offend is an important and well-established discipline in its own right (Lucas, 1991). Usually it is not the forests in themselves but rather the placing of forests in the landscape that people find attractive. Large continuous tracts of forests are less appealing than forests broken up by water, tree-lines, rock outcrops or land cleared for agriculture or grazing. Humans are creatures of the forest edges.

Forests are used for a wide range of recreational uses, such as bush-walking, sight-seeing, bird-watching, camping, nature observation, hunting, picnicking, photography, fishing, mountain-biking, use of off-road vehicles, cross-country skiing, canoeing, running, growing and concealing illicit drugs, car rallies – and this is not a comprehensive list. Not all recreational uses are compatible and some are undesirable. It can be a challenging task to manage forests in such a way that the legitimate aspirations of those who wish to use them for recreation are taken into account. Their conflicting interests have to be considered alongside the need to minimize damage to the forests.

Human empathy with forests extends to creating treed landscapes in urban areas. Indeed towns, suburbs, parks and streets with extensive use of trees add greatly to the value of the land. The trees and associated flora and fauna in streets and in private and public gardens can be a very valuable resource for amenity and recreation, and indeed the most common experience of ‘nature’ for most people on Earth.

Other Benefits of Forests

Mountain forests can protect humans from natural disturbances such as avalanches, rock falls and landslips. Forests are the home of some indigenous peoples, who depend on them for food, fibre, fuel and shelter. Forests also have a critical role in arresting the climate change resulting from increased CO_2 concentrations in the atmosphere. Trees in urban landscapes may be continuous and extensive enough to be considered as urban forests. These benefits will be discussed in later chapters.

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4 Wood and Paper Products

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Societal Demand for Forest Products

Throughout history, wood has satisfied a diverse range of society's needs. Since Palaeolithic times, it has been used to make tools and fire (Ambrose, 2001; Karkanas *et al*., 2007) and until the industrial revolution, wood was the predominant source of fuel. For many years, it was the pre-eminent material for constructing buildings and vehicles and most carts, chariots, wagons and boats were built primarily from wood. It also made other important contributions to society. It provided furniture, energy from water wheels and windmills, beams to support mine shafts and bridges, weaponry in the form of bows, arrows, gun stocks, looms for weaving and barrels for storing beer, wine and foods (Perlin, 1987; Youngs, 2004). Wood fibres have also facilitated communication and record-keeping. Paper was reputedly invented in China in AD 105. Initially, China had a monopoly on paper manufacture. Eventually paper-making knowledge was transferred to Japan, to Arabia and reached Europe in the 11th century. Before 1800, paper was usually made from fibres derived from flax or cotton, in the form of rags and linen (Cameron, 2004; Scott, 2004). The continuous paper machine was invented in 1798 and the first technologies for making pulps from wood were developed in the mid-1840s in response to a shortage of rags (Scott, 2004). The development of these wood fibre-based pulp and paper making technologies enabled a diverse range of paper products to become widely available to society and this resulted in the substantial growth of the pulp and paper industry.

For many centuries wood was one of the most widely consumed materials in the world (Geiser, 2001). Until the industrial revolution was well advanced, it was one of the primary resources that supported society and it ranked in importance only behind food and water (Namkoong, 2008). With the advent of industrialization, a diverse range of materials and energy forms began to compete with wood. For example, in 1850 wood was estimated to account for over 90% of the energy production in the USA and by 1910 this value had decreased to less than 10%, as coal became more widely available (Cook, 1971). With the passage of time, wood and paper products became less significant contributors to economic prosperity. Over the last 50 years, the contribution of roundwood and sawn wood production to global GDP in constant dollar terms has decreased by about 80%, while that for paper and paperboard has decreased by about 14% (Fig. 4.1). At the global scale, wood is not the pre-eminent material that it once was and, in 2010, its annual production was less than that of coal, crude oil and cement and iron ore (Table 4.1). However, more wood was produced in 2010 than steel, plastics and aluminium combined and, in the 21st century, wood and wood-fibre products are still widely used to meet society's needs for energy, shelter, furniture, recording information, communication, packaging and hygiene.

This chapter will describe the structure and properties of wood, outline the important categories of wood and paper products, present details on their production at the global scale and highlight the environmental benefits of using wood products. Chapter 5 will address the production of energy, non-wood forest products and advanced biomaterials.

The Structure and Properties of Wood

Trees grow by increasing in height and diameter. They do this by creating new cells at the growing tip (the apical meristem) and around the circumference of the stem where the bark meets the wood (the vascular cambium). The vascular cambium

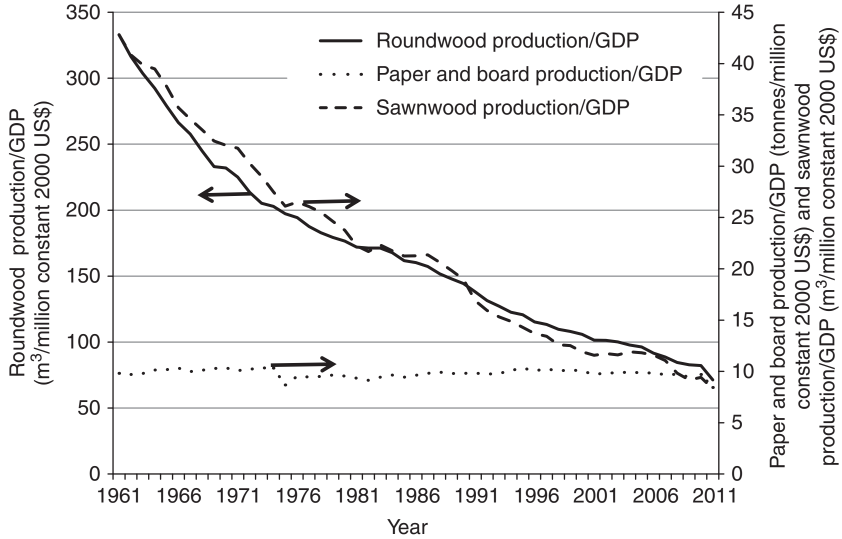

Fig. 4.1. Annual global wood-fibre production per unit of gross domestic product. (Compiled from FAO and World Bank online statistics; FAO, 2012; World Bank, 2012.)

Table 4.1. Global materials production in 2010. (From EIA, 2012; FAO, 2012; Plastics Europe, 2012; USGS, 2012a,b,c; World Aluminium, 2012; World Coal Association, 2012; World Steel Organization, 2012; *Plastics and oil data are for 2009.)

Material	Production (billion tonnes)
Coal	7.23
Crude oil	4.27*
Cement	3.31
Iron ore	2.40
Wood	2.38
Steel	1.43
Plastics	0.23*
Bauxite	0.21
Aluminium	0.04

produces cells (phloem) outwards that subsequently develop into bark and inwards (xylem) that subsequently develop into wood. The primary function of a tree's stem is to provide two pathways. The first, which occurs mainly in the wood, transports water and dissolved nutrients from the soil through the roots to the leaves. The second, which occurs mainly in the bark, moves sugars and carbohydrates produced by photosynthesis in the leaves to other parts of the tree. Wood therefore has to be somewhat like a system of pipes to facilitate its role in transport and the cells in wood are elongated axially to achieve this function. Wood also has to be strong enough to hold the tree and its canopy erect, while withstanding external forces such as wind. As a result, the elongated cells of wood in trees undergo secondary thickening to provide increased strength. The cells of wood therefore have thicker and more anatomically complex walls than the cells of smaller herbaceous plants. Much of the literature distinguishes between conifers and hardwoods. Chapter 2 presented an argument that the use of the term hardwoods is ambiguous and misleading and that more correctly they should be called angiosperms. The Food and Agricultural Organization of the United Nations (FAO) circumvents these difficulties by classifying wood products as coniferous or non-coniferous. Except for a few species, such as palms and bamboos, all forest trees that are angiosperms (non-coniferous) are dicotyledons (or more recently called by some sub-class Magnoliidae). Conifers and dicotyledons have distinctively different wood anatomies.

The predominant cell types in wood are fibres and vessels (in dicotyledons), tracheids (in conifers) and ray cells (in both). Tracheids, fibres and vessels are axially elongated cells (Fig. 4.2). Tracheids in

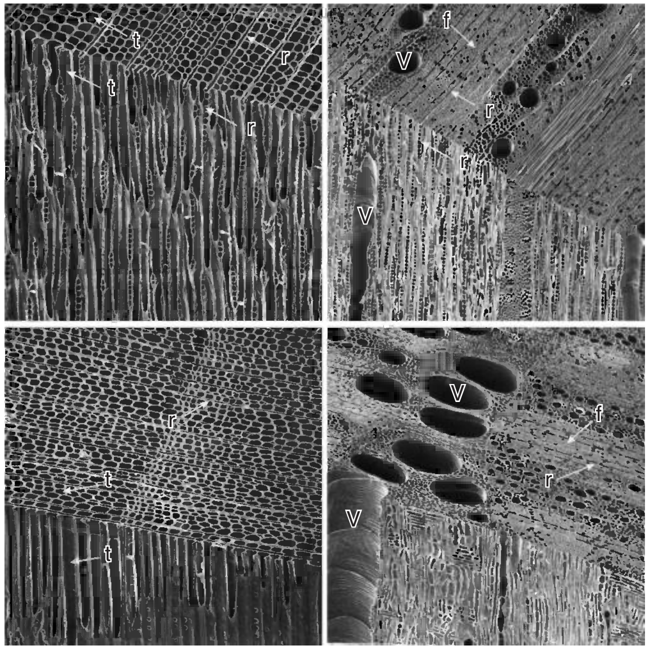

Fig. 4.2. Scanning electron micrographs of the conifer *Dacrydium dacrydioides* (left-hand side) and the dicotyledon *Quercus robur* (right-hand side) showing a transverse and tangential longitudinal face (top row) and a transverse and radial longitudinal face (bottom row). v = vessel; r = ray; t = tracheid; and f = fibre. (Scanning electron micrographs from Brian Butterfield; magnifications 90× left upper, 70× left lower, 50× right upper and lower.)

conifers perform both transport and structural functions and they are connected to each other by bordered pits (essentially holes in the wall) to facilitate sap flow. Fibres in dicotyledons are shorter than tracheids and perform only the strength function, while the elongated tube-like cells, called vessels, perform the transport function. The difference between dicotyledon and conifer wood is easily distinguished by the presence or absence of vessels. Tracheids, fibres and vessels lose their living contents (protoplasm) quite soon after differentiation and from then on are dead cells. Only the outer part of the wood (the sapwood) functions in transport and, in order to do this, the elongated transport cells (tracheids and vessels) need to be in contact with or close to a living cell over some portion of their length. These living cells (parenchyma) are oriented in radial rows called rays. Ray cells may be in a single radial column (uni-seriate) or stacked into multiple columns (multi-seriate). Most often they are lens-shaped when viewed end on (tangentially) (Fig. 4.2). There is a zone of wood adjacent to the vascular cambium, called the sapwood, which is active in transport. As the tracheids and vessels become older and further displaced from the physiological centre of activity (the vascular cambium), the adjacent ray cells die and the transport function is no longer supported. The walls and lumens (the space inside the walls) of the tracheids, fibres and vessels become progressively clogged up with extractives and the cell-to-cell pit connections break down. Differences in the amount and nature of extractives are responsible for differences in colour and durability between the woods of different species. This inner wood that is no longer involved in transport is usually darker and is called heartwood. In small, young and actively growing trees, sapwood may occupy all or most of the wood, but in older larger trees sapwood may be confined to a small ring adjacent to the vascular cambium.

There is a great variety in the way the cells are organized and this gives rise to the wide variety in the macroscopic appearance of the wood of different species and in the way that the wood behaves in service. In temperate climates, radial tree growth effectively ceases in winter. Conifers lay down thinner walled cells in the early part of the growing season (earlywood) and thicker walled cells in the latter part of the growing season (latewood) and dicotyledons display different patterns of fibre and vessel distribution across the growing season. As a result, there is a distinct pattern of annual rings across a transverse section and counting the rings near to the base of the tree will give the age of the tree. In climates where there is no distinct cold season, trees grow throughout the whole year and do not have annual rings. However, they still may have growth rings owing to differences in water availability and temperature over weeks, months or years. The wood that is formed early on in the life of the tree (near to the centre or pith) is called juvenile wood. This wood has shorter tracheids and fibres with thinner walls and greater microfibril angles. As a result, it is not as strong. This has implications in wood utilization, particularly in plantations where trees grown over short rotations have high proportions of juvenile wood. In sawnwood, knots are found where branches meet the stem. Knots weaken the timber and are generally considered to be unsightly. If the lower branches are cut off close to the stem, wood formed after this will be clear of knots. This is the rationale behind pruning trees to confine the knots to a central knotty core in order to produce clear wood outside the knotty core.

Tree stems are round, but sawn timber is square or rectangular. The appearance of the face of a sawn board will differ, depending on whether it is closer to being aligned radially (quarter sawn) or tangentially (back sawn) (Fig. 4.3). In quarter-sawn boards, the growth rings are near to perpendicular to the face of the board and the rays are parallel to the face of the board. Quarter-sawn boards expose the sides of the rays and consequently are prominently figured. The prominent flecks in quarter sawn oak, for example, are caused by the prominence of the rays. In back-sawn boards, the growth rings are approximately parallel to the face of the board and the rays are perpendicular. The rays are less prominent because their ends rather than their sides are shown (Fig. 4.3). Boards between quarter sawn and back sawn, where the rings intersect the face at angles of 30° to 60° (rift sawn), will have an appearance somewhere between that of quarter-sawn and back-sawn boards.

Wood is an anisotropic material, which means that its mechanical properties are not equal in all directions. This has advantages in that strength is maximized where the fibres or tracheids run parallel to the long edge of the board. However, the anisotropic nature of wood also creates problems, particularly during the drying of wood. Wood shrinks when it dries. Shrinkage along the length of the board is small in comparison to

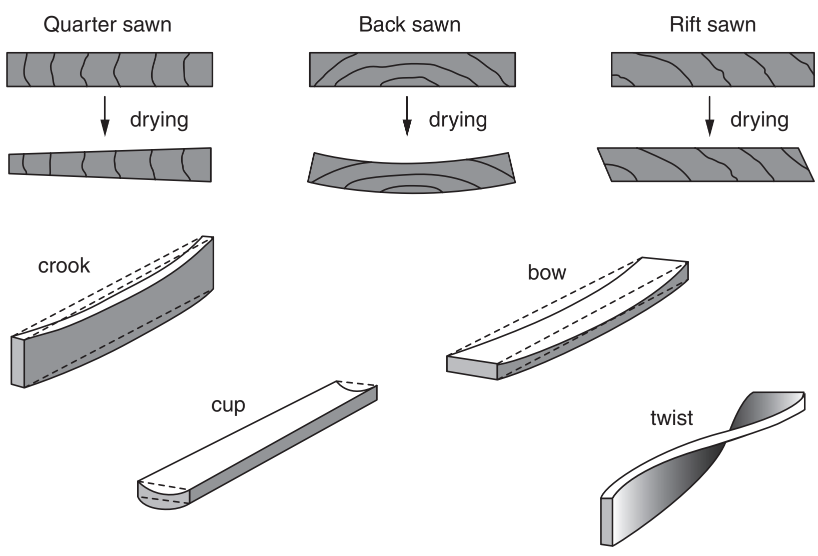

Fig. 4.3. Possible dimensional changes in sawn boards on drying (movements are exaggerated for effect).

shrinkage across the face and edge of the board. Tangential shrinkage is greater than radial shrinkage and, because growth rings are circular and board faces are flat, this can cause the boards to dry in an uneven manner. The tendency is for the curvature of the growth rings to straighten in drying. A quarter-sawn board will shrink less across the face than a back-sawn board, but may shrink unevenly across its thickness. A back-sawn board may cup across its face. A square section may become a diamond, a circular section an ellipse and a rift-sawn section a parallelogram (Fig. 4.3). Differences in shrinkage patterns along a board may cause the board to crook, bow or twist (Fig. 4.3). These differences along the board are often caused by the presence of reaction wood, which is composed of abnormal cells produced in response to uneven loading such as in a leaning tree. Reaction wood has greater longitudinal shrinkage than normal cells. Small cracks (checks) may occur on the ends and faces of boards during drying. These problems can be minimized with careful and controlled drying (seasoning) of the wood.

Wood is a lignocellulosic material that, unless burnt, will ultimately decompose under the influence of wood-degrading fungi, insects, bacteria and marine borers. This is, of course, desirable because decomposition is an integral part of the cycling of nutrients and carbon in forest ecosystems. Forest-floor litter has to decay. If it did not do so, woody material would continue to accumulate on the forest floor and the productivity of the system would grind to a halt. Wood decay may also be a boon if it is done in a controlled manner in order to pulp the wood prior to paper making. Wood decomposition, however, is a costly nuisance when it comes to using solid wood and engineered wood products as a building material. Chemical treatments have been used for centuries to reduce the rate of wood deterioration. Historically, the most commonly used 'first generation' preservatives have been oil-based creosote, pentachlorophenol and water-based arsenicals, principally chromated copper arsenate (CCA). All of these are under public scrutiny because of proven or suspected toxicities and they have been banned in several countries. In response to these concerns about toxicity and environmental impact, a 'second generation' of water-borne copper-rich systems containing complexed copper and an organic biocide have been developed and are gaining global market share (Schultz *et al.*, 2007).

Global Production of Wood Products

In 2010, about 3.40 billion m^3 of roundwood were produced from the 1.2 billion hectares of forest that were managed principally for the production of forest products (Fig. 4.4; FRA, 2010). It has been estimated that the roundwood harvest is equivalent to about 0.7% of the total growing stock (FRA, 2010). Since the early 1980s, the annual global roundwood harvest has ranged between 3.2 and 3.6 billion m^3. The volume of roundwood harvested is affected by the state of the economy, political and legislative developments, substitution by competitive non-wood products (such as concrete, steel and electronic media) and increased manufacturing efficiency (which produces a greater product yield per unit roundwood input). The official FAO statistics underestimate the real global roundwood harvest because illegal and unreported logging has been estimated to be 20–40% of the global industrial roundwood harvest, or about 300–600 million m^3/year (Nilsson, 2007).

Historically, the majority of the harvest has been used for energy production (Fig. 4.4) and the use of wood for this purpose is discussed in Chapter 5. In 2011, 56.4% of the harvest was used to directly generate energy and 43.6% served as input to the global wood products industry (Fig. 4.5). The major categories of products made from roundwood are presented in Fig. 4.6. Industrial roundwood is used as sawnwood (lumber), panels and engineered wood products (particleboard, medium density fibreboard, plywood, oriented strand board, laminated veneer lumber, glulam, paralam, oriented strand lumber) and a wide variety of other products, including composite products, post and poles and shingles. It can also be pulped and subsequently used to produce paper and paperboards. It may also be used to manufacture a variety of other products, including composites when combined with plastic or cement.

The global production of coniferous and non-coniferous industrial roundwood is shown in Fig. 4.7. Coniferous industrial roundwood comes mainly from the temperate developed world and non-coniferous industrial roundwood comes predominantly from the tropical developing world. There has been little growth in industrial roundwood production over the last 30 years, with the

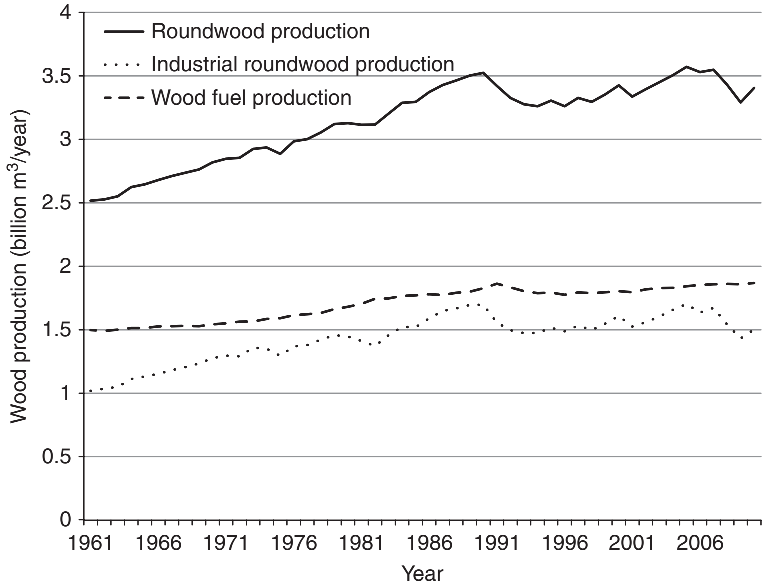

Fig. 4.4. The world production of total roundwood, wood fuel and industrial roundwood. (Compiled from FAO online statistics; FAO, 2012.)

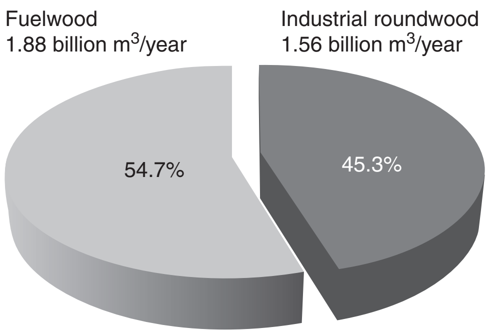

Fig. 4.5. World production of industrial roundwood and fuelwood in 2011. (Compiled from FAO online statistics; FAO, 2012.)

harvest ranging between 1.4 and 1.7 billion m^3/year. However, the proportion of coniferous wood in the harvest has decreased from 74% in 1961 to 61% in 2010 (Fig. 4.7). This trend is driven by an increasing supply of industrial roundwood from tropical areas, much of which is from plantations.

In 2010, plantations occupied 7% of the world's forest area, and between 2000 and 2010 their area increased by about 5 million hectares annually (FRA, 2010). Plantations can be an order of magnitude more productive than natural forest production and their contribution to wood production can be greater than their proportional area. Consequently, they are expected to make a substantial contribution to future wood supply (Carle and Holmgren, 2008).

Wood and Paper Products

As mentioned earlier, industrial roundwood is used to manufacture a diverse range of wood and paper products. This section presents information on the following four product categories (Fig. 4.6): sawnwood, panels and engineered wood products, pulp and paper, and other wood products. The details of the manufacturing processes for these products are addressed briefly. Readers seeking further information on these topics are referred to Shmulsky and Jones (2011).

Sawnwood

Sawnwood is used to manufacture a wide range of final products, including residential and non-residential construction, joinery (e.g. windows, doors, floors, stairs, fences), furniture and packaging. Global trends for sawnwood production are presented in Fig. 4.8. Production has been rather erratic and relatively flat since the early 1970s. It has

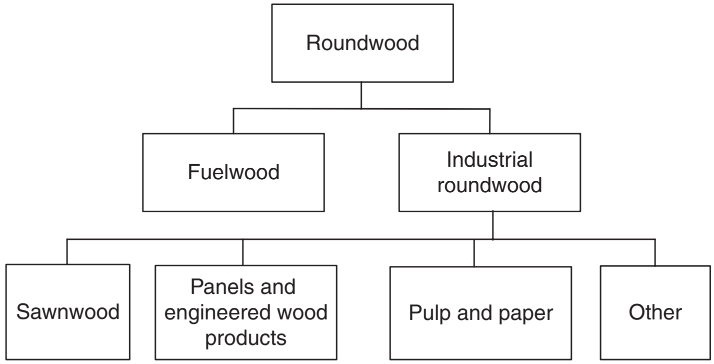

Fig. 4.6. Roundwood and wood product categories.

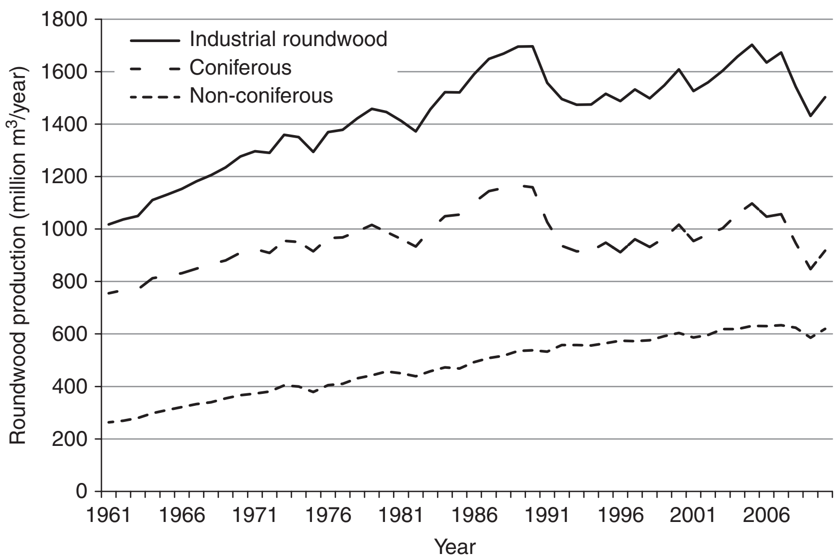

Fig. 4.7. The world production of coniferous and non-coniferous industrial roundwood. (Compiled from FAO online statistics; FAO, 2012.)

been influenced strongly by the state of the economy, which affects construction activity, by environmental regulations, which have decreased harvest volumes in several nations, and by substitution with competitive products, such as engineered wood products, aluminium, concrete and steel. Conifer sawnwood dominates production and it has consistently accounted for 70–75% of total lumber produced over the last 50 years.

Sawmilling is often the first process in the primary value chain and the starting point of a 'value cascade' as the processers attempt to recover the most valuable components from the roundwood first. Sawnwood (or lumber) is therefore a major primary wood product, but, because trees are basically a tapered cylinder and lumber is a rectangular solid, its production is necessarily wasteful. Sawnwood yields from roundwood are typically in the range of 40–60% and may be substantially lower in sawmills that do not have scanning technology and optimizing software. Lumber manufacture receives more than 50% of the global industrial roundwood production and it accounts for 50% more output than all wood-based panels combined. However, global lumber production is relatively static, while the output of wood-based panels is increasing steadily (Fig. 4.9). Sawnwood can behave badly in drying and has variable properties. It is often not

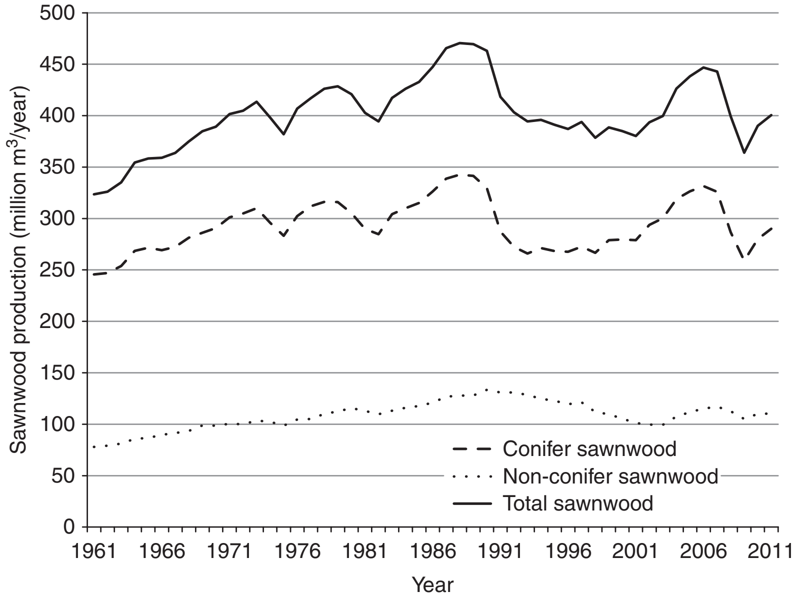

Fig. 4.8. The world production of sawnwood. (Compiled from FAO online statistics; FAO, 2012.)

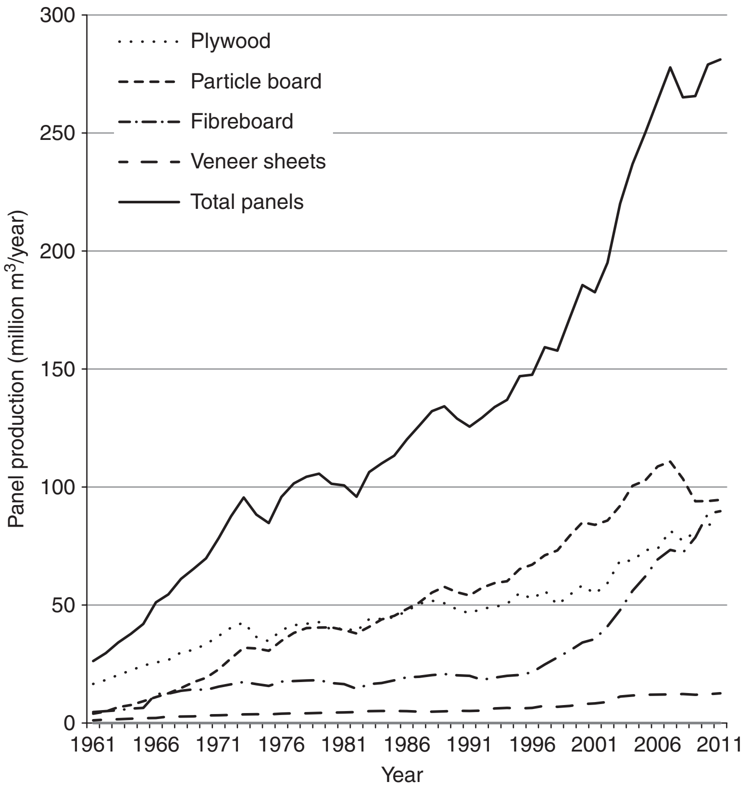

Fig. 4.9. The world production of wood panels. (Compiled from FAO online statistics; FAO, 2012.)

durable, its strength is determined by its weakest part, and pieces are limited in width. These problems can be overcome to some extent by gluing lumber or veneers together (glulam, cross-laminated timber, plywood, laminated veneer lumber) or producing small pieces of wood and then reconstituting them as panels or engineered wood products. These processes (except for plywood and glulam production) also have the advantage that they are adaptable to continuous manufacturing technologies and to capital-intensive large-scale operations where the cost of labour is minimized. Even so, solid wood still holds the predominant position in structural framing and for appearance grade markets. The fine furniture industry is also based on solid wood combined with veneer-faced panels.

Panels and engineered wood products

Panels

Wood panels are used primarily in the construction industry and the furniture sector. The principal structural panels are plywood and oriented strandboard (OSB). Although a form of plywood was used in ancient Egypt, modern plywood production developed in the early 1990s in Oregon (River *et al.*, 1991). Plywood is made by gluing together layers of dry veneer so that each layer has its grain perpendicular to the adjacent veneer. The number of layers is always odd, so that the face and back veneers have the grain running in the same direction. The core, which is the centre section of the sheet, may be laminated solid wood (as in doors), particleboard, medium density fibreboard (MDF) or veneer. Plywood made with a veneer core is the strongest and increasing the number of veneers for the same thickness creates a stronger plywood. The veneers for manufacturing plywood are peeled on a large rotary lathe and they form a tangential longitudinal section with the rays perpendicular to the face. Accordingly, the boards do not have a pronounced figure. A more pronounced figure can be obtained by slicing the veneers, in which case veneers closer to a radial longitudinal section can be obtained. Sliced veneers are expensive to produce and are only used for high-value decorative end uses. Plywood is strong and dimensionally stable. It is used in construction and also for high-value end uses when the face veneer is of high quality. It can be made suitable for outdoor applications by using waterproof adhesives.

OSB, which was developed in the 1970s, is made from strands of wood (typically 15 cm long, 2–5 cm wide and about 0.75 mm thick). The strands are dried, coated in resin and wax and formed into a mat with layers oriented largely at right angles to each other. As with plywood, the alternating directions of the layers give strength to the panels. The mat is then pressed between heated platens to cure the resins. OSB can be cut with saws, but cannot be milled satisfactorily. It is used for structural applications that don't need finishing and in North America it has taken the majority share of the structural panel market for residential housing from plywood.

Particleboard (chipboard) is made from wood chips or strands bound together with an adhesive under heat and pressure. When particleboard is used for furniture manufacture, urea formaldehyde is used as the adhesive. Where more water resistance is required, such as industrial applications or flooring, phenol formaldehyde resin is frequently used. It can be faced with a quality veneer for appearance or with a melamine laminate for a hardwearing surface. Particleboard will not bow or warp like solid wood or plywood, but it can swell when exposed to water. It can be machined, but, because of the size of the particles, there is always a risk of the surface tearing out. Also the uneven surface does not paint very well.

Fibreboards are panels formed from wood fibres that are reconstituted under heat and pressure. They come in a range of densities from low density, such as caneite (160–450 kg/m^3), to masonite (about 1000 kg/m^3), but the most versatile is MDF (around 800 kg/m^3), which is formed by combining conifer fibres with wax (paraffin wax) and resin (urea formaldehyde) and applying high temperature and pressure. MDF was developed in the 1970s and large-scale production commenced in the 1980s. It has replaced particleboard for many applications. It has a smoother surface, a more even and consistent structure and better moisture tolerance than particleboard. Because MDF has no grain as such, it can be machined (cut, drilled, sanded, filed and carved) without damaging the surface, and also can be painted. It does not bow or warp and has a very wide range of uses, including furniture, cabinets, doors, panel mouldings and floors. MDF can also be faced with decorative veneers or melamine. Both particleboard and MDF contain formaldehyde and the possibility of health risks remains a contentious issue.

Global production of wood-based panels has increased nearly 11-fold over the last 50 years, which is more than any other wood product category (Fig. 4.9). In 2011, the production of plywood, particleboard and fibreboard were very similar and each was within the range of 84–94 million m^3/year. Fibreboard was the panel product that had grown most rapidly. This was driven principally by the increased production of MDF, which accounted for about 80% of fibreboard production. The FAO includes OSB within the particleboard category, but it does not report separate OSB data. It is likely that the production of wood-based panels will continue to expand at the expense of sawnwood.

Engineered wood products

Although the FAO does not provide statistics, the global production of engineered wood products has increased substantially over the last 20 years. These products use manufacturing technology to compensate for the inherent shortcomings of sawnwood, such as its anistropy and its variability in strength. They also have a higher product yield per unit of roundwood input than lumber and may be made from lower quality tree species. This consistency in performance and use of cheap roundwood has enabled engineered wood products to compete with lumber, concrete and steel in residential and non-residential markets. In the North American market, they have taken substantial market share from sawnwood.

The variety of products has also increased over the same period. Engineered wood products may be categorized depending on the wood component from which they are fabricated, namely:

- Lumber-based engineered wood products (e.g. glue-laminated timbers (glulam) and cross-laminated timbers (CLT)).
- Veneer-based engineered wood products (e.g. laminated veneer lumber (LVL) and parallel-strand lumber (Paralam)).
- Strand-based engineered wood products (e.g. laminated-strand lumber (LSL) and oriented-strand lumber (OSL)).
- Other engineered wood products (e.g. I-joists and finger-jointed lumber).

Lumber-based engineered wood products

Glulam was the first engineered wood product and examples of its use date back to the mid-1850s. It is produced by face-laminating lumber, typically 20–40 mm thick, into a long and strong structural beam. Straight or curved beams may be produced and they are used primarily as girders, beams, arches or headers. The manufacturing process is usually labour intensive, although more recently automated plants have been developed to produce commodity grades of glulam. Initially, the lumber is stress graded and the stronger material is placed on the outer faces of the beam and the weaker material is located closer to the core, where bending stresses are less. The boards are then finger-jointed to produce long members, planed and glued, assembled and clamped. Usually a cold-curing waterproof adhesive is used to enable the long clamped beams to cure at room temperature. The beams are then planed, drilled and surface finished.

Cross-laminated timber (CLT) was developed commercially in the 1990s and it is gaining favour as an environmentally friendly technique for constructing mid- and high-rise buildings of up to 30 stories. CLT is manufactured in an automated plant that produces panels consisting of 3–7 layers of lumber, with each layer oriented perpendicular to the adjacent layer. The layers are glued together and the panels are generally 75–400 mm thick, 0.6–2.4 m wide and up to 20 m long. These panels are strong, resistant to fire and work well with modern construction techniques. They may be assembled rapidly and enable architects and engineers to build multi-storey structures with open, easily modified interior spaces and large exterior openings that facilitate the use of large windows. Over the last 5 years, CLT production in central Europe has grown at 20–30% annually (UN ECE, 2012).

Veneer-based engineered wood products

Laminated veneer lumber (LVL) is similar to plywood in that it is made by gluing veneers together, except that, in LVL, all layers have the veneer grain oriented in the same lengthwise direction. For this reason, LVL can be manufactured in a continuous, rather than a batch, process and longer pieces can be made. LVL competes with medium to large pieces of structural lumber and has several advantages over solid wood. It has uniform properties, is largely defect-free, is resistant to warping and can be fabricated into large (long, wide and thick) sizes. It is strong when edge loaded as a beam or face loaded as a plank. The manufacturing process is suitable for making large pieces from small trees. Waterproof glues can be used for applications requiring moisture resistance. LVL is a structural material with cutting, fastening and connection requirements similar to solid wood, but without the latter's inherent variability in properties.

Parallel strand lumber (PSL or Parallam) is made by clipping veneers into strands about 20 mm wide, 4 mm thick and up to 1 m long. Usually waste product from veneer, plywood or LVL manufacturing is used as the raw material. The strands are dried, glued, oriented with their length parallel to the product's long axis and then pressed and cured in a continuous process. High frequency (radio or microwave) energy is used to cure the large products (up to 25 cm in depth and width and several metres long) in minutes. The large billets produced may then be cut and sanding into the desired final dimensions. The compression that occurs during pressing increases the density of the final product so that it has higher strength properties than high-quality lumber of equivalent dimensions. Parallam competes with large lumber beams, concrete and steel in structural applications where uniform properties are crucial.

Strand-based engineered wood products

Laminated strand lumber (LSL) is made from strands that are similar to those used to manufacture OSB, rather than the clipped veneers used to make Parallam. Typically, the strands are made from lower quality tree species, such as aspen or poplar. They are 20–50 cm wide and about 300 mm long, which is approximately twice the strand length used in OSB. The green strands are dried, screened to remove fines and blended with resin and wax. The strands are then formed into a mat, with the long axis of the strands partially aligned along the mat, which is then cured in a steam injection press. The hot product is then cooled, cut to the required dimensions and sanded.

Oriented strand lumber is manufactured in a similar manner but uses flakes that are about 50% shorter than LSL. This provides OSB plants that were designed with sufficient flexibility, the possibility of making either OSB or OSL. LSL and OSL compete with various grades of high-quality lumber and LVL in applications such as beams, headers and rim boards. Compared with lumber, they have the advantages of consistent product performance, use of a low-quality feedstock and high product yields.

Other engineered wood products

Two engineered wood products, I-joists and finger-jointed lumber, do not fit into the categories outlined above. I-joists, which were developed in the 1940s, are the wooden equivalent of steel or aluminium I-beams. Their design uses the principle of providing the greatest strength where the stresses are highest and therefore having the strongest elements on the outer edges of a beam and little mass within the web between the outer edges. This approach results in a high strength to mass ratio and good material use efficiency. Modern I-joists often use LVL as the flange material and OSB as the web material and they have taken substantial market share from lumber in flooring and roofing applications. Finger-jointed lumber was developed to produce high-quality timber from off-cuts that were normally wasted during a cut-to-length operation at a sawmill or when defects are cut out from lower grade material. Finger joints seek to maintain the strength of a piece of timber over its full length and they are generally much stronger than the defects removed from the original timber. Finger-jointed lumber may be used in structural applications as studs and trusses or as elements in glue-laminated beams. Examples of appearance-grade products made from finger-jointed lumber include mouldings, balustrades, window components and weatherboards.

Other wood products

There are a wide range of other wood products that are manufactured, including wood composite products, posts and poles, shakes and shingles, log homes and wood pellets. Space limitations prevent a detailed discussion of products other than wood composites, which are one of the faster growing categories.

Wood composites

Wood composites are increasing in importance and they consist mainly of wood with plastic and wood with cement. Composites of wood with thermosetting plastics are a hybrid having some of the advantages of both wood and plastic. The wood fibre filler provides strength along the direction of the fibres and reduces the overall cost compared with plastic alone. The plastic provides lightness, durability and the ability to extrude profiles, inject mould components and heat-weld joints. The major market in wood plastic composites has been in extruded profiles for applications such as decking, railings and window and door components. More recently, injection moulding has been used to produce trim components such as caps, finials and skirts for decks and posts. Wood with plastic and carbon is also promising for external applications requiring lightness and strength. Wood and cement composites are manufactured by mixing cement with either long wood shavings, wood particles or wood fibres. These products have taken market share from asbestos cement composites, which are no longer used in many markets because of health concerns. Cement composites with long wood shavings are used in thermal and acoustic insulation as well as for partitioning in low-cost housing. Cement composites with wood particles or fibres are very water resistant and are suitable for both internal and external cladding and panelling applications.

Pulp and paper

Paper may be made from fibres of animal, vegetable or synthetic origin, but over the last 150 years wood has been the predominant source of fibre used to manufacture paper. In 1980, virgin wood fibre from trees (anatomically tracheids in coniferous species and fibres in non-coniferous species) provided about 75% of the material used to produce paper globally. By 2007, this value had decreased to about 47%. The use of recycled paper as a fibre source grew substantially over the intervening period and by 2007 accounted for just over 48% of the global fibre input for papermaking (Ajani, 2011). The remaining 5% or so of input comes from alternative fibres such as rice straw, wheat straw, rye straw, kenaf, bagasse, bamboo, jute, sisal, esparto and hemp.

Paper manufacturing occurs in two major stages. First, the pulping process converts wood into wood pulp and then paper is manufactured from this pulp. In the paper-making process, pulp fibres are suspended in water, formed into an intermeshing mat that is pressed and dried into a sheet of paper. Each manufacturing stage is described in the following sections.

Pulp manufacturing

The virgin wood fibre used to manufacture pulp may arise from roundwood or from wood-processing residues, such as wood chips from sawmills or plywood plants. Most pulping technologies require the fibre input to be in the form of wood chips, so roundwood must first be debarked and chipped before pulping. Two wood-pulping technologies, chemical and mechanical pulping, have historically been dominant and, in 2011, these two technologies accounted for over 93% of the global wood-pulp production (Fig. 4.10). Semi-chemical and dissolving grade pulps account for the remaining 7% of production.

Wood consists of cellulose, hemicellulose, lignin and extractives, with the proportions varying with the species. Typically, the organic component of wood consists of about 40–45% cellulose, 15–35% hemicellulose, 18–35% lignin and 1–5% extractives (Kollmann and Cote, 1968). Lignin imparts strength in standing trees and extractives contribute to durability and colour. However, both lignin and extractives are undesirable elements in paper and, ideally, pulping processes should remove these compounds or reduce their influence on pulp properties. The best raw material for paper making will have high holocellulose (cellulose + hemicellulose), low lignin, and fibres with relatively thin walls and a high length to diameter ratio. Longer fibres generally result in stronger papers and thin-walled fibres are easier to flatten to provide a smooth paper surface. Coniferous species have relatively long fibres (about 3–4 mm) and non-coniferous species relatively short fibres (about 1.2 mm) (Bhojvaid and Rai, 2004). The greater fibre length of coniferous species has meant that they been favoured traditionally for pulp production. However, recent advances in pulping technologies have enabled high-performing non-coniferous pulps to be developed and they have taken an increasing proportion of the market. Important coniferous species include pine, spruce, fir and larch, and important non-coniferous species include eucalypts, aspen, oak and maple (Doshi and Dyer, 2004). Plantation-grown trees are also becoming increasingly important as a fibre source, and non-coniferous species, especially eucalypts from South America, are becoming more prominent in the mix (AbuBakr, 2004). For example, in 1961, coniferous species accounted for 82% of the global pulpwood consumption and by 2011 this value had decreased to 50% (FAO, 2012).

Chemical pulping

Chemical pulping technologies, which were developed in the 1870s, effectively cook wood chips in

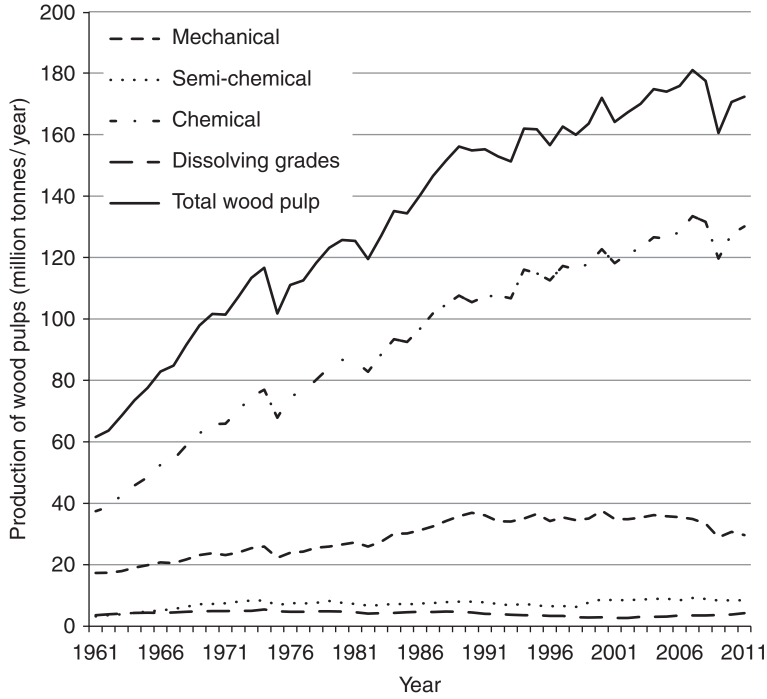

Fig. 4.10. The world production of wood pulps by type. (Compiled from FAO online statistics; FAO, 2012.)

chemicals at elevated temperatures. The chemicals and heat remove the lignin and much of the hemicellulose to liberate the cellulosic fibres. Chemical pulps therefore have a substantially different chemical composition to the incoming wood and low pulp yields (40–50% w/w) because much of the original wood material is dissolved in the pulping liquor. The major chemical pulping processes are the alkaline sulfate (or kraft) and the acid sulfite technologies, with the kraft process accounting for about 97% of chemical pulp production in 2011. The intention of these processes is to solubilize most of the lignin, extractives and much of the hemicelluloses in the pulping liquor, thereby leaving a relatively pure cellulosic pulp (Aravamuthan, 2004). Chemical pulps have the attributes of being strong (because of the long, unbroken fibres) and easily bleached to provide a white paper (because of the low amount of lignin in the pulp). They have the disadvantages of providing a lower opacity paper and a poorer printing surface than mechanical pulps. Chemical pulp is by far the most widely used pulp and its production has grown more than threefold over the last 50 years (Fig. 4.10).

Mechanical pulping

Mechanical pulping, which was developed in the 1850s, relies on mechanical abrasion to reduce wood chips into a fibrous material. Heat or low levels of chemicals are frequently used to pretreat the wood chips in order to increase the effectiveness of the abrasion. The different mechanical pulping processes are named to reflect the pretreatment processes and the form of size reduction used. Thermomechanical pulping (TMP), chemi-mechanical (CMP), chemi-thermomechanical pulping (CTMP) and stone groundwood pulping are important mechanical pulping technologies. The TMP, CMP and CTMP processes use disk refiners to reduce wood chips into pulp, usually following pretreatment of chips with steam and/or chemicals. The older stone groundwood process produces pulp by grinding small logs against a wet grindstone. Because of the gentler thermal and chemical pretreatment processes, mechanical pulping dissolves less wood material than chemical pulping. It therefore has higher pulp yields of 80–95% w/w, depending on the type of process used. Because of the mechanical abrasion that occurs in the refiners, mechanical pulps have shorter fibres and more small fibre fragments (or fines) than chemical pulps. This causes the pulps to be weaker, but they do provide a paper with good opacity, because the fines increase the light scattering. This opacity reduces light transmission through the paper and enables both sides of a page to be printed. The fines also give a smooth printing surface. The pulp also has the disadvantage of darkening with time and exposure to sunlight because the lignin remains within the pulp. The global production of mechanical pulps has stagnated over the last 30 years. In 2011 its production was 23% of that for chemical pulp, while in 1961 it was 60%.

Paper manufacturing

There are numerous grades of paper, which the FAO aggregates into four major categories based on use. These categories are: graphic papers, which incorporate all printing and writing papers including newsprint; packaging papers and boards, which include all papers used for packaging and wrapping purposes and incorporates corrugating medium and cartonboard; sanitary and hygiene papers, which include tissues, paper towels, incontinence and diaper products; and finally all other paper products (FAO, 2010). Since the mid-1960s, packaging grades have been the predominant category, followed by graphic papers (Fig. 4.11). The increasing demand for packaging grades has been driven by globalization, with high-quality packaging being required to protect valuable traded goods. In contrast, the demand for graphic papers has been affected by the development of the internet as a medium for electronic communication and the increased use of electronic storage devices has reduced demand for paper as an archival material (Hylander, 2009). Sanitary and household papers are produced in lesser quantities but are growing steadily as the standard of living increases in many developing countries.

The amount of wood pulp produced has increased about 2.8-fold over the last 50 years to reach 172 million tonnes/year in 2011 (Fig. 4.10). In contrast, global paper production has grown just over sevenfold over the same period to reach just over

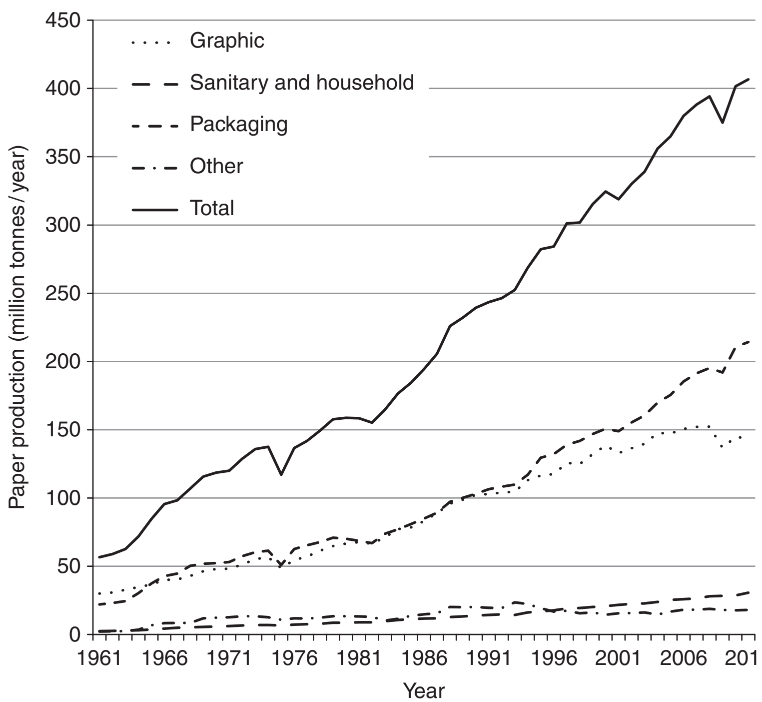

Fig. 4.11. The world production of papers by grade. (Compiled from FAO online statistics; FAO, 2012.)

400 million tonnes/year in 2011 (Fig. 4.11). The difference between these two values is largely filled by recycled paper, which in 2011 accounted for 210 million tonnes of the fibre input for paper making. Non-wood fibres, such as hemp, flax, kenaf and agricultural residues, were much less significant, with their total input for paper making in 2011 being 18 million tonnes (FAO, 2012).

Historically, paper and paperboard consumption has been related closely to per capita incomes. The USA has consistently had the highest consumption of 300–350 kg/capita, compared with a global average of about 50 kg/capita. However, in developed nations, consumption of many paper grades has stagnated over the last decade and some grades, such as newsprint in North America, have declined, as electronic news media has replaced paper media. The growth in global consumption has been driven by the increasing standard of living in many developing countries, especially in Asia. Consequently, there has been an increase in the production of paper in Asia, close to the growing markets, and a reduction of capacity in North America and Europe (Hylander, 2009).

Pulp and paper manufacturing is a very large and capital-intensive industry whose profitability depends on access to cheap wood fibre. In the northern hemisphere, the pulp and paper industry has traditionally used chips and sawdust from sawmills and plywood mills as the major source of raw material. The use of these mill residues has enabled the pulp mills to share the costs of growing and transporting the fibres with the sawmilling and panel sectors, while creating an efficient use for these by-products. However, over the last 30 years, new pulp mills in the southern hemisphere have been able to economically use purpose-grown roundwood from short-rotation plantations of softwood and, especially, hardwood species as a fibre source.

The pulp and paper industry, by the very nature of the technologies involved, has historically been one of the most polluting of all industries. Over the last 30 years, it has made considerable investment to minimize its discharges to air and water, and its environmental record has improved substantially. The industry, perhaps because of its size, has also been singled out as a driver of deforestation. There have been calls for using alternative fibre materials such as hemp. There is no doubt that the pulp and paper industry (and other wood-based industries) has, to a greater or lesser extent, been responsible for poor and non-sustainable forest practices in the past and present. The solution, however, is not to dampen demand for wood fibres but, as will be discussed in the next section, rather to sustainably manage existing forests and to increase the use of some forms of wood and fibre. The trend towards more pulp wood coming from plantations is a step in the right direction. Ultimately the package of sustainable management of forests, the establishment of plantations and the efficient use and recycling of paper is preferable to promoting any alternative source of fibre.

The kraft pulping process also produces a range of chemicals as a by-product. Terpenes, the major constituents of turpentine, and resin acids, the main components of rosin, are both generated by chemical pulp mills. Fatty acids are also recovered and these have applications in ore separation, metal working, detergents, drying agents and finishes. Rayon is a manufactured fibre made from specially treated wood pulp. It is used as a fabric for clothes and soft furnishings, in sanitary hygiene fabrics and as a strengthening agent in tyres. More recently, there has been interest in using lignin as a replacement for a variety of products derived from fossil fuels. Examples include automotive brakes, biodispersants, polyurethane foams and epoxy resins (Lora and Glasser, 2002).

Wood is Good

The global economy consumes large quantities of materials to meet the needs and wants of society. There are a much more diverse range of material and product choices confronting the modern citizen compared with the member of a Palaeolithic society and the production, use and disposal of these products have a much greater impact on the planet than in earlier times. As consumers seek to minimize their ecological footprint, a product's environmental impact has become an increasingly important factor in purchasing decisions and companies use the environmental attributes of their product as a selling point. For example, organizations that manufacture materials that compete with wood and wood-fibre based products have used the image of deforestation and forest degradation in an attempt to discredit the use of wood and to promote their own products. The US steel industry used a concerted advertising campaign with the slogan 'build your house with six used cars and not one acre of trees'. The American Plastics Council used the slogan 'save a tree – use PVC'. This advertising creates a false impression because a very good case can be presented to show, providing forests are managed sustainably, that wood and wood fibre products are often more environmentally friendly than many competitors. In fact, wood from sustainably managed forests is the only truly renewable construction material. In addition, forests and wood products in use provide substantial pools of carbon and the increased use of long-lived wood products is beneficial from a greenhouse gas perspective (Skog, 2008). Building with wood also uses less embodied energy than alternative products, such as concrete or steel.

Many of these positive environmental attributes of wood arise because it is produced by the process of photosynthesis. The chemical reaction of photosynthesis can be stated simply as:

$$\text{carbon dioxide} + \text{water} + \text{solar energy} \rightarrow \text{carbohydrate} + \text{oxygen} \quad (4.1)$$

The chemical reaction for respiration, decomposition and combustion of carbohydrate is the reverse of photosynthesis and both energy and carbon dioxide are liberated.

$$\text{carbohydrate} + \text{oxygen} \rightarrow \text{carbon dioxide} + \text{water} + \text{energy} \quad (4.2)$$

Since the industrial revolution, the concentration of carbon dioxide (CO_2) in the atmosphere has increased to the extent that it is considered to be causing global climate change, the consequences of which are thought to be so serious that extensive international negotiations have attempted to limit CO_2 emissions. Global climate change will be discussed in greater detail in Chapter 8. The increase in the atmospheric CO_2 concentration comes mostly from the combustion of fossil fuels such as coal (carbon) or oil/gas (hydrocarbons), but also from the decomposition or burning of vegetation (carbohydrates) produced by photosynthesis (equation 4.2). Fossil fuels are non-renewable resources (at least over the timescales being considered here) and they are being consumed at a rate greater than their natural replenishment. Concern over the effects of ongoing fossil fuel use and the consequence of climate change have resulted in forests, bioenergy and wood products being investigated as means of mitigating climate change.

Photosynthesis uses solar energy to sequester CO_2 and this plays a crucial role in wood being a solar energy store and a useful carbon sink. Wood is a carbon-intensive product that contains about 50% carbon on an oven dry weight basis (IPCC, 2006) and the combustion and decomposition of biomass can be CO_2 neutral or better, provided that two conditions are met. First, sufficient vegetation is maintained or re-established within the forest so that the products of equation 4.1 equal or exceed those of equation 4.2. Secondly, the carbon balance at a landscape level must be maintained or increased and this requires that below-ground or soil carbon is not depleted. Below-ground carbon is most at risk of depletion when land use change occurs, such as converting forest to pasture (Fargione *et al.*, 2008). These two conditions are effectively met when a forest is managed sustainably. This perspective is recognized internationally and the Intergovernmental Panel on Climate Change (IPCC) has stated 'In the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fiber, or energy from the forest, will generate the largest sustained mitigation benefit' (Nabuurs *et al.*, 2007).

As noted by the IPCC, wood products and bioenergy arising from sustainably managed forests can help mitigate climate change. The use of biomass from sustainably managed forests as a fuel, and this includes fuelwood, is an environmentally preferable option to the use of fossil fuels. The wood and paper products used by society accumulate in pools of various sizes and durations. Half-lives are used to evaluate how long a material stays in each pool and a half-life is defined as the time that 50% of the initial amount will remain in the pool following a first-order decay reaction. Wood products in timber-framed houses have been estimated to have a half-life in the range of 30–80 years, whereas paper products are thought to have a half-life of about 2 years (IPCC, 2006; Skog, 2008; Lippke *et al.*, 2011). Wood products in use can provide an additional and important carbon sink to that within the forest and recent studies argue strongly that these pools should be quantified and maximized. To illustrate this point, Lippke *et al.* (2011) modelled the growth of a forest stand in the US Pacific Northwest and the fate of wood products arising from this stand over several rotations. The above-ground carbon in the stand increased throughout the rotation and decreased at harvest, but, in a sustainably managed single stand, the above-ground carbon had a constant average value of 160 tonnes C/ha over the long term

(Fig. 4.12). At harvest, roundwood was removed from the stand to manufacture products and produce biofuel and the pool of products continued to accumulate with time, reaching the equivalent of 50 tonnes C/ha forest after 100 years (Fig. 4.11). Wood product pools can therefore represent a substantial carbon sink.

Wood products can have a positive net impact on carbon sequestration in one other way. If their life-cycle greenhouse gas impacts are less than those of a competitive product used by society, an indirect substitution effect occurs (Lippke *et al.*, 2011). For example, either concrete or wooden flooring systems may be used in single family homes and they are therefore competitive products. If the greenhouse gas emissions for growing, harvesting, manufacturing, transporting and constructing, demolishing and recycling or disposing of the wooden flooring system were less than those of the concrete floor, use of the wooden flooring system would provide a net greenhouse gas benefit when it was substituted for the concrete floor. Because such substitution effects only arise by comparison with a competitive product, they are termed 'indirect' effects and are not counted in greenhouse gas accounting frameworks. However, these indirect effects are considered here to demonstrate the positive greenhouse gas impacts of using wood products in place of some alternative materials.

These substitution effects occur because wood has a high embodied carbon content and a low embodied energy, because solar energy, at no cost, is the major energy input. Additional energy sources are required only for its transportation and conversion. In contrast, many other building materials require significant energy inputs during manufacturing and much of this energy comes from non-renewable fossil fuels. Several studies have compared the energy per unit of dry weight required to extract, manufacture and deliver a range of building materials and the results are summarized in Fig. 4.13. Aluminium uses large amounts of electrical energy, while wood requires the least energy. Wood is even more attractive from an energy perspective than shown in Fig. 4.13 because globally about 61% of the energy requirement for solid wood products comes from burning the wood residues arising during wood conversion and only 39% needs to be provided from external sources (Miner, 2010). For example, life-cycle inventory data revealed that using an engineering wooden I-joist for flooring instead of a steel I-beam resulted in reducing the greenhouse gas emissions by 10 tonnes of CO_2 equivalents (CO_2e) for each tonne of wood product used (Lippke *et al.*, 2011). Also the weight of concrete, bricks and steel used in construction is considerably greater than that of wood for the same purpose. One study compared the energy required to construct a wood-framed house with that required to construct a steel-framed house in Minneapolis and a concrete house in Atlanta (Lippke *et al.*, 2004). This study found that most of the energy associated with construction was used in the extraction and manufacture of the materials and that the steel house used 17% more energy and the concrete house 16% more energy than the wooden houses. Buchanan and Levine (1999) showed that a 17% increase in wood usage in the New Zealand building industry could reduce CO_2 emissions from the manufacture of all building materials by 20%.

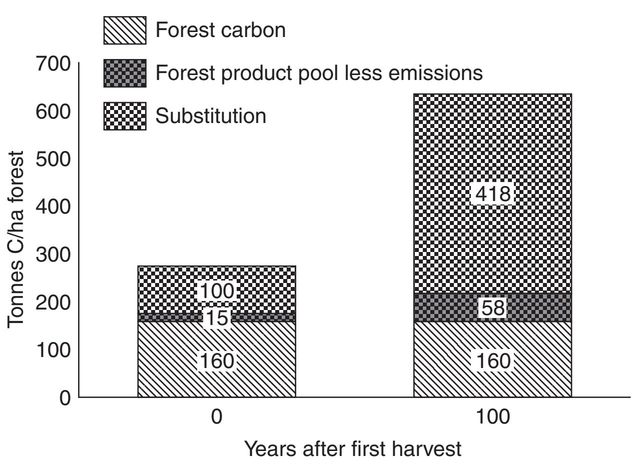

Fig. 4.12. Carbon pools associated with a United States Pacific Northwest forest stand operating on a 45-year rotation. (Compiled from data presented by Lippke *et al.*, 2011.)

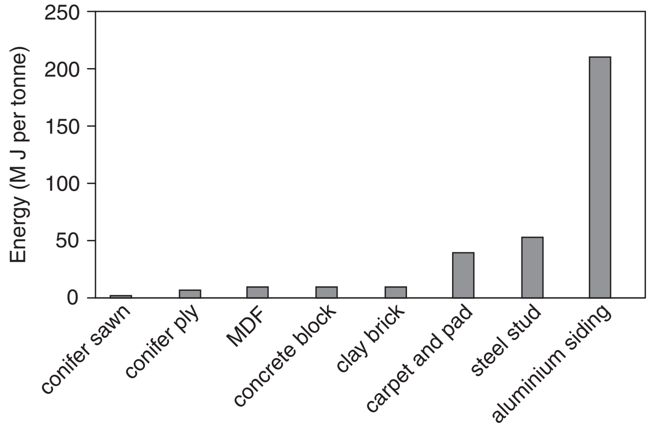

Fig. 4.13. The net energy requirements for extraction, manufacture and transport of various building materials to a residential building site in USA. (Compiled from data given by Koch, 1992.)

Lippke *et al.*'s (2011) study of forest and product carbon pools also showed the magnitude of the substitution effects. Three product pools were considered in the study; the above-ground forest carbon pool contained in a sustainably managed stand, the pool of wood and paper products in use less the emissions associated with their transportation and manufacturing and the pool arising from avoided emissions created by substituting wood products for construction materials with higher CO_2 emissions (Fig. 4.12). The model assumed that carbon entered the product pool in the year that the forest was harvested. Once the stand has reached a steady state under its defined sustainably managed regime, the forest carbon pool was effectively constant in the long term. Over the same time period, the forest products and substitution pools accumulated carbon as the stock built up over time as a result of the ongoing input of roundwood from the stand. The pool associated with wood product substitution builds up more rapidly that the other pools and clearly demonstrates the greenhouse gas benefits of using wood in construction, where feasible. The substitution benefits will vary on a case-by-case basis, depending on the material choices. Lippke *et al.*'s (2011) model is based on the average substitution profile developed by a large meta-analysis of the greenhouse gas implications of using wood products in place of other materials (Sathre and O'Connor, 2010). At the global level, it has been estimated that the substitution effects from using wood-based construction products are equivalent to 483 million tonnes of CO_2e of avoided emissions annually (Miner, 2010).

The emission and sequestration of greenhouse gases by the global forest products value chain has also been evaluated (Miner, 2010). Data were evaluated for five phases of the full life cycle of a forest product: roundwood production, manufacturing, transportation (which included transportation from the forest to the mill and from the mill to the market), product use and end-of-life. Separate estimates of global pools of pulp and paper and wood products were made for the manufacturing, product use and end-of-life stages and these data are represented by the vertically and horizontally lined bars presented in Fig. 4.14. The net value chain emissions were 467 million tonnes CO_2e/year. The greatest emissions of 583 million tonnes CO_2e/year arose in the manufacturing stage, with the pulp and paper sector accounting for about 80% of these releases. Roundwood production and transportation together discharged about 69 million tonnes CO_2e/year, which was about the same size as end-of-life emissions. The wood and paper product carbon pools were estimated to amount to 263 million tonnes CO_2e/year. Wood products accounted for more than 90% of this value because they have a much longer half-life than paper products (IPCC, 2006; Skog, 2008). End-of-life emissions arose from burning wood or paper products and their decay or sequestration in landfills. Pulp and paper products had a greater proportion of end-of-life emissions, largely because of their more rapid decay in landfills than wood products (IPCC, 2006). Although the end-of-life phase had emissions equivalent to 77 million tonnes CO_2e/year, the production of methane from paper and wood decaying in landfills was estimated to produce 235 million

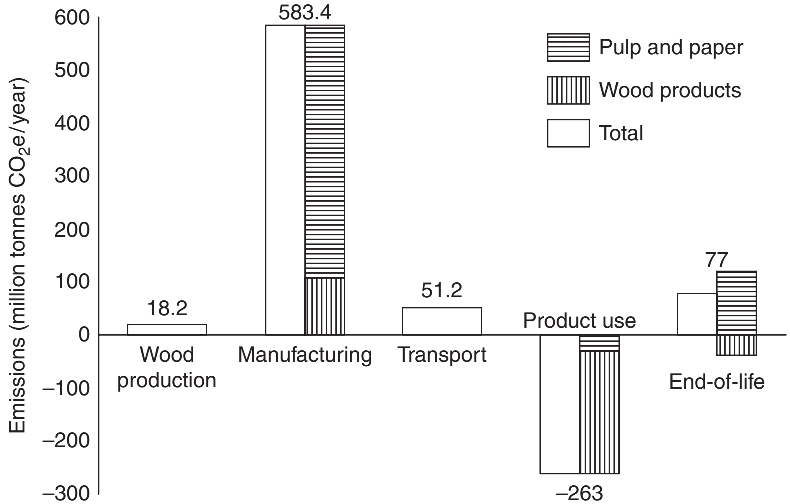

Fig. 4.14. Estimated emissions and sequestration in the global forest products value chain in 2007. (Compiled from data presented by Miner, 2010.)

tonnes CO_2e/year, which is significantly greater than the emissions from roundwood production and transportation. Much of this amount arises from the high global-warming potential of the methane produced by the anaerobic decay of paper and wood in landfills, with paper accounting for 75% of the emissions because of its more rapid degradation. The capture and use of this landfill gas for energy production represents a useful way of decreasing the forest sector's global emissions. The total end-of-life emissions are less than the methane emission value because of the sequestration effects of the increased mass of wood and paper products being landfilled, which were collectively estimated to be 158 million tonnes CO_2e/year (Miner, 2010).

Miner's (2010) analysis has disregarded the indirect effects of using wood products in construction instead of non-wood products such as steel and concrete, of recycling and reusing of paper products, and combusting wood and paper products instead of fossil fuels. While acknowledging large uncertainty in the estimates, he considered that in aggregate these avoided emissions would amount to about 900 million tonnes CO_2e/year, inferring that the forest sector value chain had a net sequestration benefit of about 430 million tonnes CO_2e/year. The majority of this net sequestration may be attributed to the wood products sector and this provides further evidence of the environmental benefits of using wood products from sustainably managed forests for construction, in place of products that require substantial fossil fuel inputs.

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5 Bioenergy, Innovative Biomaterials, Non-Wood Forest Products

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Introduction

This chapter describes the important goods and services that forests provide in terms of energy, innovative biomaterials and non-wood products. It is a complement to Chapter 4, which outlined the major lumber, panels, engineered wood products, pulp and paper products manufactured to meet society's requirements for these goods. The production of energy and non-wood products from forests are very important, especially for developing countries. Globally, more wood is used to produce energy than to create any other forest product, while non-wood forest products, including food, medicines and hides, have sustained communities for many centuries. Innovative biomaterials and liquid biofuels from forests are more recent developments, as modern society investigates how goods manufactured from fossil fuels may be replaced with those derived from sustainable sources. Many biomaterials are still in the research and development stages and they represent a very different level of product maturity to traditional energy and non-wood products. This chapter will initially discuss the use of forests to provide energy for both traditional fuel uses and for modern biofuels. The diverse range of non-wood forest products arising from forests will then be outlined before highlighting the production of forest biomaterials.

Wood for Energy

Wood has been a major source of energy throughout the history of human society and, globally, energy continues to be the major item produced from wood, accounting for 54.7% of the roundwood harvest in 2011 (see Fig. 4.5 in Chapter 4).

The regular use of fire and tools by hunter-gatherers increased the energy flow available to the human race. Before the discovery of fire, humans or pre-humans, like all other animals, obtained their energy via their own metabolism (somatic energy). The somatic energy of humans can be quantified as a Human Energy Equivalent (HEE), which is about 10 megajoules (MJ) per person per day (Newcombe, 1976). The energy use of the average hunter-gatherer probably doubled as a result of the use of fire. In early agricultural societies, it increased further to about 5 HEE as a result of fire, the use of wood as fuel, and the somatic energy of domestic animals. Since the industrial revolution and the associated use of fossil fuels, energy consumption has risen dramatically. Energy consumption in England, Germany and the USA in the late 1800s rose to about 35 HEE, with most of this increase attributed to fossil fuel consumption (Cook, 1971). In 2009, the global HEE was approximately 25 and for the USA it was about 105 (EIA, 2012; US Census Bureau, 2012). The human population has increased from about 5 million at the beginning of the age of agriculture to about 6.8 billion in 2009. Consequently, the total energy consumption of modern humans is about 6800 times that during the early stages of agriculture.

Almost all the energy used from the time of the hunter-gatherers until the present day has been solar in origin, arising from the combustion of fossil fuels or biomass produced by photosynthesis. Oil and coal reserves originate from biological organisms laid down in the Carboniferous, Permian, Jurassic and Cretaceous periods. Oil and gas are derived mainly from marine organisms, but coal is predominantly from forests, particularly swamp forests. Contemporary humans have developed a lifestyle that depends on the utilization of these energy reserves. Due to the enormous time gap between the development and the utilization of such reserves, it is all too easy to forget that coal is a product of photosynthesis and a gift of the forest.

The ability to produce energy from biomass is a strategically important means of mitigating climate change because biomass can be a carbon dioxide neutral renewable resource if it is produced in a sustainable manner (Chapter 4). Despite the steam engine being invented in 1698, biomass remained the most important source of energy globally until the late 1800s. The early modern cities of Venice, in the 17th century, and Paris, in the 18th century, relied largely on the same types of biomass fuels that supported the first urban civilizations in Mesopotamia several thousand years earlier (Smil, 2006). However, the increasing use of fossil fuels in the 19th and 20th centuries resulted in wood's share of the global energy supply declining from about 80% in 1860 to approximately 12% in 2000 (Victor and Victor, 2002). In 2008, the global energy supply from biomass was estimated be approximately 50 exajoules (EJ), equivalent to about 10% of the world's annual primary energy consumption of about 450 EJ (Dornburg *et al.*, 2008; FAO, 2008; World Energy Council, 2010). This value was greater than those for hydropower and nuclear power, which both contributed approximately 26 EJ. About 80% of the biomass energy was used for traditional purposes of cooking and heating in developing countries. The remaining 20% of biomass energy was used to provide industrial energy, electricity or transport fuels in developed countries (Dornburg *et al.*, 2008). The use of wood for energy in the USA followed an even more profound decline, with its contribution to primary energy supply decreasing from 99% in 1800 to 0.2% in 2000 (Victor and Victor, 2002). A comprehensive literature review assessed that bioenergy has the potential to provide between 200 and 500 EJ/year in 2050 when the global primary energy demand was estimated to be within the range of 600 to 1000 EJ/year (Dornburg *et al.*, 2008). Biomass therefore has the prospect of greatly increasing its contribution to the global energy supply, but major technological advances will be required to achieve this potential.

Throughout history, the major use of wood has been to provide energy and this remains the case today. Although more than 50% of the volume of roundwood removed from the world's forests annually is used as fuelwood or charcoal, there is negligible international trade in fuelwood. This is because most fuelwood is harvested in the less developed regions of the world and consumed close to the point of removal from the forest. In 2011, fuelwood removals accounted for 88% of the total harvest in Africa, 77% in Asia and 50% in South America. In the more developed regions, fuelwood removals represented less that 25% of the roundwood harvest (Fig. 5.1). In developing countries, wood and charcoal comprise between 30 and 80% of total energy consumption. Sub-Saharan Africa is particularly dependent on fuelwood. For example, in Ethiopia, more than 90% of the inhabitants depend on fuelwood for their domestic energy needs, with demand outstripping supply to the extent that 15% of the total energy requirement comes from burning agricultural residues and animal dung (Eschete, 1999).

The data in Fig. 5.1 substantially underestimate the quantities of wood used for fuel in the developed world because they do not account for the large amount of wood waste used as fuel in wood and fibre processing plants. The average proportion of the raw wood arriving at wood and fibre processing plants that is used as fuel is shown in Table 5.1. Previously, much of these wastes were either landfilled or burnt solely as a disposal mechanism and energy was not recovered. More recently, they have been considered a useful source of energy and major investments have been made to use these manufacturing by-products. Wood and fibre wastes from the manufacturing sector equivalent to 23% of the total roundwood harvest were used for energy production in the European Union (EU; Hakkila and Parikka, 2002) and in 2005 the equivalent value in the USA was 11–12% (Bowyer *et al.*, 2012). If waste from industrial operations amounted to 15% of the roundwood input and all of this was available for energy conversion, the total fuelwood for energy in Fig. 5.1 would rise to 61% of global wood production, and industrial wood products would be reduced to 39%. For example, kraft pulping, which is the dominant chemical pulping method, converts about 45% of the incoming wood mass into pulp. The other 55% of the incoming wood is dissolved in the chemical pulping solvent. This carbonaceous residue, known as black liquor, is concentrated and burnt to generate enough process steam and electricity for a modern kraft pulp mill to be a net energy producer. In 1992 in the

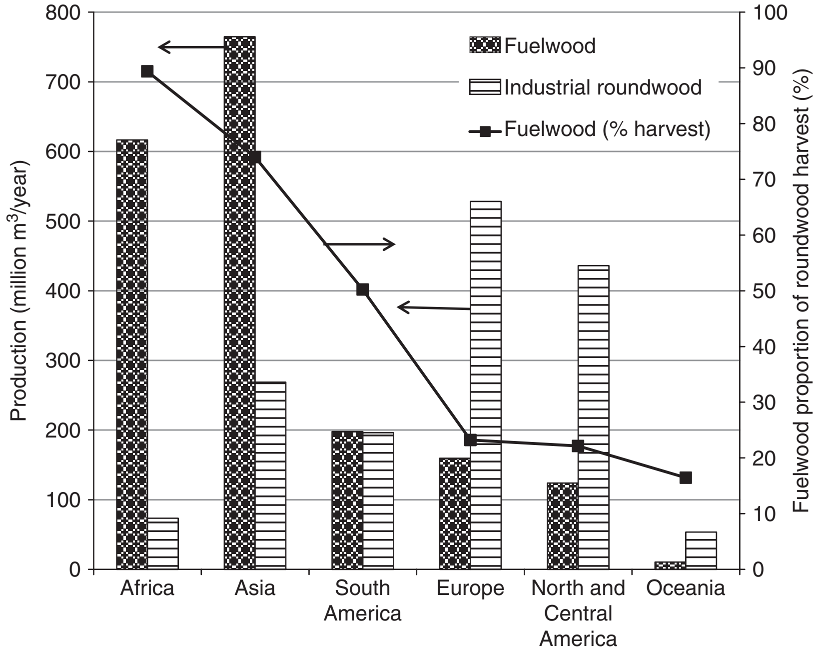

Fig. 5.1. Production of fuelwood and industrial roundwood in various regions in 2011. (Compiled from FAO online statistics; FAO, 2012.)

Table 5.1. The average percentage of the wood arriving at wood processing plants that is used as fuel (reprinted from Hakkila and Parikka, 2002, ©2002, with kind permission of Springer Science and Business Media).

Product	Fuel component of raw material	Fuel % by volume
Chemical pulp	Bark, screening residues from chips, black liquor	50–60
Mechanical pulp	Bark, screening residues from chips	10–20
Lumber	Bark, sawdust, slabs, cull logs, etc.	15–60
Plywood	Bark, log ends, waste plies, dust, screening residues, cull logs, etc.	40–75

USA, 26.5% of the energy obtained from wood came from black liquor (Zerbe, 2004).

Woody biomass can be used as a solid fuel or converted to liquid and gaseous fuels. Each of these fuel types and processes will be discussed below. Wood can be burned directly, densified to form pellets or briquettes and carbonized to form charcoal. It can be converted to a combustible gas by gasification and this gas may be subsequently converted to liquid fuels using chemical catalytic processes or microorganisms. Liquid fuels may also be produced by pre-treating wood and fermenting the resultant sugars to alcohols or a variety of organic chemicals. In addition, wood may be pyrolysed to form a combination of oils, combustible gas and charcoal. This gas may then be further processed to produce biodiesel or ethanol.

Wood as a solid fuel

Wood is used in three principal forms as a solid fuel: fuelwood, charcoal and wood pellets. Each use is described in the following sections.

Fuelwood

The use of wood as a solid fuel has both advantages and disadvantages. Properly managed, it is a sustainable and environmentally friendly source of energy. It is a 'grow your own' energy source at individual, community and national levels, which provides a major advantage compared with fossil fuels. Fossil fuels are unevenly distributed around the world and security of access to fossil fuels is a concern for many countries without their own resources. Indeed, the uneven distribution of fossil fuels has been a politically charged issue capable of bringing down governments and provoking war.

Virtually all cultures have an affinity to a wood fire, particularly an open fire, irrespective of its low efficiency. Also, in many rural areas, fuelwood can be collected at no cost (but with considerable labour). However, wood is an awkward commodity to store and transport; it produces smoke and particulates that may be harmful to health; and the amount of heat given off when it is burnt (net energy value) is low compared with fossil fuels (Table 5.2). The energy value of wood does not vary greatly between species on a weight basis, but wood varies in basic density and consequently the more dense woods provide more heat per unit of volume. The effective energy value of wood is very dependent on moisture content and wet wood is not an efficient fuel (Table 5.2). Lignin, resin, terpenes and waxes have higher energy values than cellulose and hemicelluloses and so conifers, in general, have higher energy values per unit of weight than non-coniferous species, branches have higher energy values than stem wood, and bark and leaves have higher energy values than wood (Hakkila and Parikka, 2002). Conifers, however, are often less dense than non-coniferous species.

Fuelwood meets a wide range of energy requirements in much of the developing world. More than 2.3 billion people depend on fuelwood and other forms of biomass to meet their daily domestic energy requirements and fuelwood is arguably the

Table 5.2. Net energy value of wood and other combustible fuels (MJ/kg) (averages from various sources).

Charcoal	29.5
Wood (oven dry)	19.0
Wood (air dry)	16.5
Wood (wet)	9.5
Anthracite coal	35.5
Bituminous coal	25.0
Air dry dung	17.0
Lignite coal	12.5
Peat (air dry)	10.5
Butane	49.0
Liquid petroleum gas	47.0
Kerosene	46.5

most important forest product for local people leading a subsistence existence (Cooke *et al.*, 2008). Wood is also used in industrial and commercial operations, including the generation of electricity. However, the contribution of fuelwood and charcoal to a nation's primary energy mix decreases as the GDP/capita increases (Victor and Victor, 2002). This mimics the transition from biomass to more convenient fuels that has occurred in the developed countries.

Eckholm (1975) published a leaflet called 'The other energy crisis: firewood'. This and other studies predicted dire shortages of fuelwood in the developing world, to the extent that massive deforestation and starvation were considered to be inevitable. This prompted a flurry of activity in the 1980s that culminated in 1985 in the development of an international donor-funded initiative, the Tropical Forest Action Plan (TFAP). The objectives of this plan were to decrease wood demand by using improved stoves or alternative fuels, to produce more fuelwood from existing forests and to establish plantations specifically for fuelwood. There was considerable investment in this plan but, with the benefit of hindsight, it appears that the crisis was exaggerated (Arnold *et al.*, 2003). There does not appear to be any fuelwood shortages at the national level. Fuelwood prices have failed to rise and farmers are generally not interested in planting trees to produce a low-value product. Plantations have been unable to meet their establishment costs if the wood was used as a fuel in the farmers' homes and, in order to cover these costs, the wood had to be used for an alternative higher value purpose. The irony of this is that fuelwood plantations were established on land that had previously supplied fuelwood and no longer could do so (Saxena, 1997). Consequently, many of the fuelwood planting projects promoted in the 1980s failed. Those that succeeded as fuelwood plantations often supplied fuelwood to industry rather than to the domestic market.

The predicted broad-scale deforestation from fuelwood-gathering did not materialize either. There has been and continues to be substantial deforestation in the developing world, but this is caused mainly by clearing for agriculture and generally not from gathering fuelwood (see Chapter 6). Gathering of fuelwood, however, may cause deforestation in some specific areas of high population density where the forests are communal and unregulated, in semi-arid areas and in highland areas near tree lines (see Chapter 6). Also, the rapid rise in charcoal production to service urban markets has the potential to cause deforestation because charcoal kilns need to be located close to the source of wood. A West African study concluded that charcoal production was the main reason for forest loss in those areas where charcoal production was concentrated (Ninnin, 1994). Trees outside of the forest can provide a significant proportion of fuelwood supplies. Fuelwood may come from isolated trees outside the forests, from trees felled in forest clearing operations, from wood waste from wood-processing plants and also from within the forests. In the forests, woody litter and sometimes live branches are taken. Whole trees are taken under conditions of scarcity. Even so, most of the wood taken from tropical forests is used as fuel.

Globally, there is no overall shortage of wood for fuel. Forests in developing countries have an unused annual increment of about 6 billion cubic metres, which is greater than three times the world consumption of fuelwood. The amount of wood that is burnt *in situ* when the forests in developing countries (mainly tropical forests) are cleared for agriculture and grazing would alleviate all scarcity if it could be directed towards the area of need. The reasons for scarcity, where it occurs, are distribution and transport issues as well as inequitable barriers to access.

Regional fuelwood production from 1961 to 2011 is presented in Fig. 5.2. Historically, Asia has been the greatest producer of fuelwood, but its production peaked in 1990 and it has decreased since that time. In contrast, production of fuelwood in both Africa and South America has increased steadily over the last 50 years. Over this time, African fuelwood production increased 240%, South American production increased 170%, while Asia's production declined by 9%. In the near future, Africa is likely to become the largest producer of fuelwood. Income and prices are the most important factors determining fuelwood demand and the reason for the move away from fuelwood is probably the rise in real incomes. There is the tendency to move up the energy ladder as incomes increase (Table 5.3).

Even though there do not appear to be national shortages, there still are rural regions where fuelwood is scarce and is becoming scarcer. Communities are responding to this by using less fuelwood and/or spending more time in gathering it. Changes in forest tenure have also displaced the rural poor from sources of fuelwood to which they previously had access. Indeed, in the drier parts of Africa, poor nutrition can be caused by a shortage of fuelwood rather than a shortage of food. Typically, in

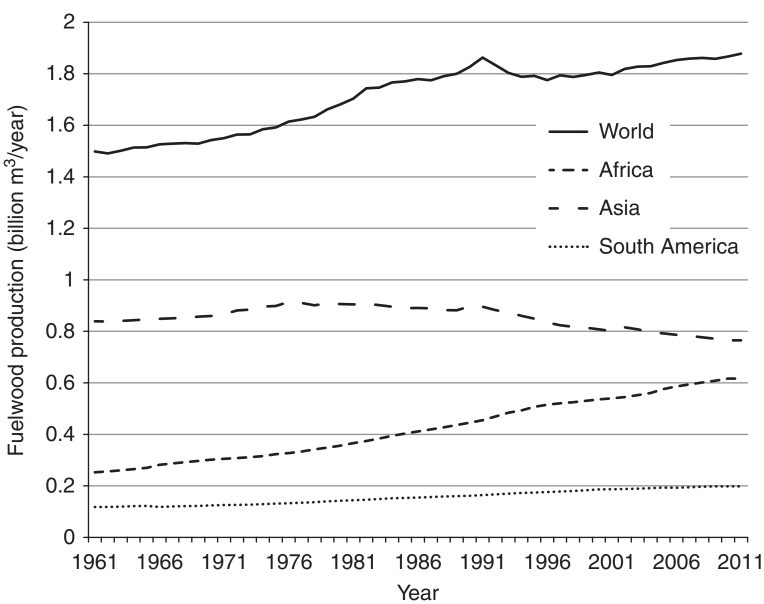

Fig. 5.2. Production of fuelwood in the world and Africa, Asia and South America. (Compiled from FAO online statistics; FAO, 2012.)

Table 5.3. The relationship between income (US$ per month) and energy use (kg oil equivalent per capita per month) in urban areas in 12 developing countries (unpublished data of Barnes *et al.*, 2002, in Arnold *et al.*, 2003).

Income class	Monthly income	Fuelwood	Charcoal	Coal	Kerosene	LPG	Electricity	Total
Low	8.59	3.63	3.28	2.38	1.33	0.15	0.60	11.59
Middle–low	15.51	2.57	2.66	3.21	1.73	0.42	0.82	11.59
Middle	25.02	2.10	2.20	2.83	1.50	1.25	1.15	11.15
Middle–high	41.94	2.62	2.54	0.67	1.14	2.09	1.77	10.82
High	116.95	1.66	1.79	0.00	0.60	3.70	4.15	11.62

areas of scarcity, searching for and gathering fuelwood can occupy a large amount of time: 4 hours or more a day would not be unusual. The time allocation increases with fuelwood scarcity and research has shown that household labour is allocated to maximize economic return (Cooke *et al.*, 2008). The fuelwood gatherer is usually a woman (unless some form of mechanized transport is involved) and consequently solutions to scarcity must be considered alongside improving the welfare of women. In rural areas there is a maximum distance (about 15 km) that a woman can scavenge for firewood, beyond which the family may need to relocate. The area around cities that depends on fuelwood can be stripped clean of fuelwood (in combination with clearing for agriculture) for a considerable distance beyond the urban fringe. However, as cities become larger and wealthier, there is a move away from fuelwood towards charcoal and other fuels and the problem becomes less intense. It is generally uneconomical to source wood further than about 100 km from a centre of population. For greater distances, it is more efficient to transport charcoal, which provides greater energy per unit of weight.

Eating more uncooked food is not a solution to fuelwood scarcity. Cooking is necessary to make starchy foods digestible, to remove toxins and kill parasites, to boil drinking water and to preserve food. Reducing the number of meals per day is not a solution either. Experience has shown that health problems occur when the stomach is loaded up with large amounts of not very digestible food. Undercooking of food may save fuelwood, but this can also lead to health problems if it does not remove the toxins or kill the parasites. Cooking over an open fire is common and this wastes about 94% of the heat. Considerable effort has been invested in developing and promoting fuel-efficient stoves that can reduce fuelwood consumption by at least 50%. This has been only partly successful because many cannot afford the improved stoves. Also, an open fire provides light as well as heat, keeps away insects and provides a social centrepoint. For example, despite concerted government initiatives in India to promote the use of improved stoves, a survey over six states showed that less than 10% of houses contained improved stoves (Gundimeda and Köhlin, 2003). It is very easy and inexpensive to at least double the fuel efficiency of an open hearth simply by enclosing the fire with bricks or constructing a simple mud-baked oven. Poor uptake of improved stoves confirms that scarcity of fuelwood or alternatives is not a universal problem in the developing world.

In some parts of the world where fuelwood is unavailable or too expensive, agricultural and animal residues are burnt as fuel. This removes nutrients that would otherwise be returned to the soil and consequently soil fertility is reduced, crop yields fall and forests may need to be cleared to provide additional land for cultivation. Cow dung is burned in sub-Saharan Africa, Ethiopia, Iraq, Bolivia and Peru, but particularly in India where 54–124 million tonnes of cow dung are burned annually (Habib *et al.*, 2004). The potential production lost due to declining soil fertility resulting from burning cow dung has been estimated to be 20 million tonnes of grain each year (Eckholm, 1975). However, the burning of dung does not necessarily mean that there is a shortage of fuelwood because the mass of fuelwood consumed in India is about three times that of dung. The incorporation of dung into the fields requires labour and associated costs. Farmers may well choose to forego the increases in soil fertility in favour of using dung as a low cost and easily obtainable fuel in preference to fuelwood.

Traditionally, fuelwood has been regarded as free and rural people collected it at no cost from wherever they could. This remains the case in rural areas of developing nations and a significant proportion of consumption does not enter the cash economy. However, considerable amounts of fuelwood are also traded and selling fuelwood can be a major source of income for the rural poor. The low price, however, gives little incentive to farmers to grow trees specifically for fuelwood. Price is the main factor regulating the choice of fuel, but households may still choose fuelwood even when it is more expensive than alternatives because of security of supply and because it requires no expensive stove (Boberg, 2000).

The trend for developing countries to move up the energy ladder is inevitable and appropriate. However, the developed world is now looking at increasing the amount of biomass in their energy mix and, in the long-term, developing countries may choose to do so for the same reasons. Ultimately the best option will be to increase biomass supply rather than decrease demand because many alternatives to bioenergy are finite and environmentally inferior.

Charcoal

The production of charcoal from wood differs from combustion (equation 4.2 in Chapter 4) in that the wood is heated in an enclosure in the absence of air or with a restricted air supply. In traditional operations, the technology is simple and the capital investment is low. The enclosure can be as basic as a pit in the ground or a simple kiln constructed out of bricks or earth. Industrial operations are more capital intensive and the enclosure may be a kiln or retort, but the fundamentals of the process are the same. The production of charcoal requires an external energy source until the pyrolytic reactions become self-sustaining. As the temperature of the wood charge in the kiln increases, the wood absorbs heat and releases water vapour. The temperature stays at or slightly above 100°C until the wood is dry. Further heating to 270°C causes the wood to absorb more heat and the wood begins to break down, releasing carbon monoxide, carbon dioxide, acetic acid and methanol. From 270°C to 290°C the exothermic decomposition of wood commences (wood releases heat) and various gases and some tars are released. From 290°C to 400°C the decomposition continues and several combustible gases – carbon monoxide, hydrogen and methane – together with carbon dioxide and the condensable vapours water, acetic acid, methanol and acetone are produced. From 400°C to 500°C the residual entrapped tar is driven off and the fixed carbon content of the charcoal rises to about 75% (FAO, 1985). Throughout the cooling process the kiln must remain sealed from any air entry because this would reduce the charcoal yield.

During charcoal production there is a loss of gaseous carbon and consequently a net loss of mass and energy. For example, charcoal from *Acacia bussei* at a distillation temperature of 500°C produced charcoal equivalent to 23% of the dry wood weight and an energy yield of 38% (Hollingdale *et al.*, 1999). In some traditional operations, the charcoal yield can be as low as 10% of the weight of the wood and the energy yield as low as 20% (Smil, 2006). The loss of energy in manufacture must be balanced against the advantages of producing a fuel that has about twice the energy value of air-dried wood per unit of weight, is less costly to transport, is smokeless, is easier to store, does not rot and is immune to insect attack. It is more efficient to transport the more compact and energy-intensive charcoal within urban communities than to burn wood. Charcoal is also used in industrial applications. For example, in Brazil, charcoal from eucalypt plantations is an important primary fuel in the smelting of iron.

Over the last 50 years, global charcoal production has increased much more than fuelwood production, with charcoal increasing almost threefold, while fuelwood has increased by only 25% (Fig. 5.3). Africa has exhibited the greatest increase in charcoal production of nearly 500%. In contrast, Asian production has increased by 220%, while South American production has been rather erratic and shown little increase since 1980. The combined aggregate of fuelwood plus charcoal is still rising, albeit at a declining rate, and much less rapidly than the equivalent growth in population (Arnold *et al.*, 2003).

Wood pellets

As the global demand for bioenergy has increased over the last few decades, so has the need for commodity biomass that is uniform, dense and readily transported. Wood pellets have been identified as the most suitable such commodity at present and its global production and trade has increased substantially over the last decade. In 2010, global

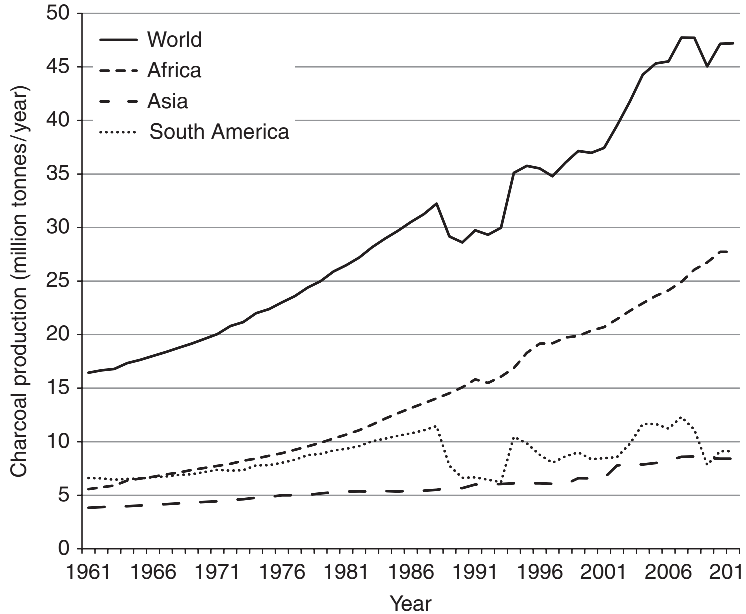

Fig. 5.3. Historical production of charcoal in the world and Africa, Asia and South America. (Compiled from FAO online statistics; FAO, 2012.)

pellet production was estimated to be 14.3 million tonnes, which was approximately ten times the 1.5 million tonnes reported for 2000 (Cocchi *et al.*, 2011). The EU is the major global market for wood pellets, accounting for about 85% of global demand. Much of the demand for pellets has been driven by the EU's increased use of biomass for the production of heat and power, which been growing at about 25% annually in response to incentives and tax credits provided in order to meet the EU's greenhouse gas emission targets (Magelli *et al.*, 2009).

The basic density of wood varies with species and usually lies within the range of 350 and 650 kg/m^3 and the moisture content may vary from about 50 to 120% on a dry weight basis (Kostiuk and Pfaff, 1997). Pelletization increases the specific density of biomass to more than 1000 kg/m^3 and results in a low and uniform moisture content. Wood pellets can be stored easily and handled using conventional grain handling facilities available at most ports.

Most pellets are made from sawdust and shavings and therefore most pellet mills are located at, or close to, a sawmill. Pellets are produced by initially drying the sawdust or shavings in a continuous rotary dryer and then passing the dry material though a hammer mill with a screen size of 3.2–6.4 mm. The dry, milled particles are compacted in a press mill at a temperature high enough to melt the lignin. They are then cooled and are ready for transportation and storage. The resultant pellets are typically 6–8 mm in diameter, 10–12 mm long and have an individual density of 1000–1200 kg/m^3 (Mani *et al.*, 2006).

Wood as a gaseous fuel

Two thermochemical technologies may be used to produce gas from wood: pyrolysis and gasification (Fig. 5.4). Pyrolysis, which is usually undertaken at about 450–500°C, uses elevated temperatures and a restricted air supply to convert the biomass into three co-products: syngas, liquid 'bio-oil' and solid charcoal. The yield of each product is dependent on reactor design and operating conditions. Modern systems usually seek to maximize bio-oil production and, for this reason, the pyrolysis process is described in the following section on the production of liquid fuels from wood (Bridgwater, 2012).

In gasification, biomass is reacted with air, oxygen or steam at temperatures in the range 600–1100°C (usually around 850°C) using conditions that ensure that the combustible gases created do not burn. A wide range of reactor types and operating conditions are used (E4tech, 2009). When air is used as the gasification medium, 'producer gas' is formed with a typical composition of 22% carbon monoxide, 18% hydrogen, 3% methane, 6%

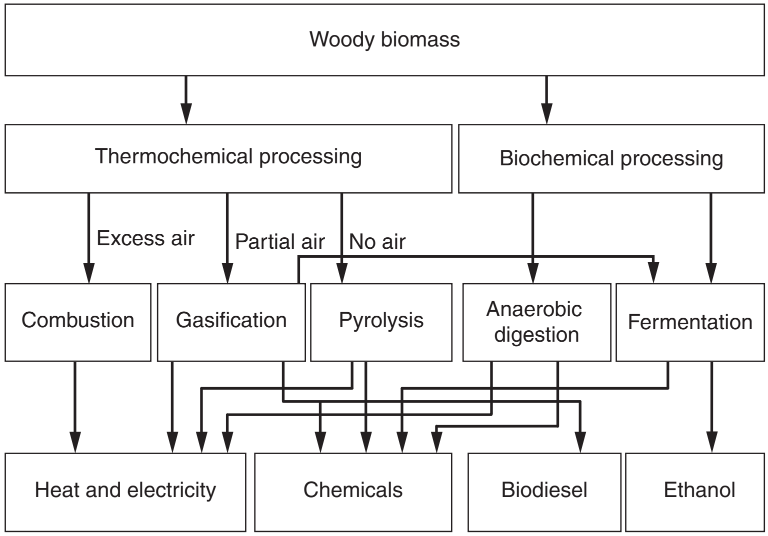

Fig. 5.4. Pathways for the conversion of biomass to energy and/or chemicals. (Adapted from Arumugam *et al*., 2007.)

carbon dioxide and 51% nitrogen. It may be cleaned and used in industrial boilers, or it can be used as a low-grade fuel for motor vehicles. Producer gas from burning wood, charcoal or coal was used as an alternative to petrol during the Second World War in periods of acute petrol shortage. It is a motor fuel of last resort because of its low calorific value (4–6 MJ/m^3) (McKendry, 2002). When oxygen or steam is the gasification medium, the 'syngas' produced consists typically of 40% carbon monoxide, 40% hydrogen, 3% methane and 17% carbon dioxide, although the proportions of these components varies with the type of gasifier and the operating conditions. This producer gas has a moderate energy content (12–18 MJ/m^3) and it needs to be cleaned before use, to remove tars, particulates and inorganic compounds (McKendry, 2002). Syngas may be burned directly, used to power gas engines or turbines to produce electricity or used as a feedstock to produce chemicals or liquid fuels. The production of liquid fuels from wood using gasification is discussed in the following section.

Commercial development of biomass gasifiers has occurred in three major phases (E4Tech, 2009). Initially, gasifiers were built in the mid-1980s for direct heat and power applications. In the mid-1990s, a second group was built to produce syngas with little or no nitrogen. From 2007, the third phase took place, with a focus on biomass gasification for liquid fuel production. These latter plants are very large, in the range of 1500–2000 oven dry tonnes/day of biomass input, to take advantage of economies of scale.

Wood as a liquid fuel

The development of a satisfactory liquid fuel from sustainable sources to replace petroleum-based fossil fuels is a major technological challenge. There are obvious advantages in having a fuel in liquid form. It is portable, easily transported, dispensed and used with existing infrastructure because the transportation sector predominantly uses liquid fuels. Ethanol and biodiesel are the two major biofuels produced from plant materials (Fig. 5.4). Ethanol can be blended with petrol. It burns cleanly and does not produce many of the harmful emissions of petrol. In contrast, biodiesel can be substituted for diesel. The global production of these biofuels is growing rapidly, with the amount manufactured tripling between 2000 and 2007 to account for about 1.5% of global road transportation fuels in 2007 (Sims *et al*., 2008; IEA, 2009a).

It is important to differentiate between first-generation and second-generation biofuels. First-generation bioethanol and biodiesel are produced from carbohydrate- or oil-containing plants that have been grown traditionally for food or animal feed purposes and that have mature production technologies (Sims *et al.*, 2008). Ethanol production from arable crops such as sugarcane, sugar beet and cereal grains, is a well-developed and long-standing technology. Sugarcane and sugar beet have free sugars that may be readily fermented to ethanol. Cereal grains contain starch, which may be enzymatically hydrolysed to soluble sugars that may be subsequently fermented to ethanol. Brazil has produced fuel ethanol since the 1970s and 20–25% of its motor fuel requirements come from ethanol derived from sugarcane. The USA's production of fuel ethanol from maize increased rapidly after 2000, and by 2006 it had surpassed Brazil's production. In 2009, Brazil's annual production of ethanol was about 25 billion litres and in the USA, about 40 billion litres were manufactured. Global production was about 74 billion litres in 2009. Biodiesel has been produced traditionally from plant oils or animal fats. Plant-derived biodiesel is produced by expressing and purifying the oils present in oil-rich plants such as soybean, sunflower, rapeseed and palm. In 2009, global biodiesel production was about 12 billion litres.

Despite their rapid growth, the cost and sustainability of first-generation biofuels have been increasingly questioned (Mastny, 2006; Sims *et al.*, 2008). These fuels are perceived to compete with the food supply, increase food prices, have modest greenhouse gas reduction benefits and to presently only be economic through the use of subsidies. These limitations have driven an increased interest in second-generation biofuels, which are considered to be free from many of the challenges confronting first-generation biofuels. Second-generation biofuels are produced from biomass containing polymeric carbohydrates (cellulose and hemicellulose) and other organic materials, such as lignins, extractives and tannins. Examples of these materials include forest and agricultural residues, wood processing by-products and municipal organic waste. Collectively, these materials are termed lignocellulosic biomass, because cellulose, hemicellulose and lignin are the dominant components. Lignocellulosic biomass is more challenging to convert into biofuels using biochemical pathways than arable crops. This is because the polymeric carbohydrates require complex pretreatments to convert them into monomeric compounds that can subsequently be fermented into a biofuel.

Second-generation biofuels can be produced by thermochemical or biochemical pathways (Fig. 5.4). The technologies for producing these biofuels are presently at the demonstration and pilot scales and no technology presently has a clear advantage over its competitors. Commercial-scale production of second-generation biofuels is not anticipated before 2015 (Sims *et al.*, 2008).

The two thermochemical conversion technologies that may be used are gasification and pyrolysis. Modern pyrolysis reactors seek to maximize bio-oil production by using flash pyrolysis, which heats the biomass to about 500°C for about 1 second. Finely ground biomass (< 3 mm) is fed into a pressurized reactor and, under these conditions, about 75% of the biomass is converted into bio-oil, 12% to char and 13% to syngas. With lower temperatures and longer residence times, less bio-oil and more gas are produced (Bridgwater, 2012). The bio-oil typically has a heating value of about 17 MJ/kg or about half that of a conventional fuel oil. It has a water content of 20–25%, is acidic, highly viscous and does not mix well with conventional oils. It therefore requires upgrading before use. Its favoured use is as a substitute for fuel oil or diesel in static applications, such as boilers, furnaces, engines and turbines. Over the last decade there has been a surge in commercial developments in pyrolysis and a recent review indicated that 42 industrial-scale reactors had been built by 2012 (Bridgwater, 2012).

There are four major options for producing chemicals or liquid fuels from syngas (E4tech, 2009). First, synthetic diesel may be produced by Fischer-Tropsch (FT) synthesis. This chemical catalytic process, which converts carbon monoxide and hydrogen into hydrocarbons, was developed in Germany in the 1920s and has been used commercially to produce liquid fuels from coal gas in Germany and South Africa during periods when fossil fuel consumption was limited. There has recently been substantial interest in using this technology to convert syngas to liquid fuels. Problems with this technology include the high cost and the large scale required (Sims *et al.*, 2008, E4tech, 2009). Second, syngas may be fermented to ethanol and other chemicals by anaerobic microorganisms. Third, methanol may be produced using chemical catalysis. Finally, a mixture of methanol, ethanol, propanol, butanol and small quantities of higher molecular weight alcohols may be produced by catalysis. At present, the production of biodiesel using the FT pathway has attracted the greatest interest, especially in Europe, and substantial investment has been made in large-scale demonstration plants.

There are five key phases in the biochemical pathway: feedstock harvesting and transportation to the processing site; comminution to provide a small and consistent particle size; thermal and/or chemical pretreatment to facilitate enzymatic access to the polymeric carbohydrates; enzymatic hydrolysis to produce sugars; fermentation of sugars to ethanol, or other chemicals; distillation to provide a concentrated product. Alternatively, the sugars can be converted to biogas (methane and carbon dioxide) by anaerobic digestion. To date, most of the focus has been on ethanol production. A diverse range of pretreatment processes have been investigated, including water-based treatments, acidic, alkaline and organic pulping technologies (Sims *et al.*, 2008). These processes seek to improve the access of enzymes to the carbohydrate polymers present in the biomass, facilitate their hydrolysis to sugars and convert any by-products, such as lignin and extractives, into commercially useful forms. Yang and Wyman (2007) provide a review of the different pretreatment processes and highlight their advantages and disadvantages. Once the polymeric carbohydrates are hydrolysed to monomeric sugars, these are fermented and distilled to produce ethanol, which may then be used in the existing fuel distribution system. A promising strategy for the biochemical pathway is to integrate the hydrolysis and fermentation of carbohydrates into a bio-refinery concept with the lignin, extractives and perhaps some of the hemicellulose being removed before cellulose hydrolysis. This concept is considered in more detail in the biomaterials section of this chapter.

Historically, fossil fuels have been less expensive than fuel ethanol. Consequently, subsidies and supportive policy frameworks are generally required to sustain the bioenergy sector over the first few decades of development. A recent study estimated that ethanol could be produced in 2010 for US$0.80–0.90/litre and forecast that this value would reduce to US$0.55–0.65/litre by 2030. The comparable estimates for biodiesel were US$1.00–1.20/litre in 2010 and US$0.60–0.70/litre in 2030 (Sims *et al.*, 2008). With technological learning that occurs with experience and with the price of oil expected to increase, biofuels should become more cost competitive and their production may increase substantially (Hettinga *et al.*, 2009). Studies have forecast slow but steady growth in biofuel production and estimated that by 2030 biofuels may account for 5–10% of global transport fuel consumption (Sims *et al.*, 2008; IEA, 2009b).

Forests managed for biomass production

As noted earlier, by 2050, bioenergy has the potential to provide between 200 and 500 EJ/year, equivalent to 30–50% of the global primary energy demand. In order for this potential to be satisfied, sufficient land and sustainably managed forests are required. This section initially considers sustainable management of forests for biomass production, identifies the different needs of developing and developed nations and finally evaluates whether sufficient land is available.

The sources of fuelwood from a forest are much wider than for industrial roundwood. Forest residues, trees that are too small for industrial use, pre-commercial thinnings, mortality, trees that are of too low a quality for industrial use and even litter from the forest floor can be used as fuelwood. Consequently, taking forest biomass for energy has the potential to remove a larger quantity and a more diverse range of material from the forest than for industrial roundwood production. Care needs to be exercised because the maintenance of soil fertility depends on the cycling of nutrients and carbon and if these are removed excessively from the site in biomass, soil fertility may be reduced. Foliage, small branches and litter contain a greater concentration of nutrients than stem wood and these should be left in the forest if possible. The return of the ash to the forest following combustion of the biomass removed would alleviate this nutrient loss to some extent. Also, any impact on conservation of biodiversity created by the extensive removal of biomass would need to be evaluated (Hall, 2002). On the plus side, the more thorough cleanout in a combined biomass and timber management regime would reduce the risk of fire and damage from insects and disease (IEA, 2002). In addition, as noted in Chapter 4, the forest climate benefits will only accrue if the forested area is maintained or increased and the forest is managed sustainably.

In the developing nations, the gathering of fuelwood need not cause significant deforestation and, properly managed, forests used primarily for biomass production should increase the forest area rather than decrease it. The use of biomass as a fuel together with sustainable forestry practices should therefore be encouraged rather than discouraged.

Fuelwood can be obtained from native forests and plantations that are managed primarily for timber production or it may come from plantations established specifically to provide fuelwood. However, in the developing world, there are few situations where farmers grow trees specifically for fuel. The extensive areas of energy plantations, the widespread uptake of improved cooking stoves and the proliferation of gasification units envisaged under the Tropical Forest Action Plan have not materialized. Probably the best strategy for the rural farmer is to grow multipurpose tree species where fuelwood supply is just one component of an overall land use system that meets broader objectives. Agroforestry systems are particularly attractive because they can provide food, fuel and fibre in a sustainable manner that delivers a broader range of products in a way that limits risk while caring for the land, reducing soil erosion and maintaining soil fertility. The most successful schemes have been where the rural farmers have been part of 'community-based participatory forest management', where the rural community shares in the planning, management and benefits. This is particularly important for managing land that is held in common. Community forestry will be considered in more detail in Chapter 10. Technologies need to be simple, decentralized and inexpensive. Subsidies, for example in seedling distribution, and the removal of legal disincentives to plant can assist.

In the early 1980s, the National Academy of Sciences developed a list of potential species for fuelwood and other products for the developing world (Table 5.4). Some of these species are very aggressive and care needs to be taken that they do not become weeds when introduced as an exotic species into a new habitat. Local species should be preferred if they are suitable.

In the developed world, two approaches to biomass provision are being explored. In the first approach, the management and silviculture for biomass production is being integrated with that for higher value timber production while ensuring that environmental values are safeguarded. The second

Table 5.4. Potential fuelwood species. (Collated from National Academy of Sciences, 1980, 1983.)

Humid tropics	Tropical highlands	Arid and semiarid regions	
Acacia auriculiformis	*Acacia decurrens*	*Acacia brachystachya*	*Haloxylon persicum*
Albizzia falcataria	*Acacia mearnsii*	*Acacia cambagei*	*Parkinsonia aculeata*
Bursera simaruba	*Ailanthus altissima*	*Acacia cyclops*	*Pinus halepensis*
Calliandra calothyrsus	*Alnus acuminata*	*Acacia nilotica*	*Pithecellobium dulce*
Casuarina equisetifolia	*Alnus nepalensis*	*Acacia saligna*	*Populus euphratica*
Coccoloba uvifera	*Alnus rubra*	*Acacia senegal*	*Prosopis alba*
Derris indica	*Eucalyptus globulus*	*Acacia seyal*	*Prosopis chilensis*
Eucalyptus brassiana	*Eucalyptus grandis*	*Acacia tortilis*	*Prosopis cineraria*
Eucalyptus deglupta	*Eucalyptus robusta*	*Adhatoda vasica*	*Prosopis juliflora*
Eucalyptus pellita	*Eucalyptus tereticornis*	*Ailanthus excelsa*	*Prosopis pallida*
Eucalyptus urophylla	*Gleditsia triacanthos*	*Albizzia lebbeck*	*Prosopis tamarugo*
Gliricidia sepium	*Grevillea robusta*	*Anogeissus latifolia*	*Sesbania sesban*
Gmelina arborea	*Inga vera*	*Azadirachta indica*	*Tamarix aphylla*
Guazuma ulmifolia	*Melaleuca quinquenervia*	*Balanites aegyptiaca*	*Tarchonanthus camphoratus*
Hibiscus tiliaceus	*Melia azedarach*	*Cajanus cajan*	*Zizyphus mauritiana*
Leucaena leucocephala	*Robinia pseudoacacia*	*Cassia siamea*	*Zizyphus spina-christi*
Maesopsis eminii	*Sapium sebiferum*	*Colophospermum mopane*	
Mangroves		*Combretum micranthum*	
Mimosa scabrella		*Conocarpus lancifolius*	
Muntingia calabura		*Dalbergia sissoo*	
Pinus caribaea		*Emblina officinalis*	
Psidium guajava		*Eucalyptus camaldulensis*	
Sesbania bispinosa		*Eucalyptus citriodora*	
Sesbania grandiflora		*Eucalyptus gomphocephala*	
Syzygium cumini		*Eucalyptus microtheca*	
Terminalia catappa		*Eucalyptus occidentalis*	
Trema		*Haloxylon aphyllum*	

approach relies on intensive and sustainable management of highly productive species to generate biomass solely intended for the production of energy or pulp and paper. The production of higher quality roundwood needed to produce timber or veneer is not a target of these management regimes. The most common species for energy plantations are poplars (*Populus*), willows (*Salix*) and eucalypts (*Eucalyptus*). A plantation with an area of 11,250 hectares and a sustainable productivity of 10–15 tonnes per hectare per annum would produce enough biomass to fuel a 30-MW power station and create sufficient electricity for 30,000 houses for 1 year (IEA, 2002).

The drive to create sustainable bioenergy systems has led to an assessment of how much land may be available for biomass production and how forest productivity can be increased. Anthropogenic activities have already greatly impacted the Earth's ecosystems. In 2000, humans used about 28% of the planet's above-ground net primary productivity, equivalent to an annual global anthropogenic harvest of 8.2 billion tonnes C (Haberl *et al.*, 2007). Forests have a relatively low productivity compared with agriculture and, using FAO and IPCC data, the roundwood harvest in 2000 was equivalent to 0.77 billion tonnes C or 9.4% of the global anthropogenic harvest (IPCC, 2006; FAO, 2012). The total global anthropogenic harvest had a gross energy value of about 300 EJ per year, of which about 16% was used for the provision of energy services (Dornburg *et al.*, 2008).

The use of biomass for energy production may reach 200–500 EJ/year in 2050 (Dornburg *et al.*, 2008) which would require an increased annual harvest of 5–14 billion tonnes C, inferring that the present global biomass harvest would need to be doubled by 2050 (Haberl *et al.*, 2007). All of this increased harvest would be required for energy production and the land would not be available to provide food.

Most studies that have assessed how this quantity of biomass may be obtained have emphasized the role of biomass plantations (Berndes *et al.*, 2003) and two key factors in achieving increased biomass production are land availability and productivity. From a land availability perspective, it has been calculated that between 0.4 and 2.0 billion ha might be needed (Berndes *et al.*, 2003). This is an area similar to that presently used for cultivated crops and from 10 to 50% of the total global forest area (FAO, 2010). Alternatively, it may more readily be visualized as being 0.4–2.0 times the area of Canada, and the use of such large areas of the Earth's surface for biomass production has raised environmental, social and economic concerns. It is probable that agriculture will use the more productive sites and forestry will use less productive land. The maximum productivity for the lands that that may be available for establishing forests for biomass production has been estimated to be in the range of 10–29 tonnes/ha/year (Berndes *et al.*, 2003). These mass productivities are affected by the wood density of the tree species used and non-coniferous species generally have higher densities than coniferous species. Using typical wood densities, these mass productivities may be converted to volumetric productivities in the range of 15–58 m^3/ha/year, which is much higher than the present global average of about 1.6 m^3/ha/year for forest land designated for production or multiple use purposes (FAO, 2010). Advanced tree improvement technologies to create more productive plantation species is therefore an important element of producing sufficient biomass for bioenergy.

Non-wood Forest Products

Non-wood forest products (NWFP) have been defined as goods of biological origin other than wood, derived from forests, other wooded lands and trees outside forests (Vantomme *et al.*, 2002). NWFP therefore constitute all plant and animal goods, excluding wood, that are provided by forests. The definition of NWFP has been the subject of much debate and the decisions as to what constitutes NWFP can seem arbitrary. Sometimes when a forest tree species is established as a plantation to specifically provide NWFP, the boundary between forestry and horticulture becomes blurred. An example would be a plantation of walnuts that are planted initially for the nuts, but are eventually utilized for the timber. Also, the FAO considers that rubber plantations are part of the forest plantation estate, but that palm-oil plantations are not. Rubber trees are tapped for latex when young and utilized for timber when they are older and past their efficient latex-producing years. The variety of NWFP is very great and they can sometimes be as, or more, economically important than traditional wood products. However, reliable global data on their production and trade are lacking. Although there is evidence of over-exploitation of some NWFP, sustainable management of NWFP is virtually non-existent globally. This is of great concern, not only because of a reduction in biodiversity, but also because of the loss of livelihood to those communities that depend on NWFP for their survival. The *Global Forest Resources Assessment 2010* undertook a global survey of NWFP (FAO, 2010) and much of the quantitative information draws on this source. In 2005, the global value of NWFP was estimated to be US$18.5 billion and the ten most economically important NWFP are presented in Table 5.5. Notably, the top five categories accounted for 90% of the total value. These data are considered to be underestimates because of the difficulty in obtaining and reporting accurate information. China and India are the world's largest producers and consumers of NWFP.

Food

Food products from plants include fruits, seeds, flowers, bark, roots and mushrooms and food products from animals include meat (from both vertebrates and invertebrates), honey, bird nests and eggs. The range of food coming from 'wild' plants and animals in the forest is so diverse that only isolated examples can be given here. In Africa, edible NWFP are important for sustenance during periods of food shortage and honey and bees wax are also important. Southern and eastern Asia are the major producers of wild culinary herbs and wild spices (nutmeg, mace, cinnamon and *Cassia*) and of the wild edible mushrooms *Morchella* spp. (morels), *Auricularia auricula-judae* (jews ear), *Tremella fuciformis*, *Lentinus edodes* (shiitake), *Trichloma matsutake* (matsutake) and *Pleurotus ostreatus* (hiritake). Edible pine nuts are produced from *Pinus gerardiana* in India, Afghanistan, Pakistan and China, *Pinus koraiensis* in Russia, Manchuria, China and Korea, *Pinus pinea* (stone pine) from around the Mediterranean and *Pinus cembroides* (Mexican pinyon) from south-western USA and Mexico. Brazil nuts and palm hearts are important wild food products from South American forests as well as *Araucaria* seeds, mushrooms (*Boletus luteus*, *Lactarius deliciosus*) and maté, an addictive but harmless stimulant obtained from leaves of *Ilex paraguariensis*, which is extremely popular as a beverage in Argentina, Uruguay, Paraguay and southern Brazil. The forests of Central America contain more than 100 tree or palm species with edible fruits. The latex (chicle) from sapodilla (*Manilkara zapota*) is used for making chewing gum. Hearts from the manicole palm (*Euterpe oleracea*) are the principal source of income for Amerindian communities in the coastal wetlands of Guyana. Berries, honey, mushrooms (for example, the truffle *Tuber melanosporum*) and nuts are important in Europe and mushrooms, berries and maple syrup in North America. Many forest trees for food have become 'domesticated' and are grown in plantations (pecans, walnuts, beech nuts, pine nuts, acorns, cashews, maple syrup, dates, coconuts, *Macadamia* nuts, avocados, citrus, stone fruits, bananas and almonds). Forest trees produce a range of oil seeds, although oil from olives (*Olea europaea*) and oil palm (*Elaeis guineensis*) is now obtained from plantations and would not be considered to be a NWFP. Illipe nuts, the fruits of some *Shorea* trees, contain an oil with properties similar to cocoa butter. In Morocco, edible oils are obtained from the argan tree (*Argania spinosa*).

The consumption of bushmeat (antelopes, gazelles, monkeys, wild boar and porcupines) in Africa has raised legitimate concerns about wildlife conservation. For example, bushmeat consumption in the Congo basin has been estimated at 5 million tonnes per annum, which is double the production rate (Fa *et al.*, 2002). Meat is also a significant NWFP in Europe and North America, but here it is called game meat rather than bushmeat and is obtained more for sport and recreation rather than as a staple for basic sustenance. Generally, hunting and fishing in European and North American forests are under some form of management and regulation.

Forests can provide fodder for domestic animals and flowers for bees. Fodder from trees is very important in the drier parts of Africa

Table 5.5. The value of the ten most economically important NWFP in 2005. (From FAO, 2010.)

NWFP category	Value (million US$)
Food	8614
Other plant products	2792
Wild honey and beeswax	1805
Ornamental plants	984
Exudates	631
Plant materials for medicines	628
Wild meat	577
Materials for utensils, construction, etc.	427
Hides, skins and trophies	183

(*Acacia*, *Khaya*, *Faidherbia* and *Balanites*), South America (*Prosopis* spp.) and in continental and southern Asia.

Medicinal plants and animals

Forests are a very rich source of plants and animal parts used in traditional medicine and also in western medicine. Forests are also a rich genetic resource for future medicines yet to be discovered and developed. More than 80% of the world's population uses traditional medicines from plants for their primary health needs. This is mostly concentrated in the developing world, but the developed world is steadily increasing its use of medicinal plants. In the developed world, 25% of all medical drugs are plant-based and in the developing world it is near to 75%. Over 25% of all prescriptions in Western Europe and North America and near to 60% of those in Eastern Europe are unmodified or slightly altered plant products. In 1996, the USA had a turnover of US$4 billion in herbal drugs (Tiwari *et al*., 2004). Traditional medicine based on medicinal plants is very well developed in Asia (particularly China and India), Latin America and Africa. One-third of the plants listed by the ancient Egyptians as being of pharmaceutical value are still used for this purpose today. The ancient Greeks used extracts from willow (*Salix*) to relieve pain. The active ingredient in willow led to the development of aspirin, one of the most widely used drugs in the world. The antimalarial quinine is obtained from the *Cinchona* tree and this is still used, often in combination with other drugs, to treat malaria today. Many plants have proven medicinal properties. There are so many species that no attempt will be made here to single out any more. In Ethiopia alone there are 600 plant species listed as being important in traditional medicine. About 4000 species of medicinal plants are recognized in Asia.

The growing global demand for medicinal plants has led to over-exploitation and species endangerment. Conservation issues are discussed by Bhattarai and Karki (2004). The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) is an international convention aimed at conserving threatened and endangered species. Signatories to the convention have agreed not to trade in species listed as endangered. Also attempts are now being made to certify NWFP (Shanley *et al*., 2002). China is the world's largest producer and exporter of medicinal plants, followed by India. Egypt and Morocco are the main African exporters of wild medicinal plants, while Chile and Mexico are the major producers and exporters in Latin America. Germany, France and Bulgaria are significant European exporters and the USA is also an exporter. The proportion of medicinal plants that are cultivated compared with those obtained from the wild is increasing. Conflicts between western medicine and traditional medicine have been intense in the past and continue to be so, but there has been a growing trend towards co-existence and learning from each other.

Aromatics for perfumes and cosmetics

Essential oils are volatiles that are extracted from the plant by distilling, compressing, steaming or dissolving. They are called essential from the word 'essence'. Essential oils from aromatic plants (*Thymus*, *Rosmarinus*, *Acacia* and *Eucalyptus*) are important products of Egypt, Morocco and Tunisia. Essential oils derived from the seeds of the nutmeg tree (*Myristica fragrans*) are a major export of Grenada. South-east Asia and eastern Asia are major producers of essential oils from sandalwood (*Santalum* spp.), agarwood (*Aquilaria* spp.), snowbell (*Styrax* spp.) and blue gum (*Eucalyptus globulus*). In South America, essential oils are distilled from rosewood (*Aniba rosaeodora*), andiroba (*Carapa* spp.) and sassafras (*Ocotea pretiosa*). Tea tree oil (*Melaleuca alternifolia*) is produced in Australia. Essential oils traditionally have been used in cosmetics, perfumes and as aromatic additives to otherwise non-aromatic or unpleasant substances such as in disinfectants and cleaners. Recently, however, they have become very popular in aromatherapy, where they are vigorously promoted, often without any scientific evidence, to cure many ills and to provide good health and well-being.

Frankincense or olibanum (*Boswellia* spp.), myrrh (*Commiphora myrrha*) or opopanax (*Commiphora* spp.) are aromatic resins from Somalia, Ethiopia and Sudan that have been prized since ancient times. The first record of plant hunting was in 1495 BC, when Queen Hatshepsut of Egypt commissioned an expedition to Somalia to collect myrrh trees, which she subsequently planted in her garden (Musgrave *et al*., 1999). Camphor from *Cinnamomum camphora* is a product of South-east Asia.

Fibres for construction, craft and utensils

Rattan (*Calamus*, *Daemonorops*, *Plectocomia* and *Korthalsia*) is the most important internationally traded NWFP. There are about 600 species, of which 10 are important commercially as canes used principally in furniture making. Production is centred in South-east Asia and particularly Indonesia. However, rattans have been depleted through over-exploitation and through loss of forest habitat. Bamboo (*Phyllostachys* and *Dendrocalamus*) has very wide use in Asia for both construction and handicrafts and is now being extensively grown as a crop by farmers. Kapok (*Ceiba pentandra*) is an insulating material and comes mainly from Thailand and Indonesia. In Ecuador, fibres from the palm *Carludovica palmata* are used for making panama hats. In Chile, young branches of *Salix viminalis* are woven to produce handicrafts and furniture. In Central America, various palms (*Desmoncus* spp., *Sabal* spp., *Astrocaryum* spp. and *Carludovica palmata*) provide leaves, fibres and canes suitable for construction and handicrafts. In the Caribbean, a wide variety of NWFP are used for making utensils and for handicrafts (FAO, 2001).

Materials for commerce and industry

Resins are present in special ducts in the wood and bark called resin canals. Resins exude if the tree is wounded, their function being to heal the wounds and impart resistance to fungal infection and insect attack. Resins may be classified as hard resins or oleoresins. Hard resins are solid, transparent, colourless, odourless and brittle substances that are low in oil content. They are the best material for manufacturing varnishes. Oleoresins have high amounts of oil as well as resins and have a distinct aroma and flavour. The sources and uses of the main hard and oleoresins are presented in Table 5.6.

The main oleoresins are from *Pinus* species and they are highly water resistant. The ancient Greeks used them to caulk the hulls and decks of their boats and they remained important as a source of pitch throughout the history of wooden ships. Because of their traditional use as a caulking agent in boats, they became known as naval stores. The resins were originally obtained by destructive distillation of wood, but for the last 300 years they have been obtained by tapping live trees in the same way as rubber trees are tapped for latex. The main products derived from pine resin are rosin and turpentine (Table 5.6). Pine resin is produced from about 10 main pine species and production is dominated by China, Russia, Scandinavia, Italy, France, Portugal, Spain and the USA. Today, however, terpenes (the main constituents of turpentine) and resin acids (the principal constituents of rosin) are obtained mostly as by-products of the pulp and paper industry (see Chapter 4).

Gums are also exudates from trees, but they consist largely of carbohydrates and are used as

Table 5.6. Hard resins and oleoresins. (Adapted from Bhojvaid and Chaudhari, 2004.)

Resin	Tree	Use
Hard resins		
Copal	*Agathis*	Manufacture of linoleum
Dammar	Dipterocarps	Paper, varnish, lacquer, paint, inks, polishes, water-resistant coatings, incense, medicine
Mastic	*Pistacia*	Chewing gum, flavouring, varnish, medicine
Dragon's blood	*Daemonorops*	Violin varnish
Oleoresins		
Rosin	*Pinus*	Paper sizing, printing ink, paint, varnish, leather, soap, batteries, synthetic rubber, perfumes, fireworks, adhesives
Turpentine	*Pinus*	Paint, varnish, waxes, insecticides, germicides, perfumes, pharmaceuticals, soap, aromatics
Benzoin	*Styrax*	Aromatics, pharmaceuticals, medicine
Styrax	*Liquidamber*	Perfumes, pharmaceuticals
Balsam	*Myroxylon*	Perfumes and medicine
Copaiba	*Copaifera*	Shampoos, soaps and cosmetics, perfumes
Elemi	*Canarium*	Lacquers, varnishes

additives in food and cosmetics. Perhaps the best known is gum arabic, an exudate from *Acacia senegal* from sub-Saharan Africa. Gum arabic has an osmotic pressure and colloidal content similar to blood and has been used as a surgical adhesive. It was also used as an adhesive on stamps. Today its major use is in the pharmaceutical industry as a thickening and suspending agent. *Acacia senegal* is a multi-purpose tree. It not only produces gum arabic, but also is a useful fodder tree and a nitrogen fixer. India is the main producer of karaya gum, an exudate from *Sterculia urens*, which is used as a fibre deflocculating agent in paper production, as a thickener for foodstuffs and cosmetics and for finishing textiles. Argentina produces gum brea from *Cercidium australe*, which can be used as a substitute for gum arabic. (Frankincense, myrrh and opopanax are also gums.)

Tannins are carbohydrates found in wood, bark, roots, leaves and seeds of plants that traditionally have been used in curing (tanning) animal skins to make leather. The process of tanning is very old, dating back at least to 10,000 BC, and oak and chestnut were historically important species. Tannins are extracted by boiling or soaking in water and then concentrating the extract. Most tannins of tree origin come from the fruit of tara (*Caesalpinia spinosa*) and Peru is the major producer. The quebracho tree (*Schinopsis* spp.) is an important source of tannins from Argentina and Paraguay. Acacia and mangroves are other sources. Synthetic tannins are also used in modern leather tanning and tannins are also used in the manufacture of adhesives.

Dyes were used by the earliest civilizations and trees of historical importance were alder, ash, walnut, oak and birch. Today most dyes and colorants are synthetically produced from coal-tar derivatives. Vegetable dyes, however, are still used in developing countries and their use is increasing in developed countries in art and craft. Peru is the major producer of the rich yellow orange colorant annatto (from the seeds of *Bixa orellana*) and of a carmine colorant from cochineal (from the insect *Dactilopius coccus*). Brazilwood (*Caesalpinia sappan*) from South-east Asia and mainly India is valued for red dyes, and *Caesalpinia echinata* from South America for its red–yellow dies. *Pterocarpus* from western Africa produces a bright red dye and *Chlorophora* from South America produces a yellow dye.

Latex is a milky emulsion that exudes from cells under the outer bark called laticifers. Some contain long-chain hydrocarbons that are elastic and the most commercially significant elastic latex is that produced by the rubber tree (*Hevea brasiliensis*), a native of South America that is extensively planted in South-east Asia, particularly Malaysia. Over 90% of the world's supply of natural rubber comes from South-east Asia, with the residual production coming from equatorial Africa and South America. The latex comes from tapping the tree and the latex is coagulated to form natural rubber. The tree is first tapped at about age 5 years and tapping continues to about age 20. After tapping, the plantation can be left to about 30 years, at which time it provides a timber crop that is often used to make furniture. Natural rubber is considered to be the best rubber, but two-thirds of world supply is now manufactured from petrochemicals. Natural rubber has some unique properties that synthetics have not been able to reproduce. It has high resilience, low heat build-up in tyres, excellent strength at high temperatures and excellent fatigue resistance (Allen, 2004).

Cork is produced from the bark of many species, but the best quality comes from the bark of the cork oak, *Quercus suber*, grown in Portugal, Spain and North Africa (Algeria, Morocco and Tunisia). Cork is a good insulator, is light, and is a viscoelastic material that can withstand large deformations without fracture and with good dimensional recovery. This has led to its use in flotation devices, as an insulation material, as a floor covering, in antivibrational joints in structures and as sealants in engines (Pereira and Tomé, 2004). Lower quality cork can be high-temperature bonded with natural resins to make agglomerates that can be used as sheets for floor coverings and insulation. However, the economic viability of the cork industry is determined by the use of cork for stoppers in the wine industry. Currently cork stoppers are under serious competition from screw-top seals, which many wine aficionados consider to be at least as good as, if not better than, the best-quality cork. The future of cork as a stopper for wine depends on marketing it on lifestyle values, rather than on its technical merits.

Shellac is a traditional and contemporary finishing agent for fine furniture. It is produced from lac, the protective coating of the scale insect *Coccus lacca* from India and South-east Asia. Tung oil from the Chinese trees *Aleurites fordii* and *Aleurites molucanna* is another fine protective finish for furniture and wood work. In Brazil, a hard wax, carnuba wax, is obtained from the seeds of the carnaúba palm (*Copernicia prunifera*) and is used as a wax finish on cars. Citronella (*Cymbopogon* spp.) from South-east Asia and the Caribbean and neem (*Azadirachta indica*) from India have insect-repellent properties. Indeed, neem has an almost cult-like following as an eco-friendly tree with a myriad of uses. Sphagnum moss (*Sphagnum cymbifolium*) is the live moss that grows on top of the dead peat moss in a bog in cool moist climates and is most often found in the open, but also occurs in forests. Both mosses are used in horticulture and plant propagation.

Ornamentals, trophies, live plants and animals

Ferns, *Ficus* spp., orchids and aquatic plants are among the wide range of plants that come from the forest and are traded. Animals traded include amphibians, birds, reptiles, frogs, primates and lemurs. Some species traded are included on the CITES endangered species lists. Christmas trees are produced commercially in Europe, North America, Canada, Japan, Australia and New Zealand. Decorative foliage from the forest is produced in both Europe and the USA, often as by-products of the pruning necessary to shape the Christmas trees (Hammett and Murphy, 2004). Decorative NWFP include vines, floral arrangements, dried decorations, wreaths and religious ornaments. Hunters in Europe, North America, New Zealand and elsewhere take pelts and wall trophies from their kills. There are no reliable data on the amount of pelts and trophies (or of game meat) taken by the hunters.

Innovative Biomaterials

Fossil fuels were produced from plant materials over millions of years and, since the start of the industrial revolution, they have played a crucial role in meeting society's need for energy and materials. However, humanity's ongoing dependence on fossil fuels is not sustainable and researchers are now investigating whether it may be feasible to shorten the time-frame needed by nature to form fossil fuels and more directly convert plants into the energy and materials that society needs. Consequently, several nations are investigating the development of a 'bioeconomy', based on renewable plant materials, to replace our present fossil fuel-based economy. Just as oil refineries fractionate crude oil into a range of products including petroleum, diesel, propane, kerosene and a variety of petrochemicals, researchers are pursuing the development of a biorefinery to fractionate lignocellulosic material into a variety of energy and biomaterial products (Clark and Deswarte, 2008). The production of energy from biomass has been discussed earlier in this chapter. This section briefly addresses the production of innovative biomaterials that are intended to compete with materials presently created from fossil fuels.

Forest biorefineries are multi-product manufacturing plants that convert forest biomass into fuels, co-products and direct energy. The co-products may include plant extracts, chemicals, solvents, plastics, lubricants, food products, carbon fibres, nutraceuticals or fragrances, depending on the technology used (Ragauskas *et al.*, 2006). Most research programmes are focusing on increasing the diversity of products manufactured from biomass and they are pursuing strategies that either modify existing pulp and paper mills or develop green-field plants. Initially, much of the emphasis has been on the production of biofuels, as mentioned earlier. However, these are commodity products that have historically found it economically challenging to compete with petrol and diesel. In order to manufacture higher value products and more economically utilize the incoming biomass, a variety of biomaterials are undergoing commercial evaluation but, unfortunately, as the product's price increases, the market size tends to decrease (FPInnovations, 2011).

One product presently undergoing pilot-scale production trials is nanocrystalline cellulose. Very small cellulose fibres, termed nanocrystalline cellulose, have tensile, optical, electrical and chemical properties that differ from larger cellulose fibres (Hubbe *et al.*, 2008). Nanocrystalline cellulose has a strength-to-weight ratio eight times that of stainless steel and the potential to be a renewable, recyclable and abundant material with a wide range of applications. It may be used instead of petrochemicals in optically-reflective films, barrier films, high-durability varnishes, medical applications, innovative bioplastics, high-impact resistant glass and lightweight body armour. It is produced by taking a kraft pulp, which has had the lignin and hemicellulose present in the wood removed (see Chapter 4), grinding it in a mill, treating it with acid to remove impurities and then forming crystals of purified cellulose. Nanocrystalline cellulose has been forecast to form the basis of a US$600 billion industry by 2020 (Ferguson, 2012).

Lignin is a by-product of many biorefining processes and presently most of the lignin is burned to produce steam or electricity, both of which are relatively low-value commodity products. Several studies have investigated the production of higher value materials from the various forms of lignin that may be produced by biorefineries. Uses for lignin include phenolic resins, epoxies and adhesives. The aromatic nature of lignin enables it to be used as a replacement for phenolic adhesives. Trials have revealed that lignin may replace up to half the phenol in the phenol formaldehyde resin used as a glue in plywood manufacture and as much as 30% of the resin in other structural wood panels, with negligible changes in panel strength (FPInnovations, 2011). Lignin may also be used to substitute for polyolefins, which are used in plastics manufacture (Stewart, 2008). In addition, it may be used to replace fossil fuel-derived carbon black in rubber formulations, especially in vehicle tyres where it provides strength and durability. Importantly, lignin has been spun into carbon fibres, which are in demand by the aerospace and automotive industries because of their low weight (Kadla *et al*., 2002). Presently, most carbon fibre is manufactured from the petrochemical polyacrylonitrile and, although commercial production from lignin may be 5–10 years in the future, this is a very attractive potential new product for the forestry sector (FPInnovations, 2011).

In addition to utilizing cellulose and lignin, many studies have investigated the production of chemicals from linocellulosic biomass. A detailed review specified 12 key intermediate chemicals that could subsequently be converted into a wide variety of bio-based chemicals and materials. These 12 building-block chemicals were: three 1,4-diacids (succinic, fumaric and malic), 2,5-furan dicarboxylic acid, 3-hydroxy propionic acid, aspartic acid, glucaric acid, glutamic acid, itaconic acid, levulinic acid, 3-hydroxybutyrolactone, glycerol, sorbitol, and xylitol/arabinitol (Werpy and Petersen, 2004). Once commercial technologies are available for the production of these intermediate chemicals from biomass, then a diverse range of products required by modern societies could be manufactured and the economic performance of biorefineries could be enhanced.

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6 Forest Dynamics in the Tropics

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Tropical Deforestation: A Global Concern

A long history of deforestation exists in many parts of the world (Richards and Tucker, 1988). As discussed in Chapter 1, the loss of valuable forest resources had already become a matter of concern in Europe by the 18th century. In order to deal with this challenge, the science of forestry was created (Westoby, 1989). The early forestry practice focused not only on safeguarding and managing strategic timber resources, but also on the maintenance of protection forests in mountainous areas as a means of climate and water control.

The colonial forestry services transferred these ideas to tropical countries. For instance, at the end of the 19th century on the Indonesian island of Java, the establishment of mountain forest reserves was proposed as a strategic means for maintaining hydrological functions. This resulted in a policy that in West Java and East Java all forests above 1570 m and 1255 m respectively should be designated as watershed protection forests. To assure proper hydrological conditions, the deforested lands in these regions should be reforested again (Galudra and Sirait, 2009).

The concerns about deforestation as a major force of environmental degradation obtained a new urgency in the 1980s as result of the global environmental movements that emerged at that time (see Chapter 11). These global issues concerned the loss of tree resources for preventing erosion in mountainous regions as well as preventing desertification in arid regions and providing energy to poor people (Eckholm, 1975; Thompson, 1988). As a result of the UN Conference on Environment and Development in Rio de Janeiro in 1992, the need to control tropical deforestation became high on the global agenda of stimulating sustainable development. Tropical (rain)forests became symbols of the intrinsic values of nature and essential repositories of biodiversity. The loss of these forests through deforestation was not only regretted because of serious losses of biodiversity, but was also related to serious environmental deterioration, such as micro and meso climate change and disturbed hydrological cycles (see Chapter 3). Hence, controlling tropical deforestation became a major environmental challenge (Grainger, 1993; Critchley and Bruijnzeel, 1996).

In the early 21st century deforestation caused additional concerns because of its contribution to global climate change. Within the global discussions on the need of climate change mitigation and options for reduction of carbon dioxide emissions as a means to prevent global warming, much attention is given to the carbon sequestration potential of forests and the option of maintaining and increasing carbon storage in forests (see Chapter 8). The concerns on negative impacts of tropical deforestation were not limited to these environmental issues, but also included social issues (Sponsel *et al.*, 1996). It is estimated that 410 million people live in or near tropical forest areas, including 60 million indigenous people; these people depend on these forests for their livelihoods (see Chapter 10). Deforestation seriously threatens the culture of these people and often brings with it a loss of rights to their ancestral homelands.

How to Control Tropical Deforestation?

Due to the multi-faceted impacts of deforestation, this process arouses not only great concern but also considerable debate. The discussion is greatly influenced by a polarization between those who promote development and those who promote conservation as solutions to the problems of tropical deforestation.

Broadly speaking, those promoting development consider that overpopulation and poverty are the driving forces in tropical deforestation in developing countries. They note that tropical countries of today are in a similar situation to Europe in the 17th and 18th centuries and North America in the 18th and

19th centuries, when deforestation occurred to provide agricultural and grazing land to support a rapidly increasing population. They note that today these regions are no longer clearing forest for agriculture, that forest areas are stable or increasing, that standards of living have been raised and that population growth has decelerated. They argue that the way forward for developing nations is to follow the same path and that some deforestation is inevitable in order to achieve a stable agricultural land base. They recognize that people from developing countries resent the suggestion that they should deny themselves the very resources that the developed countries utilized in order to become developed. They do not believe that the developing countries should pay the cost of conserving their forests when the benefits of doing so accrue to the developed world. In summary, they argue that policies, programmes and incentives to promote development are the way to proceed.

On the other hand, those promoting conservation see conservation of the tropical forest as essential for maintaining the Earth's environmental stability. They believe that the consequences of clearing too much tropical forest would be catastrophic to global life support systems and that the fate of the planet is at stake. They argue that all biodiversity has an intrinsic right to exist and that humans are the guardians of that right. They reason that the extent of clearing is greatly contributing to global climate change and that biodiversity is being recklessly reduced. They argue that overpopulation and poverty are not the main drivers of tropical deforestation, but that inefficient use of already cleared land, inequitable distribution of land, unjust systems of land tenure and the disintegration of traditional agricultural systems are the main causes. They say that, in the long-term, the value of keeping the forests is greater than any alternative land uses. They argue that developed countries, power brokers in developing countries and multinational corporations are conspiring to ensure that the developed world can maintain its current levels of consumption at detrimental costs to both tropical forests and its inhabitants.

Regrettably the debate between these extremes has become somewhat entrenched. Clearly both have valid points, but neither can claim to own the whole truth. There are no generic off-the-shelf solutions and, as in most social issues, some compromise is necessary to achieve useful outcomes. It is exceedingly unlikely that the tropical forests will be conserved by persuading the developing countries that they have an obligation to do so, at least not until the bulk of the population of these countries are well-fed, well-clothed and well-housed.

In order to overcome the polarized opinions, the influential Brundtland report – *Our Common Future* (WCED, 1987) – suggested that rather than considering conservation and development as antipodes, attention should be given to their relationships with each other, and to consider options for combining conservation and development (Chapter 11). This requires a good understanding of the nature and scope of deforestation as well as its relation to the related concept of forest degradation. It also requires understanding, not only of processes and impacts of deforestation, but also of alternative types of forest dynamics in the form of forest enrichment and forest transitions. Considering deforestation as a component of a multi-faceted process of forest dynamics and looking at processes of degradation and aggravation helps to clarify the opposing opinions on solutions to deforestation. This helps to understand that there exist a variety of forest types transcending the dichotomy between natural 'wilderness' forests and cultural landscapes devoid of forests, as well as multiple trajectories of forest dynamics each having a specific relation to socio-economic development.

Basic Definitions

'Deforestation' is often used as a generic term referring to the long-term or permanent loss of forest cover and implies the conversion of forest to an alternative permanent non-forested land use such as agriculture, grazing or urban development. Such conversion does not only involve a loss of tree cover, but also results in the loss of ecosystem functions. Such loss in forest quality may not only take place because of deforestation, but also because of forest degradation. This process refers to the loss of one or more of the ecosystem functions of the forest even though an area remains forested. The boundary between deforestation and degradation is blurred. Both processes are almost always the result of human impact on the forests. The human activities can roughly be divided into five categories: selective removal of certain species, partial or complete removal of the vegetation, burning, introduction of other plant species, and introduction of animal species that alter the forest. These activities can be undertaken at various levels of intensity and in various combinations, depending on the type of land utilization and the period over which this utilization takes place. This variation in human impact complicates the reporting of forested, degraded and deforested areas. For example, fallow areas previously cleared by farmers using shifting cultivation practices may either be abandoned to revert to secondary forest or later reused again for agriculture. Harvesting trees for timber production (logging) is not deforestation unless the forest is degraded to such an extent that it is turned into grassland or shrub. Logging also does not necessarily lead to forest degradation, but it often does so in tropical forests. However, even deforested areas eventually may revert to forest, given enough time for ecological succession processes to take place. Logging and fuelwood gathering can also accompany deforestation for agriculture and grazing when the trees from clearing operations are utilized rather than burnt or discarded.

These examples demonstrate that the boundary between deforestation and forest degradation depends on the interpretation of what constitutes a forest. The international statistics of the FAO define a forest in a structural manner as 'a land spanning more than 0.5 ha with trees higher than 5 metres and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agriculture or urban use' (FAO, 2010, p. 209). In the FAO statistics a further distinction is made between primary forests, in which species composition and forest ecological processes have not been significantly disturbed by human activities (36% of global forest cover), naturally regenerated forests with selective logging and other forms of human use (57% of global forest cover), and plantation forests established primarily for timber production (7% of global forest cover).

Other definitions define forest as an ecosystem, e.g. by stating that forests are complex tree-dominated ecosystems with particular structural and abiotic components, assembled within temporal and spatial limits and with a self-sustained successional dynamic determined by its own biodiversity, including the determining anthropogenic interfaces. According to this interpretation a distinction should be made between forests and plantations. In the view of FAO, timber plantations are still characterized by major forest ecological processes. Although the ecological provisioning services of major forest products have been increased in such plantations (Chapter 9), most environmental regulation services, e.g. in respect of watershed functioning and micro-climate regulation, are maintained. In this view, the transfer of natural forests into plantation forest is therefore not considered as deforestation. But this interpretation is contested by some ecologists, who consider that the timber plantations have often lost so many ecological functions and/or biodiversity that they cannot be considered as representing forests as a natural ecosystem. The different interpretations of whether plantations should be classified as forests or not is further complicated because FAO does not consider tree plantations that provide non-timber commodities (e.g. oil palm, rubber) to be a forest. Several studies have indicated that there is no simple dichotomy between natural vegetation types used for collecting timber and non-timber forest products and artificial plantations used for cultivating commodities, but rather there is a gradual continuum in anthropogenically adapted forest types, including several types of agroforestry systems (see below). The decision whether the adapted tree-dominated vegetation types should be considered forests or agricultural systems is often based on convention rather than on strict ecological criteria. The interpretation of whether a tree-dominated land-use system is a forest or an agricultural system is often influenced by land ownership. If plantations or agroforestry systems occur on formally designated forest land managed by forestry authorities, they are often denoted as forest. But when they mainly occur on private farm land or on land of commercial estates, they are more likely to be denoted as agricultural systems.

A second complication in interpreting deforestation rates is the timescale considered. The removal of forests may be part of a longer-term cyclical process of forest dynamics. This is illustrated by the example that forests cleared by shifting cultivators are fallowed after some years of agricultural cropping and revert to secondary forest. Another illustration is the cutting of forests as a means to establish farms by colonizers. In order to survive, they initially grow annual crops. But after being established they may start growing tree crops with the result that after several years the farms include agroforestry plots or even mixed woodlots. Such land-use dynamics may not only occur at a local scale, but also at a regional scale. Both in Europe and the USA, historically a shift in land use from net deforestation to net reforestation has taken place. Such forest transitions have also occurred in some tropical countries. They may result from either natural succession on abandoned lands or from reforestation and afforestation. FAO defines reforestation as the planting of trees on temporary unstocked forest lands, and afforestation as the planting of trees on land that was not previously classified as forests, or through natural expansion of forests through natural succession on land that was previously under another land use.

Main Pathways in Forest Land-Use Dynamics

When concerns about tropical deforestation and forest degradation emerged, initially these processes were interpreted as one-way processes involving the loss of forests or forest ecological services. But alternatively the processes are increasingly interpreted as concerning dynamics in forest land use. In this view, the process of tropical deforestation can best be understood by considering it as a component in the process of land use dynamics rather than as a process of ecological deterioration. Within such a land-use perspective, forest dynamics can take several forms, ranging from forest demise to forest extension and from forest degradation to forest enrichment.

Tropical deforestation

According to the *Global Forest Resources Assessment 2010* (FAO, 2010) in the early 21st century annually around 13 million hectares of forests were converted to other uses or lost through natural causes. In the 1990s this rate was estimated at an annual loss of 16 million hectares, and hence the rate of deforestation shows signs of a decrease. Still, the rate of deforestation remained high. Moreover, there were important differences between continents and regions (Fig. 6.1). South America and Africa continued to lose forests, but in other regions such as Europe and Asia there was even an expansion. In countries such as Indonesia and Brazil deforestation is still common, but in other countries such as China and India forests are recovering (Table 6.1); in Brazil the rate of deforestation is decreasing (Box 6.1). The data on such trends need to be considered with caution, because there are several uncertainties about the trajectory

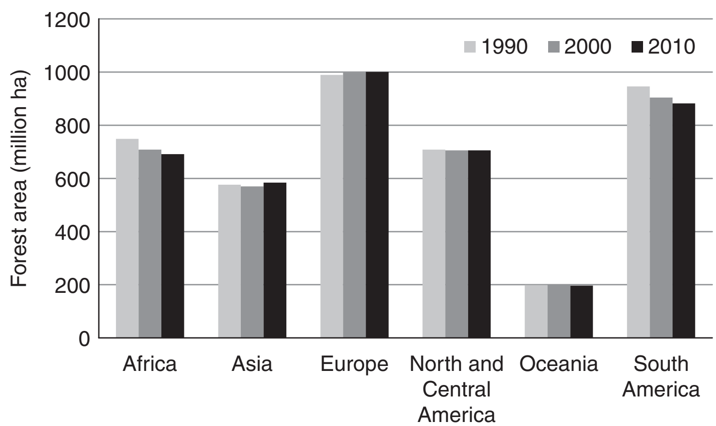

Fig. 6.1. Major regional trends in forest area. (From FAO, 2010.)

Table 6.1. Annual forest change in countries of Africa, Asia and South America with worst deforestation and main forest extension over the period 1990–2010. (Source: FAO, 2010.)

Net forest loss (million ha/20 year and % forest cover/20 year)		Net forest increase (million ha/20 year and % forest cover/20 year)	
Brazil	55,317 (10%)	China	49,720 (32%)
Indonesia	24,113 (20%)	India	4495 (7%)
Nigeria	8193 (48%)	Vietnam	4434 (47%)
Tanzania	8067 (19%)	Chile	968 (6%)
Myanmar	7445 (19%)		
Zimbabwe	6540 (29%)		
Sudan	6432 (8%)		
Democratic Republic of the Congo	6228 (4%)		
Venezuela	5751 (11%)		
Bolivia	5599 (9%)		

Box 6.1. Forest dynamics in the Brazilian Amazon

The Amazon basin in Brazil is often referred to as an example of the disastrous impacts of tropical deforestation. At the end of the 20th century, this region became popularly considered as the greatest wilderness area on Earth, where tropical rainforests are still undisturbed by human activities. Books such as *Amazonia: Man and Culture in a Counterfeit Paradise* by Meggers (1971) contributed to the image that the forests formed a green blanket that protected a 'humid desert' of poor leached soils and inhospitable climate. In this representation the area was never densely populated due to the inhospitable environmental conditions, and the disappearance of the forests would result in ecological disaster, including the loss of the historically evolved biodiversity. But the Brazilian government had a contrasting image of the region. They considered the Amazon forests as unopened-up lands with great promise for development and made the conscious decision to colonize the Brazilian Amazon. They did so by constructing highways and railroads, by encouraging transmigration into the area and by providing subsidies for large-scale agro-pastoral activities, mainly cattle ranching. These subsidies were in the form of grants, tax holidays, subsidized credits, exemption from import taxes and land concessions. The government was successful in meeting its development objective, but at the expense of 15% of the Brazilian Amazonian rainforest being cleared by 1995 and still continuing (Table 6.1). The programme came under intensive criticism for its ecological as well as social consequences (e.g. Downing *et al*., 1992; Anderson *et al*., 2002). Forest fire was a major tool for reclaiming forests, and the images of large areas of burning forests fuelled concerns of ecological disaster. These concerns were highlighted at the 1992 UN Conference of Environment and Development that was organized in Rio de Janeiro. The international concerns and increased understanding of the environmental services provided by the Amazon forests resulted in many initiatives to conserve the Amazon forests by innovative conservation schemes and in new Brazilian policies that were more conservation- than just development-oriented. As a consequence, at the beginning of the 21st century the views on the Amazonian forest dynamics have changed. There were increasing signs that a gradual change from eco-catastrophe to reduced deforestation is occurring (Hecht, 2011). Although there still remain concerns on Amazon deforestation, since 2004 the Brazilian rate of deforestation has declined by more than 70%, from over 25,000 km^2/year to around 7000 km^2/year. These developments were hugely impacted by the growing understanding that deforestation cannot be stopped by protecting forests in set aside conservation areas, but rather should be reversed by stimulating a matrix of forested landscapes, including development and sustainable use of agroforestry systems and adapted forests. At present over 40% of the Brazilian Amazon is subject to some form of protection, of which 60% are managed by local populations. These are not simple set-aside areas, but rather areas in which sustainable use and development activities are allowed. In addition, several commercial firms started to behave in a more ecologically and socially conscious manner and new forms of green marketing of forest products and various types of payments for the forest environmental services are developing. These developments are not just the result of government policies, but also of new social movements striving for human rights and environmental justice, and of formation of new alliances and partnerships between the governmental, civil society and market organizations (Hecht, 2011).

The new types of conservation areas were stimulated by new scientific understandings of the nature and scope of human-adapted forests. During the late 20th century, several studies challenged the popular notion of the pristine nature of the Amazon landscape and identified a long historical process of co-evolution between ecological and human conditions. The notion of the Amazon as an area where only scattered tribal people mainly living from hunting and gathering could survive was proven to be false. Archaeological research indicated that, before the conquest of the Amazon by European colonists, several complex societies existed whose population density was much higher than at present. The diseases brought by the European colonists in combination with slavery and warfare resulted in a huge decline of the original population. They had greatly altered the forest vegetation into a domesticated landscape. They did not have iron (this was only later imported by the colonial conquerors) and the cutting of forests with stone axes was very time-consuming. Consequently, they did not open-up large tracts of for cultivation, but rather developed an arboricultural landscape around their settlements by altering the configurations and species composition of the forests. Hence, the Amazon biodiversity is not just an ecological heritage from pristine forests, but rather results from a complex historical process of co-evolution between human society and forest vegetation (Heckenberger *et al*., 2007; Clement and Junquiera, 2010). The biodiversity is impacted by traditional knowledge and practices on both use of forest products as well as on managing tree species for human use. The recognition of the relevance of such traditional knowledge–practice systems on maintaining a forest cover greatly stimulated the development of indigenous reserves and protection areas permitting sustainable use.

of forest cover change (Grainger, 2010). These are partly caused by the difficulty discussed above in how to define a forest. It is also complicated by the difficulty of monitoring forest cover change in areas where both deforestation and reforestation are co-occurring. For instance, the FAO estimated in 2005 global deforestation as a net change in forest area, but further refined the estimates in 2010 by also considering afforestation and natural expansion of forests. As a result, the original estimates on global rate of deforestation in the period 1990–2000 were revised from 13 million hectares per year to almost 16 million hectares per year.

Forest degradation

Similar to deforestation, the process of forest degradation is also anything but straightforward. In its most elementary sense, 'degradation' refers to a reduction to a lower rank. It implies a human scaling of a certain phenomenon. Degradation may be related to the loss of ecosystem structure and composition (e.g. loss of biodiversity), or to the loss of ecological services in the form of provisioning, regulatory or supporting functions. Both the degradation of provisioning services (e.g. loss of useful species) and regulatory services (e.g. decreased soil and water conservation features) lead to a loss of production capacity. Degradation thus concerns a human-induced decrease in both ecosystem quality and production potential. The term is often used in relation to specific forest functions, e.g. in relation to harbouring biodiversity and wildlife, production of timber or (subsistence) products for local people, protection of watersheds, or sequestration of carbon. In each of these cases there are specific notions regarding the benchmark for ranking the human influence and the manifestations of a good forest and a degraded forest (Table 6.2).

Forest enrichment

Depending on the kind of activities, human impact on forests and tree resources may be either positive or negative. From an ecological conservation perspective, attention is mostly focused on negative human impacts resulting in degradation in the form of loss of biodiversity and ecosystem services. This negative human impact is related to human overexploitation and to decreased production potential. This notion is reflected in many discussions on forest dynamics that emphasize processes of deforestation and forest degradation. They take the natural pristine forest as a benchmark and consider that most human activities (other than conscious

Table 6.2. Different types of degraded forests. (Modified after Lele and Kurien, 2011.)

Main forest function considered	Hallmark for good forest	Manifestation of good forests	Manifestation of degraded forest
Harbouring biodiversity and wildlife	Natural, pristine, vegetation	Mainly old-growth vegetation or successional vegetation types resulting from natural causes	Any 'non-wilderness' forest type
Timber production	Stand of trees that maximizes timber production and fulfils requirements of sustained yield	Both natural forests and mixed or single species plantations managed either by selective felling or clear felling	Conversion to any non-timber land use
Production of (subsistence) products for local people	Multi-species vegetation complex providing mix of locally useful forest products, including non-timber forest products	Different forms of forest ranging from natural forests to forest and mixed-tree gardening systems often harvested by non-destructive techniques	Any vegetation that reduces the particular mix of local forest products
Watershed protection	A stand of trees protecting forest soil and hydrological functioning	A stand of trees with good canopy and soil cover	An opened-up forest with exposed soils
Carbon sequestration	A stand of trees with high rate of carbon sequestration	Any dense tree vegetation that will not be cut or burned down	Any vegetation with lower carbon content than maximum possible at the site

conservation practices) are detrimental to forests. Alternatively, from a socio-economic development perspective, in human impact assessments attention is also given to human agency in enriching natural resources through a process of domestication. In this perspective, the production of resources rather than pristine forests is taken as a benchmark for evaluating forest dynamics. Forest-based human activities do not necessarily result in a loss of production potential; they may also increase the biological production potential of forest resources. The ecologically oriented focus on deforestation and degradation has in several cases obstructed the recognition of such local practices of adjusting forests to the local needs and even extending them (Fairhead and Leach, 1998). In the beginning of the 21st century increasing attention was given the multifaceted nature of forest dynamics and the interactions between the processes of degradation because of human exploitation and resource enrichment through human creativity in stimulating the production capacity of valuable forest resources. The recognition of the multiple dimensions of biocultural relations helps in identifying trade-offs between ecological conservation and human development (Lamb *et al.*, 2005).

The adjustments of forests to better suit the needs of local people results in the creation of domestic forests (Michon *et al.*, 2007). As a result of bringing the forest into the domestic domain, the natural forests are changed into an anthropogenically adapted forest with an enhanced production capacity for biological objects valued by people. Four main phases may be distinguished in this process, each characterized by a specific intensity of management (Wiersum, 1997):

1. Controlled procurement of products from natural forests: essentially social controls on access and harvesting intensity.
2. Conscious management of useful trees through protection of productive trees, stimulation of production capacity by tree tending activities (e.g. coppicing, removal of competing trees) and protection or stimulation of regeneration.
3. Cultivation of selected wild trees in plantations.
4. Cultivation of genetically selected or improved tree crops in intensively managed plantations.

An example of these different phases in adjusting forests to human needs is given in Table 6.3. As demonstrated by this example, the intermediate

Table 6.3. Ecological and management characteristics of different coffee production systems in south-west Ethiopia ranging from natural forests to coffee plantations. (After Wiersum, 2010.)

	Forest coffee system	Semi-forest coffee system	Garden coffee system	Coffee plantation system
(Agro)ecosystem characteristic	Natural vegetation Original forest structure and composition	Adapted natural vegetation Modified forest structure Stimulation of coffee plants	Transformed forest structure Polyculture of planted crops with maintained wild species	Monoculture (with shade trees)
Dominant management practices in respect to harvesting control and stimulation of production	Social control on coffee extraction	Manipulation of tree vegetation for shade management and decreased competition Transplanting coffee wildlings	Artificial regeneration of valuable species Agronomic cultivation practices	Intensive cultivation Use of external inputs (fertilizers, pesticides)
Methods of coffee regeneration	Unassisted natural regeneration	Protection of natural regeneration Purposeful spacing of wild seedlings	Protection of natural regeneration Transplanting of wild seedlings or nursery-raised seedlings	Use of nursery-raised seedlings of selected cultivars
Genetic composition	Wild genotypes	Wild genotypes Landraces	Landraces Cultivars	Cultivars
Average annual yields	About 50 kg/ha	100–300 kg/ha	400–500 kg/ha	Over 750 kg/ha

phases of tree domestication involve an adaptation of the natural vegetation through enrichment by valuable tree species. This may not only involve enrichment by timber trees as a forestry practice, but also incorporation of fruit trees or cash crop trees as an activity by local people. As a result of such local practices, natural forests may gradually be transformed in forest gardens or other multistorey tree cropping systems. In contrast to the domestication of agricultural crops, the intermediate phases of domestication of tree crops do not result in degradation in the sense of a loss of ecological integrity and functioning of the natural forest vegetation. Rather, they increase the ecological provisioning services, but, if well-managed, do not impair regulatory functions such as watershed protection and carbon sequestration. Although biodiversity may still be maintained in the early phases of the domesticated forests, during the later phases biodiversity and wildlife are impoverished, especially when selected cultivars are grown in monoculture plantations. As an alternative, it has been suggested that new types of domesticated forests should be considered in the form of a 'back-to-nature' or 'natural products' type of cultivated forests managed by eco-friendly management practices, including use of new types of cultivars adjusted to more natural forest conditions (Michon *et al.*, 2007).

The examples of enriched forests demonstrate that the process of forest dynamics can be interpreted in two different ways. In an ecological sense, it can be interpreted as concerning a change of forests as an ecological system in the form of either a succession from a pioneer vegetation to an old growth vegetation or as a decline of ecological stature as a result of loss of species composition and structure. But the dynamics can also be interpreted as concerning integrated socio-ecological systems and involving co-evolutionary pathways involving biological, ecological and social processes. As indicated above, the present concerns about environmentally friendly and socially responsible sustainable development may offer scope for developing new kinds of forests adapted to human needs. But this notion is criticized by other researchers, who point out that several of the historically developed anthropogenic forests are gradually losing their biodiversity or are even replaced by commercial tree-crop plantations (Belcher *et al.*, 2005; Scales and Marsden, 2008). The causes for the loss of their ecological stature are often similar to factors causing deforestation and degradation of natural forests (see below).

Forest transitions

As illustrated by the examples that local farmers may not only overexploit and remove forests, but that they may also domesticate forest and enrich them with valuable species, in the early 21st century the grand theories on deforestation and forest degradation have gradually been replaced by the understanding of the variety of location-specific forest–people interactions and related forest dynamics. This is also demonstrated by the increased attention on forest transitions (Palo and Vahanen, 2000; Meyfroidt and Lambin, 2011). Forest transitions refer to a structural reversal in forest land conditions involving a change from net deforestation to net reforestation. Although the data on long-term trends in forest area are often still rather uncertain (Grainger, 2010), in several countries forest transitions have been observed. They have historically taken place in several European countries and in North America, where they were often related to a change in economy from agriculture to industrialization decreasing land pressure. More recently, they have also been observed in several less industrialized countries, such as China, India and Vietnam (Table 6.1).

Forest transitions involve two different types of forest dynamics, i.e. natural forest regrowth and establishment of tree plantations. The monitoring of forest recovery is beset by difficulties, due to both definitional problems of what forests are (see above) and technical problems in delineating different areas of natural regrowth and different types of forest and tree-crop plantations. Consequently, estimates vary, especially on natural forest regrowth (Meyfroidt and Lambin, 2011). FAO estimates that the global rates of gross natural regrowth in the period 1990–2000 and 2000–2010 were 4.0 and 2.9 Mha/year respectively, and the global rates of increase in plantation forests were 4.3 and 4.9 Mha/year respectively.

The ecological impacts of such transformations are subject to debate. People who take natural pristine forests as the benchmark of good forests consider that these new forests, especially commercial forest plantations of exotic tree species, cannot replace the biodiversity of old-growth forests. But people who have a different benchmark for judging forests (Table 6.2) may be more positive. Rather than just valuing forests for biodiversity conservation, they value forests for providing essential goods and environmental services (e.g. in the form of watershed protection) for human needs. They also often point out that many forest plantations do not consist of monocultures of exotic trees but of mixed indigenous species, and that biodiversity in plantations often increases with age due to natural succession (Lamb *et al.*, 2005; Lemenih and Bongers, 2010). Moreover, they argue that high productive plantations may take exploitation pressure away from natural forests. These contrasting opinions reflect the different stances regarding how to solve the problems of tropical deforestation discussed above.

Forest Dynamics as a Process of Co-evolution in Social and Ecological Conditions

As demonstrated by the emergence of the new scientific notions of domesticated forests and forest transitions, during the past decade many of the original ideas on forest dynamics were found to be lacking and new ideas were developed. The notion that deforestation should not be considered as a one-way process of environmental degradation, but rather as a specific manifestation of a process of socio-ecological dynamics is a common denominator in these new notions (Hecht *et al.*, 2010). This has brought with it a new understanding of the history of tropical forests dynamics. These new understandings are well illustrated by the changing views on forest dynamics in the Amazon (Box 6.1).

This changing understanding on forest dynamics in the Brazilian Amazon demonstrates the importance of not combatting deforestation with strict conservation policies and practices aimed at conservation of pristine forests, but rather with stimulating conservation and sustainable use of forested landscapes including a mix of natural and domesticated forests. This requires new forms of socialization of forests with attention to solving the underlying causes of deforestation rather than just the control of the direct causes. It also requires dealing with processes of socio-ecological dynamics that are location-specific and may result in different types of forest landscapes. Depending on their specific nature, four categories of forest lands may be distinguished, representing different types of forest–people interactions and different types of forest dynamics (Chomitz, 2007):

Frontier areas: Areas subject to deforestation as a result of a high pressure on forests for agricultural expansion. The interactions between forest and people are contentious, with forest and land ownership often being insecure or even conflicting. This results in different forms of land grabbing by either commercial enterprises or landless people, and lack of attention to long-term sustainability of forest land use. This results in rampant deforestation.

Areas beyond the agricultural frontier: Two different types of such areas may be distinguished, i.e. remote areas with natural forests inhabited mainly by few and indigenous people, which are under low pressure due to poor infrastructure limiting exploitation of natural resources, or remote rural areas with outmigration and depopulation. In the first case, the areas are beyond an expanding agricultural frontier, and in the second case beyond a retracting agricultural frontier. The first areas offer good options for natural forest conservation, provided that the traditional interactions between forest and indigenous people are maintained. This requires the recognition of their land-use rights and resource-use practices. The second category of areas is related to a significant shift in forest–people relations. These areas provide good options for forest transitions in the form of either plantation development or natural succession on abandoned agricultural lands.

Forest–agricultural mosaic lands: In these areas with a relatively high population density and good accessibility to markets, land ownership is relatively well defined. The land values are relatively high and farmers manage the mosaic lands for combined production of agricultural and tree crops. Small remnants of natural forests may be maintained (e.g. on steep slopes) for environmental purposes, but most of the remaining forests consist of different types of forest and tree plantations. In these areas a balance in forest–people interactions has developed, with forests playing an important role in combined production of agricultural and tree crops, local environmental stability and landscape identity.

Driving Forces

Causes of deforestation

The causes of deforestation are often complex. As mentioned earlier, they are often related to overpopulation and poverty. But in several temperate countries during the last century, in spite of population growth, forests have recovered. This indicates that the relations between social and demographic conditions and forest dynamics cannot be simply attributed to population growth. They are primarily related to different types of human activities. Since the 1990s, it has been hotly debated whether deforestation involves unsustainable practices of small farmers, land grabbing practices by commercial enterprises or government policies of opening up forest lands by roads and/or stimulating transmigration of people from disadvantaged areas to the 'empty' forest lands. Gradually, these debates became better informed by the results of studies that assessed the various causes of deforestation. These may be distinguished as direct causes and underlying causes (Table 6.4). The direct causes are related to activities of the people who are actually doing the deforesting; they concern local practices of individual farmers or households, local communities or commercial enterprises. The activities of the agents of deforestation are based on their decision-making processes that are influenced by several factors at the local, regional or national level. The local actors of deforestation often can not influence these factors and often respond in a rational manner to external forces that compel them to do so. For instance, due to a lack of access to agricultural technology, they engage in shifting cultivation techniques, even though, as a result of population growth, fallow periods become too short to sustain such practices. Alternatively, landless people from disadvantaged rural areas may consider forests as promising new lands for farming and hence migrate to newly opened-up forest areas. They may do so on their own accord or participate in governmental transmigration programmes. However, deforestation may also be caused by commercial enterprises, which may or may not be environmentally responsible, and sometimes act in a corrupt business environment. A famous example of international commercial interests resulting in deforestation is the so-called hamburger connection: the demand for hamburgers in the USA caused the extension of large cattle-grazing complexes in the Amazon. Other often mentioned culprits are irresponsible logging firms, who without regard to legal requirements and sustainable practices reap forests for valuable timber.

Such direct agents and activities are sometimes relatively easy to identify, but they may also be intertwined. For example, in the second half of the 20th century, the Brazilian government stimulated transmigration of disadvantaged farmers from the dry north-eastern part of Brazil to the Amazon, where the agricultural potential was considered as being higher. If people could prove that they had improved the land by cutting forests and establishing agricultural cultivation, they could get formal title to the opened-up forest land. Commercial enterprises made use of these legal provisions by enticing poor people to open up forests under these regulations and then to sell their land rights to the

Table 6.4. Causes of forest decline. (After Geist and Lambin, 2002.)

Direct causes		Underlying causes	
Agricultural expansion	Shifting cultivation Permanent cultivation Cattle ranching Colonization	Demographic factors	Population growth Migration and colonization
Infrastructure extension	Roads and railroads Markets Settlements Mining, reservoirs	Economic factors	Poverty Inequitable land and resource distribution Commercialization
Impact of resource scarcity on intensity of forest product extraction	Commercial timber Fuelwood and charcoal	Technological factors	Agrotechnical change Change in forest exploitation techniques (e.g. use of chainsaws)
Pre-disposing environmental factors	Fires Unfavourable climate and weather conditions Forest fragmentation	Policy and institutional factors	Rural development policies Fiscal policies Forest property rights and regulations Policy climate: corruption
		Cultural factors	Forest frontier mentality Undervaluing the forest

firms, and next to move to another forest plot where the scheme was repeated. Thus, although the direct cause of deforestation was rural poverty and the government policy of colonization to solve this problem, the advancing frontier process was highly impacted by a complex system of forest property rights and regulations, socio-political relations between different actor groups and unequal power relations. Such indirect causes, which drive the actions of these actors, are often more difficult to identify. Different people do not only interpret the relative importance of various direct causes of deforestation in contrasting ways, but also their relation to underlying causes.

The different opinions on causes of deforestation are closely related to opinions on how to control them. This is illustrated by two main types of causes that have been hotly debated as to their importance: agricultural expansion and forest exploitation. In the first case, the causes for deforestation are related to activities outside the forest sector, but in the second case, they are related to forestry practices. The juxtapositioning of these two causes illustrates quite different opinions on how to deal with deforestation. In the first case, deforestation is related to actors outside the forestry sector and stresses underlying socio-economic and political factors that prevent foresters from protecting forests against other interests and adequately maintaining and managing the forests for their multipurpose functions. It is argued that stopping deforestation requires policy and development actions that properly value forests and that safeguard them against agricultural expansion and corrupt practices in handing out land-use permits. The control of deforestation is primarily interpreted as involving a rural development approach that takes human pressure away from the forests. In the second case, deforestation is related to a loss in ecological status of the forests as a result of opening up of forests for human use. It is argued that even in case of environmentally sound forest exploitation techniques, the required transport infrastructure results in the attraction of migrant farmers or land speculators. Hence, deforestation is related to an improper way of managing the forests. The stopping of deforestation requires not only alternative techniques for using forests in a less-damaging way, but also other forms of organization that are primarily conservation rather than timber production-oriented. Obviously, the stemming of deforestation requires actions both inside and outside forests.

Forest transition pathways

The increased understanding that deforestation is not the only pathway of regional forest dynamics, and that in several areas has been replaced by a process of forest transition, has added new insights into the forces driving forest dynamics. Forest transitions involve three main pathways (Lambin and Meyfroidt, 2010): a stabilization of the deforestation process through the incorporation of forest remnants in a mixed land-use system, reforestation as a means to counter depletion of major forest resources or decline of essential forest regulatory services, or natural forest succession on abandoned agricultural lands.

Stabilization of deforestation by incorporation of forests in mosaic landscapes

Many studies on deforestation only focus on the disappearance of forests, but give little attention to the landscape that is developed. It is often suggested that deforestation concerns a linear process of changing forest into agricultural or grazing lands or commercial tree-crop plantations. However, in most deforestation studies relatively little attention is given to what kind of actual land-use change is involved, and whether or not the new land-use systems include new types of tree-based or even forest-analogue vegetation. For instance, studies on deforestation in forest margins by smallholder farmers often focus only on agricultural cultivation. None the less, several studies illustrate that the farming systems of smallholder farmers at the forest fringe often include multiple practices and a gradual expansion of tree gardening systems and woodlots. The initial income derived from logging practices may be used for investing in perennial agroforestry cultivation (e.g. Fujisaka and Wollenberg, 1991). The reason for smallholders to combine crop cultivation with tree-based production systems is to diversify their farming system and thus to decrease their vulnerability to ecological hazards (e.g. droughts or erosion in mountainous areas) and economic shocks (e.g. price fluctuations of single commodity crops). The 'domesticated' farm forests (Michon *et al.*, 2007) involve intensive management of high-value tree resources; it requires relatively high inputs of labour as well as proper knowledge on the value of biodiversity for local use and marketing. The gradual transfer of forests into forest landscape mosaics may also include the conservation of natural forests, e.g. on steep slopes where they protect farm lands against avalanches and mud slides, or as cultural heritage sites such as sacred forests. This type of forest transition is primarily caused by local development of farming systems. In many forest statistics, the decrease in the original forest cover is recorded, but the subsequent increase in tree cover is not reported because it is considered as a form of agriculture land use.

Reforestation as a means to improve forest ecosystem functioning

As a result of deforestation, in several countries governments are concerned about the scarcity of forest products and the loss of forest environmental services. Such scarcity may manifest itself through high prices for (strategic) forest products, increasing landslides on steep slopes and more frequent and higher flood damages in lower watersheds. It can also result in greater public demands for recreational areas and rehabilitation of degraded sites. In response to such manifestations of forest scarcity, in several countries major efforts have been undertaken to stimulate reforestation. As discussed above, in China these efforts contributed to a forest transition. Sometimes these plantations are criticised because of the limited number of, sometimes exotic, species used. But others argue that the plantations assist in creating improved ecological conditions on degraded sites, stimulating natural succession and providing good scope for active ecosystem restoration (Lamb *et al.*, 2005; Lemenih and Bongers, 2010).

Forest succession on abandoned farm lands

In several countries economic development has resulted in a growing importance of the secondary (industrial) sector and the tertiary (services) sector in comparison to the primary (agricultural) sector. The development of a modern economic sector increases urban wages, making it attractive for poor rural farmers to change their jobs. This creation of off-farm job opportunities has in several marginal rural areas resulted in massive migration of farmers to urbanized areas and the countryside becoming depopulated. On the abandoned agricultural fields, a new forest succession could take place.

These different pathways are driven by two fundamental forces: (1) negative socio-ecological feedbacks that result from the desire to counter the decline of essential forest resources by a reversal in land-use conditions and (2) socio-economic dynamics that are not a direct result of forest dynamics but that none the less result in a forest recovery (Lambin and Meyfroidt, 2010). The socio-ecological feedbacks include measures to overcome either scarcity in essential forest resources limiting socio-economic growth or scarcity of land. These feedbacks may result in stabilization of forest frontiers and creation of forest mosaic lands or in reforestation of marginal farmlands. The formation of forest mosaic lands illustrates how the need for forest products and services within smallholder farming systems may stimulate farmers to intensify their land use and incorporate forest-analogue systems in their farming systems. Alternatively, erosion and disturbed hydrological functioning in watersheds may result in government schemes for watershed reforestation as a means to overcome the negative impacts of scarcity in protection forests. Or timber companies may establish new tree plantations as a means to promote more efficient production of scarce timber resources. In all cases it concerns endogenous changes within the localities or regions that are confronted by the negative repercussions of deforestation.

The socio-economic dynamics often concern exogenous changes that originate from outside the affected area. For instance, economic modernization in tropical countries often involves a growth in urbanization and rural–urban migration. Especially in the case of marginal lands, this may result in abandoned farm lands, where natural forest succession can take place. Other socio-economic dynamics may involve political changes in respect to land ownership. Both local people and forestry enterprises are only willing to invest in reforestation where it is clear they have secure land rights and that profits of forestry investments are secured over the medium to long-term of tree production cycles. The socio-economic dynamics may also involve changes in global trade in forest products. For instance, policies from timber-importing countries for only importing legally produced and/or sustainably managed timber may result in more trust in tropical forest products by western consumers and higher prices for the environmentally friendly products. This may stimulate further investments in forest management and reforestation. Another promising trade innovation consists of new schemes for payments of environmental services, e.g. within the framework of climate policies (see Chapter 8). Rich countries where economic modernization has taken place are increasingly willing to pay for the provision of global environmental services and invest in forest conservation and extension in poor countries that would otherwise lack the financial resources to invest in these activities. These new programmes counter the undervaluation of forests, which has often resulted in deforestation, and bring with it new opportunities for forest owners to obtain an income from forests; this stimulates investments in forestry.

Policies that Enhance Forest Conservation and Extension

The understanding of not only which factors cause deforestation, but also which factors contribute towards forest transitions has significantly increased recognition of what measures can stimulate a decrease in deforestation and assist in a further extension of forests. Originally it was thought that by assessing which factors caused deforestation, it would be possible to identify how these driving forces could be controlled. This line of thought assisted in the identification of various ways in which to control the direct causes of deforestation, e.g. by increased demarcation of forest reserves as a means to control agricultural expansion, stricter forms of fire control, better planning of infrastructure development and stimulation of more sustainable forms of forest exploitation. It proved much more difficult to control the underlying causes, which are mostly located outside the forest sector and could not be directly addressed in forest policies. The increased insights of the different pathways to actual forest recovery and the factors involved provided better understanding of the various location-specific processes of forest stabilization and extension and the processes involved. They also resulted in the identification of a greater variety in potential forest types and configurations than previously considered. These developments contributed towards increased understanding that forests should not just be conceived of as ecological systems, but rather as essentially socio-ecological systems. Forest products and services are an expression of human values, and the multiple types of human cultures and organization are reflected in quite diverse ways in which forests are used and managed, often as a component of local livelihood systems. Hence, forest conservation policies should be based on the notion of social forests rather than on the notion of set-aside conservation areas (Hecht, 2011). Policies to control deforestation and enhance forest conservation and extension should take the complex interactions between people and forests into account and acknowledge that location-specific forces drive deforestation and forest transitions. These forces are often located outside the forest sector and concern practices of external people rather than forest-related people. The studies on forest transitions also indicate that it is essential that forests have a locally accepted 'boss' who is able to balance the various demands on the forest. Due to the ongoing process of socio-economic change, the development of clear and socially acceptable rights and responsibilities in managing forest for multiple benefits not only requires improved forest technology, but also institutional changes and innovation. It requires the linking of global concerns to location-specific processes, and joint efforts of professional foresters conscious of global and national concerns and interests, and other stakeholder groups such as local people, civil society organizations and market enterprises (Chapter 11). The policies should not only focus on improving multiple use and multi-actor forest management, but also on increasing the value of forests in order to make forests more competitive with other forms of land use.

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7 Sustainable Forest Management

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Introduction

'Science-based' forestry has been practised in a formal sense for 300 years and throughout much of this time it has been considered by foresters to be sustainable. Yet some of these early forests consisted of trees planted well outside their normal range, often as single species, even-aged monocultures. They were managed according to the principle of sustained yield, with the value of interest being the production of timber. Almost everything else was considered to be a constraint on production and was treated accordingly. Techniques such as fertilization were widespread, with the need for fertilization not being seen as inconsistent with sustained yield. Pests were managed vigorously, and production was maintained by removing any trees infected by disease or damaged by biotic or abiotic agents.

In the mid-20th century, a remarkable change in approach occurred, and a range of forest values began to be recognized. Forests began to be seen as places where multiple values could be maintained, although many would argue that it is not possible for every forest stand to satisfy every need. The principle that all forest stands should be able to meet all needs is however still maintained in some parts of the world, such as the state of Baden-Wurttemberg in southern Germany. In most places, it has been recognized that while all values may be maintained within a forest, only some values can be maintained at the stand level, resulting in the frequent adoption of landscape approaches to forest management (e.g. Dudley *et al.*, 2006). This has led to difficulties: critics of forestry often point to the unappealing appearance of a fresh clearcut and argue that this is inconsistent with sustainability. The controversy over the management of publicly owned natural forests has been particularly notable in the Pacific Northwest of the USA (Rajala, 1998), Australia (Ferguson, 1996) and New Zealand (Norton, 2003), and the concept of sustainable forest management has in part emerged because of this debate. In such situations, it is important not to equate all forms of forestry to the logging of natural forests, although it remains one of the more controversial aspects of forestry. Similarly, plantation forestry should not be considered representative of forestry as a whole. Generally, there is an ongoing movement towards a more ecological approach to all forms of forestry (Lindenmayer and Franklin, 2003; Angelstam *et al.*, 2005), tempered by the need to ensure that the livelihoods of forest-dependent peoples are maintained.

With growing interest in sustainability and sustainable development, there has been increasing interest in the concept of sustainable forest management. At the United Nations Conference on Environment and Development, held in Rio de Janeiro in 1992, an attempt to develop a global convention on forests failed, but a major output from the Conference was a non-legally binding statement of principles for the management, conservation and sustainable development of forests. This outlined what was considered to be sustainable forest management at the time, and led to the definition of sustainable forest management that the Ministerial Conference for the Protection of Forests in Europe, the Food and Agriculture Organization of the United Nations (FAO) and others have adopted, namely:

> The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems.
>
> (MCPFE, 2003)

The FAO has acknowledged that sustainable forest management has been defined in many different ways since then, and to a certain extent, the value of the term has been lost. This has led some to call for a new term, the sustainable management of forests, but this seems unnecessary. Instead, the FAO (2012) argues that sustainable forest management is characterized by seven key thematic elements:

1. Extent of forest resources;
2. Biological diversity;
3. Forest health and vitality;
4. Productive functions of forest resources;
5. Protective functions of forest resources;
6. Socio-economic functions; and
7. Legal, policy and institutional framework.

These seven themes have been used repeatedly in international and national agreements about sustainable forest management, and are recognized by international policy fora such as the United Nations Forum on Forests and the FAO Committee on Forestry. Given their widespread use, it is important to understand how each relates to the concept of sustainable forest management but, at the same time, it must be remembered that ensuring the integrity of one or two of the components is insufficient: all need to be satisfied to truly meet the requirements of sustainable forest management.

Their recognition is important since the need for sustainable forest management is recognized internationally. In 2008, the United Nations General Assembly (UNGA) approved four global objectives for forests and these have been reaffirmed by Member States in UNGA resolution 62/419 (UNGA, 2008):

1. Reverse the loss of forest cover worldwide through sustainable forest management, including protection, restoration, afforestation and reforestation, and increase efforts to prevent forest degradation;
2. Enhance forest-based economic, social and environmental benefits, including by improving the livelihoods of forest-dependent people;
3. Increase significantly the area of protected forests worldwide and other areas of sustainably managed forests, as well as the proportion of forest products from sustainably managed forests; and
4. Reverse the decline in official development assistance for sustainable forest management and mobilize significantly increased, new and additional financial resources from all sources for the implementation of sustainable forest management.

The frequent references to sustainable forest management well illustrate the importance that is still being given to the concept within the global forest policy community.

Criteria and Indicators

The thematic elements listed above have been translated into many different sets of criteria and indicators (Grayson and Maynard, 1997). Criteria represent the overall values that society wishes to obtain from forests, such as the maintenance of biological diversity or the conservation of soils and water. They differ between regions, but are broadly similar. For example, the maintenance of biological diversity is recognized as a criterion of sustainable forest management in most regional agreements, frequently being the first listed.

Indicators are intended to be measures by which progress towards a particular criterion is measured. Two problems have arisen with such indicators. First, they have very little meaning unless a target value is specified, but the science underlying such targets is largely inadequate. Very often, it is suggested that the target should be to keep indicators within the range of natural or historic variation. This assumes that such variation is known, but the manner in which extreme events are dealt with is largely unsatisfactory. Such targets also fail to take into account climate change, which may be shifting the entire range of variation (such as the extent and severity of forest fires). Targets also bring together science and politics, although this should be seen as an opportunity rather than as a problem. Some targets defined strictly on scientific principles may be impossible socially, culturally or economically, and a key part of sustainable forest management is to identify what is practical given the constraints that a manager may be under. This is why public participation is so important in sustainable forest management: there is a need to obtain and then maintain the approval of the public, sometimes referred to as the social licence to practice forestry (Burton *et al.*, 2006).

A further problem with indicators, as many governments have found, is that monitoring indicators represents a significant cost. When criteria and indicators were being initially designed, one of the criteria specifically dealt with institutional capacity, including the ability to monitor the indicators being used to assess sustainable forest management. Few countries report on this (Australia being a notable example that does), although the FAO does now include assessments of the amount of information reported for each indicator, together with assessments of the reliability of the data.

The following seven sections examine each of the thematic elements of sustainable forest management adopted by the FAO. The individual sections rely heavily on information provided in the *Global Forest Resources Assessment 2010* (FAO, 2010).

Extent of forest resources

The extent of forest resources in a country or globally is an important aspect of sustainable forest management. Many concerns about forests relate to the loss of forest cover in different parts of the world, which is generally seen as something undesirable. However, in itself, this is a difficult topic. Most developed countries have already lost a significant proportion of their forest cover, and efforts for the past 100 years or more have focused on restoring some of the original forest cover. The losses occurred in historical times, often when the countries were in the process of developing their economies. Some developing countries consider that it is unfair that their development should now be constrained by the need to maintain forest cover, and a number of countries have actually designated forest areas for conversion into other forms of land use, especially industrial agriculture. Both Malaysia and Indonesia, for example, have designated areas of conversion forest: areas of natural forest that will be cleared for other forms of land use.

The desire to maintain forest resources can perhaps better be placed in the context of the need to maintain forest cover to satisfy a number of ecosystem services, such as the maintenance of biological diversity (discussed in the next section), by the need to maintain supplies of an important resource (wood) and by the need to restore and rehabilitate forest landscapes that have become degraded over time. As such, this criterion is about more than forest area, and in the Global Forest Resource Assessments undertaken by the FAO, six indicators are now used. These include the area of 'forest' and 'other wooded land' in every country; the characteristics of those forests, namely whether they consist of primary forests, other naturally regenerated forests or planted forests; the area of particular forest types of interest (in 2010, these were mangroves, bamboo and rubber plantations); the standing volume of wood; forest biomass; and the carbon stock held in woody biomass, dead wood, litter and forest soils.

At smaller scales (such as management units), there is an increasing desire to see sufficient areas of each forest ecosystem type in an area being maintained, as well as a range of seral stages. At a global scale, there are major concerns about the loss of particular biomes (Hoekstra *et al*., 2005), such as savannah forests and mangroves. Regionally, there may be a desire to see adequate representation of all forest types being maintained, and indeed this is an essential component of ecosystem-based management, a form of sustainable forest management that is described below.

Globally, there are just over 4 billion hectares of forest, with more than half (53%) being located in the five most forest-rich countries: the Russian Federation, Brazil, Canada, the USA and the People's Republic of China. Conversely, 64 countries have 10% or less forest cover, and have a total population of over 2 billion people (FAO, 2010). A further 1.1 billion hectares of other wooded land exists – this is land that is not classified as forest, but with tree cover. It includes roadside strips, land with a very low tree cover, and other areas not classified as forest. Just under one third (31%) of the world's land surface is covered by forests, with a further 9% being classed as other wooded land. A new category of land use assessed by the Global Forest Resources Assessment (GFRA) includes trees outside forests, referring to land with trees that is not classified as either forest or other wooded land. The category includes orchards, urban parks and other areas with trees, and accounts for 79 million hectares, although this is likely an underestimate of the actual area.

Despite considerable efforts to stop deforestation, it continues, although reportedly at a lower rate than in the past. In the 1990s, approximately 16 million hectares of forest were being lost annually, whereas this had dropped to 13 million hectares annually in the first decade of the 21st century. Brazil and Indonesia have been particularly successful in reducing their official rates of deforestation, although illegal logging is rampant, particularly in Indonesia. The primary cause of deforestation is the conversion of forest to agriculture, although natural causes are also important (for example, in Australia, where drought and forest fires have caused widespread forest losses in recent years). The greatest annual forest losses (when expressed as a percentage of the remaining area) in the period 2000–2010 were in the Comoros (–9.3%), Togo (–5.1%), Nigeria (–3.7%), Mauritania (–2.7%) and Uganda (–2.6%). An annual loss of 9% of the forest area is clearly unsustainable, even in the short term. When forest cover as a whole is considered, the rates of loss are lower, because there has been significant afforestation in some countries, especially in China. Overall, the net loss of forest cover is about 5.2 million hectares annually (for the period 2000–2010), whereas the equivalent loss in 1990–2000 was 8.3 million hectares annually (FAO, 2010).

The greatest concern about deforestation is the loss of primary forest – forests that have had no discernible human influence. These currently account for 36% of the total forest area, whereas planted forests account for only 7% of the total forest area. Natural and planted forests represent two ends of a wide spectrum of different types of forest. From many perspectives, the more natural a forest is the better, but this is not necessarily the case for timber production. Primary forest often contains a significant proportion of biomass that is unsuitable for harvesting and that may simply be discarded on site. On the other hand, a managed plantation may contain a very high proportion of biomass that can be utilized, but may lack other qualities. A significant element of sustainable forest management is finding and maintaining the right balance of naturalness. The GFRA records naturally regenerated forests, suggesting that they are more natural than planted forests. This is not as evident as it seems – it is possible for an exotic species to regenerate naturally, as happens with Sitka spruce (*Picea sitchensis*) in the United Kingdom, and many forest restoration efforts, using local species, involve planting. The situation may be even more complex when forest structure rather than species composition is emphasized. For example, Angelstam *et al.* (2005) illustrate an example of a 'transformation from a monoculture to a more nature-based form of forest management', yet the transformation involves replacement of the Norway spruce (*Picea abies*), which is native over much of central and northern Europe) with a mix of species including Douglas fir (*Pseudotsuga menziesii*), which is native to western North America. The GFRA statistics indicate that in the period 2000–2010, there was a loss of 40 million ha of primary forest (0.4% annually), either through deforestation or reclassification as naturally regenerated forest (following selective logging or other human interventions).

The total growing stock in the world's forests is estimated to be about 527 billion m^3, corresponding to an average of 131 m^3 per hectare. Some of the highest growing stocks have been reported from countries in central Europe and in some tropical areas. However, these figures are averaged for an entire country: the highest standing stocks in individual stands lie outside such areas (e.g. the primary forests of the Pacific coast of the USA and Canada). The growing stock on other wooded land is estimated to be about 15 billion m^3, equivalent to an average of 13.1 m^3 per hectare (FAO, 2010). Trends in growing stock are difficult to discern, especially as the standard of reporting is not very reliable and there are many uncertainties surrounding the origin of some of the data.

More than 650 billion tonnes of carbon are stored in the world's forests, with 44% in biomass, 11% in dead wood and litter and 45% in the soil. Carbon stocks are, however, declining, with an estimated annual loss of 0.5 Gt during the period 2005–2010, primarily due to the loss of forest area (FAO, 2010). There is some controversy surrounding changes in carbon sequestration by forests, although it appears that the amount of carbon stored per hectare of forest may be increasing (Pan *et al.*, 2011).

Biological diversity

Forests represent a critical habitat for species. It is estimated that more than half of the world's terrestrial plant and animal species depend on forests as their primary habitat (Secretariat of the Convention on Biological Diversity, 2012). Conversion of forests to other forms of land use has been an important cause of the loss of biological diversity, and so maintaining the diversity of species in existing natural forests has been an important role for foresters. Where natural forests have been converted, for example to plantations, enhancing biological diversity is an important goal of sustainable forest management. Similarly the rehabilitation and restoration of degraded forests and other lands is aimed in part at restituting their biological diversity.

Within this theme, there is generally an aim to maintain biological diversity across a range of scales. At the broadest scale is representation across landscapes. This level of diversity is often termed gamma diversity (γ-diversity) (Whittaker, 1960). As indicated above, this is an important aspect of ecosystem-based management. However, there are also concerns to maintain species and genetic diversity.

At a practical level, maintaining biodiversity often means maintaining appropriate amounts of habitat within a management unit, and ensuring that vulnerable or endangered ecosystems are protected.

The diversity within a particular stand is frequently referred to as alpha (α) diversity, whereas across a management unit there may be a greater level of diversity related to inter-site differences (known as beta (β) diversity) (Whittaker, 1960). The diversity of forests makes it very difficult and costly to undertake full biological inventories. In fact, no forest area anywhere has had a complete inventory of all organisms present, principally because so many species remain undescribed. Many areas have had partial inventories however, and some biological groups, such as higher plants, birds, mammals and reptiles have been surveyed in many areas. Nevertheless, there are very few countries where complete surveys have been done, and most of these depend on some form of randomized sampling. Such surveys may or may not be of value when determining whether forest management is successfully maintaining biological diversity, and careful design of monitoring programmes is required if they are to be cost effective (Gardner, 2010).

Noss (1999) describes a number of factors, including loss of old forests, simplification of forest structure, decreasing size of forest patches, increasing isolation of forest patches, disruption of natural fire regimes and increased road building, that are having an adverse effect on the biological diversity of forests. In most cases, the effects are determined from individual case studies, making it difficult to generalize across management units. For example, in some areas, a road may have relatively little impact, whereas in others it may be very significant. A wide variety of strategies to reduce the impact of forestry on biodiversity have been proposed (Lindenmayer and Franklin, 2002): many of these focus on the maintenance of habitats and habitat structures rather than on the organisms themselves. These are sometimes referred to as coarse-filter strategies. In other cases, emphasis is placed on individual species, referred to as fine-filter strategies. The latter are important, given that nearly 7000 forest and savannah species are critically endangered, endangered or vulnerable (IUCN, 2012).

Globally, about 12% of forests (460 million ha) have been designated as having conservation of biological diversity as their primary function. Most of these lie within protected areas, but such areas are afforded varying levels of protection. In some cases, the protection is real, as is generally the case for national parks in Europe and North America. In other cases, areas that have been formally designated as protected may be subject to illegal logging, as has happened in Madagascar (Innes, 2010). The Secretariat of the Convention on Biological Diversity has estimated that of the 825 terrestrial ecoregions present worldwide (which include both forest and non-forest areas), only 56% have 10% or more of their area protected (Secretariat of the Convention on Biological Diversity, 2012). This suggests that the biodiversity present in many forest areas may be at risk through inadequate levels of protection.

From the point of view of a forest manager, the adequate protection of biodiversity presents some challenges. In particular, deciding how much forest should be protected from human disturbance is controversial, and may range from relatively small proportions (e.g. 10%) to the entire forest area for some endangered forest types. Conversely, biological diversity may be compromised if human activities result in fewer natural disturbances, and this is particularly true of fire suppression. In many parts of the world, the exclusion of fire from forests has led to significant changes in ecosystem composition, form and function, and restoration is now required, often involving the controlled use of fire (e.g. Russell-Smith *et al*., 2009; Kouki *et al*., 2012). Increasingly, managers are dealing with the maintenance of biodiversity by changing their focus from what can be extracted from a stand to what needs to be left in order to maintain the system, a focus that is referred to as 'retention forestry' (e.g. Gustafsson *et al*., 2012). Overall, maintaining biodiversity presents many challenges for the forest manager, but there is also an increasing amount of knowledge that can be drawn on (e.g. Lindenmayer and Franklin, 2003; Lindenmayer and Fischer, 2006; Bunnell and Dunsworth, 2009; Hunter and Schmiegelow, 2010).

Forest health and vitality

While apparently obvious, the maintenance of forest health and vitality is difficult and controversial. To a certain extent, this (and the next) aspect of sustainable forest management dates back to the time when the production of timber was the primary (and only) purpose of forestry. Foresters were concerned about protecting forests from biotic and abiotic disturbances, including wildfires, airborne pollution, climatic damage, diseases and insects. However, in recent years, there has been increasing recognition that it is important to allow some disturbances if the overall health of the ecosystem is to be maintained. There has also been growing interest in adapting forest management practices in such a way that they mimic natural disturbances as closely as possible (Perera *et al.*, 2004; Gauthier *et al.*, 2009; Kuuluvainen and Grenfell, 2012). A major difficulty lies in determining the nature and extent of natural disturbances, especially in the light of climate change (Dale *et al.*, 2006; Dukes *et al.*, 2009), with modelling suggesting that climate change will influence the relative merits of forest protection and forest harvesting (Colombo *et al.*, 2012). A further difficulty is associated with determining what level of disturbance is acceptable, since all forms of disturbance are likely to affect one or more of the criteria that a forest manager is trying to maintain. Furthermore, it is increasingly evident that disturbances may interact with each other: a wind storm or drought may, for example, increase the susceptibility of a forest stand to attack by insects, and trees attacked by pathogens may be more susceptible to windthrow (Parker *et al.*, 2006).

Edmonds *et al.* (2011) discuss the concept of forest health in detail. They provide a list of eight indicators that can be used to determine whether or not a forest is healthy, but point out that there are many more possible indicators. Some of these overlap with other criteria described in this chapter, but are included in Table 7.1 because they are all closely associated with the health of forest ecosystems.

Table 7.1. Indicators of healthy forest. (From Edmonds *et al.*, 2011.)

1. Trees and understory plants are vigorous and healthy. Species, age class distributions and stand densities are within historical ranges for the site, and growth and mortality are consistent with the ecosystem type and age of dominant trees.
2. Vegetation diversity is balanced between the supply and demand of light, water, nutrients and growing space.
3. The forest can tolerate and recover from known disturbances.
4. Soil erosion is minimal, with clean water flowing from streams, except during extraordinary runoff events. Stream banks are stable and there is ample riparian vegetation.
5. There is a diverse range of aquatic species, and aquatic indicator species are present in appropriate numbers.
6. Wildlife diversity and presence is appropriate for the ecosystem, especially in riparian zones.
7. Insect, disease and fire frequencies are within the normal ranges for the ecosystem.
8. Ecological processes are operating within the natural range of variability.

The indicators in Table 7.1 are not without problems. For example, they rely heavily on the natural range of variability, but this may be changing as a result of climate change. It also assumes that this range of variability is known. Often, such variability is based on a relatively short period of time, whereas long-term studies of forest change reveal that forests have changed markedly over the last several thousand years, with these changes being driven by long-term ecosystem dynamics, natural climate change and other processes (e.g. Hallett and Hills, 2006; Genries *et al.*, 2012). The indicators are oriented towards natural forests, and their application to, for example, plantations is difficult. It should not be automatically assumed that a plantation of exotic species is unhealthy: in fact, forestry may have a major role to play in adapting landscapes to climate change by moving seed sources and species (Pedlar *et al.*, 2012).

Globally, these difficulties are reflected in the FAO's Global Forest Resources Assessments. Reporting is sporadic and often incomplete. Many countries lack the capacity to monitor forest health adequately, and few forest managers have the expertise to do so. Data are unreliable and, while it is possible to provide estimates of areas affected by particular forms of disturbance, these do not necessarily indicate the severity of the disturbance. For example, although 18.1 million hectares of forest in British Columbia has been attacked by the mountain pine beetle (*Dendroctonus ponderosae*), not all trees within this area are lodgepole pine (*Pinus contorta*), the primary species attacked by the mountain pine beetle, and not all pines are killed. A more accurate figure is the volume of timber that has been killed (710 million m^3 by 2012), but this figure is entirely utilitarian and provides no indication of the ecological impacts of the beetles.

Productive functions of forest resources

As indicated above, this aspect of sustainable forest management is also a legacy of a time when timber was the sole focus of forestry. Today, the primary concern is to ensure that forests can maintain a supply of goods and services without compromising their ability to do so for future generations. The types of goods being considered include both wood and non-timber forest products, such bamboo, rattan, fruits and a wide range of plants used in medicinal products (Shackleton *et al.*, 2011). Of a number of services that forests provide, the supply of clean water is particularly important and will likely increase in significance with climate change.

According to the 2010 GFRA, the assessment of the productive functions of forests

> indicates the economic and social utility of forest resources to national economies and forest-dependent local communities and reflects the wish to maintain an ample and valuable supply of primary forest products, while at the same time ensuring that production and harvesting are sustainable and do not compromise the management options of future generations for productive or other functions of forests.
>
> (FAO, 2010, p. 85)

The FAO collects information on several indicators related to this criterion, including the area of forest designated for production, the area of planted forests, areas afforested and reforested, removals of wood products and removals of non-wood forest products (NWFPs).

In 2010, 1.2 billion hectares of forest were being managed primarily for the production of wood and non-wood products, and a further 949 million ha were being managed for multiple purposes, including the production of wood and non-wood products. The amount of forest being managed for production has been declining, with some of the forest being designated for other purposes, including other forms of land use. Europe has the highest proportion of forest specifically devoted to production (52%), whereas the proportion is much lower in other regions (FAO, 2010).

Planted forests now make up about 7% of the total forest area (264 million ha), and this figure is expected to continue to rise, with the area of planted forest increasing by about 5 million ha annually. Much of this planting is done in the temperate and boreal regions of Europe and North America, primarily with native species. Only about 25% of the planting is done with exotic species – mostly in sub-Saharan Africa, Oceania and South America (FAO, 2010).

Between 1998 and 2007, more than 10 million ha were afforested or reforested annually. Afforestation occurs on land that was not previously forested, whereas reforestation occurs immediately after the forest cover has been lost. Most afforestation and reforestation was done with indigenous species. The GFRA's statistics indicate that exotic species were used in 29% of the afforested area, and 36% of the reforested area. These figures need to be interpreted with care. The seemingly high proportion of reforestation with exotic species does not necessarily represent replacement of native forest with exotic species. Rather it reflects the short rotation times of many exotic plantations, which when managed well are quickly replaced after they are harvested. The rate of reforestation over the past 10 years has been about 5 million ha annually.

Globally, the GFRA reports that, in 2005, wood removals from forests amounted to 3.4 billion m^3 annually – approximately 0.7% of the total growing stock. This is an underestimate of the actual amount of wood removed from forests, because much of the wood removed for fuel is not recorded. Of the reported amounts, about half of the wood removed is for industrial roundwood and the other half is used for fuel. In some countries, the majority of wood removed from forests is used for fuel, so the under-reporting of removals may be very significant. Wood is also removed from other wooded land – in 2005, this was reported to be 299 million m^3 (FAO, 2010). However, this again is likely to be seriously under-reported.

Other important forest products include exudates, other plant products, honey and beeswax and ornamental plants such as orchids. Such removals appear to be particularly important in Asia, but are likely under-reported in many other parts of the world. There is a wide variety of such materials, and the 2010 GFRA has attempted to break them down into a number of categories (Table 7.2).

By far the most important product (as reported) is plant-derived food. A wide range of foods are derived from forests globally, with camellia, oilseed, nuts and bamboo products being among the most important, especially in Asia. Under-reporting elsewhere means that other food products may be very important but are not being recognized. The second most important category consisted of exudates, with gum arabic being particularly important in Sudan, and pine resin, lacquers and tannin extracts being important in China. Considerable concern exists in some parts of the world over the hunting of forest animals, with the products often being generically labelled as 'bushmeat'. Some of the best-documented examples relate to the hunting of primates in the forests of central Africa, a phenomenon that has been aided by the development of roads used for the extraction of logs (Remis and Robinson, 2012). The demand for bushmeat is such that in some parts of the world, forests have been emptied of large animal and bird species, regardless of

Table 7.2. Product categories used by the *Global Forest Resources Assessment 2010.* (From FAO, 2010.)

Plant products/raw material	Animal products/raw material
Food	Living animals
Fodder	Hides, skins and trophies
Raw material for medicine and aromatic products	Wild honey and beeswax
Raw material for colorants and dyes	Wild meat
Raw material for utensils, handicrafts and construction	Raw material for medicine
Ornamental plants	Raw material for colorants
Exudates	Other edible animal products
Other plant products	Other non-edible animal products

whether or not they have been designated as reserves (Redford, 1992; Harrison, 2011).

Forest managers traditionally only consider timber and other wood products when looking at forest ecosystem productivity. However, today's management must acknowledge that there are many more products that are derived from forests, often simultaneously to the production of wood products. There is a need for management to recognize this, and to also recognize that practices that may favour one product may compromise others. For example, the use of herbicides to control brush may inadvertently destroy plants used by local people for food or medicine. As with other criteria, public consultation may help resolve some of these potential conflicts.

Protective functions of forest resources

Forests have long being recognized as having protective functions and were frequently set aside specifically for the purpose (Mayer and Ott, 1991). On steep slopes, they can provide protection against landslides and other forms of mass movement and can help prevent, divert or abate snow avalanches. They can also help moderate hydrogeomorphic, hydrological and aquatic systems (Sakals *et al.*, 2006), and may play a critical role in regional climates. Within the FAO's system of sustainable forest management, ecosystem conservation is included under this theme, but forests designated as having a primary function of biodiversity conservation are not considered under this reporting theme.

According to the 2010 GFRA, 330 million hectares of forest have been designated as having the primary function of soil and water conservation, avalanche control, sand dune stabilization, desertification control or coastal protection. This is likely an underestimate, because many multiple-use forests have a primary role as protection forests. The area of protection forests has been increasing, primarily due to the aggressive afforestation programme in China that has been occurring since 1998 (Wang *et al.*, 2007). Many natural forests in mountain areas are off-limits to harvesting because harvesting might increase the likelihood of a landslide or other mass movement. Such forest areas are, technically, protection forests, but are rarely designated as such. Some forests today are being specifically created to sequester carbon; they should also be considered as protection forests.

In the European Alps, there has been a long history of forest management aimed at protecting communities from the adverse effects of snow avalanches (Brang *et al.*, 2006) and other natural disasters. Bans on harvesting were placed on forests located in particularly sensitive areas, such as steep slopes directly above communities, and special silvicultural techniques are still used in these forests (Ott *et al.*, 1997). Many riparian protection zones were set up to help stabilize stream banks and prevent stream avulsions, where a stream moves out of its current channel, usually during flood conditions. Today, large-scale logging bans exist in some areas in an effort to reduce the extent of large-scale flooding, with the ban on logging in the headwaters of China's major rivers being one of the best-known examples (Wang *et al.*, 2007).

For forest managers, the need to ensure that forests fulfil their protective functions is important. If a landslide occurs on land that has been logged, the area of land available for re-planting will be reduced until the soil recovers. This may take hundreds of years in some environments. There may also be impacts on infrastructure, such as roads or buildings, possibly leading to loss of life. The landslide may enter a stream with major potential consequences downstream, especially if the landslide creates a temporary dam. Habitat may also be disrupted; for example, fish spawning beds may be affected by silt, a problem that also occurs in areas where forest management practices have triggered soil erosion (e.g. Hartman *et al.*, 1996). Identifying potential geomorphic risks on forested slopes is a specialized task, and may require the services of a geotechnical engineer; this should occur at the planning stage, and any potential risk areas excluded from harvesting zones.

Socio-economic functions

Forests provide many different benefits to people, and this thematic area is intended to cover them. They include direct benefits, such as employment and products that can be marketed. However, they also include a wide range of intangible benefits, such as cultural, spiritual and recreational values. These functions can be difficult to measure: they include a wide range of values, some of which can be measured quantitatively whereas others can only be assessed qualitatively. In addition, some benefits are still being determined, such as the role of forests in promoting human health.

Most economic benefits can be directly measured from their market value. However, some may be more difficult to assess, especially when there are no markets (subsistence economies). Many of the intangible benefits are also difficult to measure, such as the aesthetic values associated with forests. Interestingly, there have been many important developments in the valuation of goods and services coming from forests, but few of these have been incorporated into either the Global Forest Resources Assessment or the regional systems of criteria and indicators. Australia provides some of the best information related to this criterion but, generally, reporting is extremely unsatisfactory.

The 2010 GFRA provides very limited information in its section on socio-economic functions. It talks about several institutional issues before examining the value of wood and NWFP removals, employment in forestry and the area of forests designated for social services. Globally, the value of wood removals in the period 2003–2007 was about US$100 billion annually. Most of this value was attributed to industrial roundwood removals, but, as previously noted, fuelwood removals are under-reported. In addition, fuelwood is often associated with subsistence economies, making it difficult to value accurately. NWFP removals were estimated to be worth US$18.5 billion in 2005, but this is likely a serious underestimate of the true value.

According to 2010 GFRA, about 10 million people are employed in forest management and conservation (FAO, 2010). This figure is not very reliable, as there are major difficulties in separating it out from other forms of employment. For example, should staff employed in forested national parks be included? If so, in a country like Canada, how are those associated with forested parks separated from those associated with non-forested or partly forested parks? The same issue extends to the forest products sector, with considerable uncertainty associated with where a line is drawn in employment. This problem is best illustrated by considering a town located in a forest area and containing several forest-related industries, such as a sawmill, plywood plant and furniture manufacturing plant. In theory, all the employees dealing directly with wood, wood products and NWFPs should be counted as being part of the forest sector. However, should those indirectly involved also be included? If the houses in the town are wood-frame construction, should joiners, roofers and other trades be included? Should those responsible for servicing the community also be included, particularly if the town is heavily dependent on the forest products sector? If the forests are used for grazing, should the employment associated with this be included? There is no general agreement over the answers to these questions, and attempts to identify the multiplier associated with forest-sector employment have generally shown just how interrelated the employment in communities is.

Another indicator used by 2010 GFRA is the area of forest designated for the provision of social services such as recreation, tourism, education or the conservation of cultural and spiritual heritage. Globally, this amounts to 4% of the world's forests. Some countries have, however, designated considerably more. For example, Brazil has allocated 119 million hectares, more than 20% of its forest area, to the protection of the culture and way of life of forest-dependent peoples. The global figure of 4% is likely a major underestimate because many countries have forests classified as having multiple purpose use that are available for social services. Similarly, forests designated primarily for the conservation of biological diversity may have important social functions. These figures also fail to take into account the area of forest that is managed in consultation or participation with indigenous peoples. The management of such areas may be very different to the management that would have occurred without such involvement (see, for example, Howitt, 2001; Walsh and Mitchell, 2002).

At the scale of the management unit, there are major questions over the role of the forest manager in many of the potential economic and social benefits. From a forest products perspective, a forest manager is generally only responsible for delivering the product from the forest. What then happens to that product is no longer an issue for sustainable forest management. However, some argue that forest management is only sustainable if the communities depending on the forest are sustained. According to this viewpoint, a manager must be concerned with what happens to the products. For example, are logs processed locally or exported? To what extent are the forest products generating a value-added industry? Is any of the money generated by the sale of forest products being re-invested in local communities? Furthermore, a forest manager must be concerned with other interactions between the forest and people. For example, a forest may be used for a variety of recreational activities, and these could be compromised by inappropriate management actions. There is often a divergence of opinion between forest managers and local community representatives over these and other issues related to economic and social functions, and invariably the best way to reach a resolution is through appropriate levels of meaningful consultation.

Legal, policy and institutional framework

This final criterion is sometimes omitted from national schemes of sustainable forest management since it is often taken for granted. However, it is critical that all the legal, policy and institutional arrangements are in place to ensure that the remaining criteria can be properly addressed. This includes having participatory decision-making, appropriate governance and effective law enforcement. It also includes having an appropriate monitoring and assessment process in place. Without such monitoring, the effectiveness of management, whether it involves the management of conservation areas or the regulation of forest practices, cannot be ensured (e.g. Vuohelainen *et al.*, 2012). FAO (2012) goes on to say that sustainable forest management should address broader societal aspects, including 'fair and equitable use of forest resources, science research and education, infrastructure arrangements to support the forest sector, transfer of technology and capacity building, and public information and communication'. This is important because it is apparent that simply designating forests as reserves will not ensure that they are protected. In fact, studies drawn from around the tropics suggest that there is a direct link between the existence of community-level management and the maintenance of forest cover (Porter-Bolland *et al.*, 2012).

The 2010 GFRA places a lot of emphasis on the presence of forest policy statements and forest laws in individual countries under this thematic element. Many countries have such statements, but it is impossible to determine how effectively they are using the FAO's methodology (which relies on asking individual countries to respond). The same applies to national forest laws; these may exist, but there is much less certainty over the effectiveness of their enforcement. Much the same applies to the ratification of international conventions that relate directly or indirectly to sustainable forest management, another indicator used by FAO. While a country may ratify a convention, ensuring that its principles are applied throughout a country is another matter entirely.

A trend in forest governance that is apparent in many parts of the world is decentralization (e.g. Edmunds and Wollenberg, 2003; Pierce Colfer *et al.*, 2008; Moeliono *et al.*, 2009). Central governments are increasingly giving more say to local people in the management of their forests. Community forests represent one form of this decentralization, although the extent to which real control is transferred to communities differs markedly between different systems (Pierce Colfer, 2005a; Menzies, 2007). Much of the problem lies in the distrust that governments (and, in many cases, professional foresters) have for the ability of communities to manage their own forests. Yet there are numerous examples that illustrate communities often do have such an ability (Gibson *et al.*, 2000; Pierce Colfer and Pfund, 2011). There is sometimes particular concern over the devolution of control to indigenous communities, and this has been an ongoing issue in many parts of the world (e.g. Campbell, 2002; Stevenson and Natcher, 2009). Many of the problems can be related to poor levels of communication between those in authority and those seeking to increase their control over the forest (e.g. Greskiw and Innes, 2008).

From the perspective of a forest manager, this area may seem rather esoteric. However, forest managers can make an important contribution to research, education and public information. In some cases, there may even be a requirement to do so to gain certification (see below). Unfortunately, such activities are often seen as having relatively low priority, especially when under financial pressure. In some parts of the world, this has resulted in forest management having lost its social acceptability or 'social licence', namely the approval of the public to manage forests (e.g. Shindler *et al.*, 2002). In such situations, forest management can become very difficult, and may even be stopped through political actions. This has been particularly apparent in Australia and New Zealand.

In areas with strong governance, forest managers are generally required to demonstrate compliance with existing laws, regulations and codes of practice. Compliance may be checked on the ground by government officials, but increasingly remote sensing is being used to assess compliance. Most such schemes are looking for compliance with documented standards. However, in some jurisdictions, such as British Columbia, Canada, a results-based code of practice has been introduced. Instead of taking a very prescriptive approach, for example specifying the width of riparian buffer strips, managers are required to ensure that certain values, such as water quality, are maintained. How they do this is left to their professional judgement, although the government maintains the Forest and Range Evaluation Program (http://www.for.gov.bc.ca/hfp/frep/) that specifically examines whether the values are being successfully maintained. Such a system has the potential to be quite successful, but is dependent on the skills of the forest managers. As a result, it is more likely to be successful in areas where forest managers have not only an advanced level of education, but also where the standards of professional foresters are regulated through professional associations.

Certification

With sustainable forest management emerging as a paradigm for forestry, there has been much interest in demonstrating that forest managers are actually managing their forests sustainably. A major mechanism has emerged for doing this, known as forest certification. Essentially, forest certification involves an audit of the forest management practices being followed in a management unit. The practices are compared against a standard – these differ both between and within certification schemes. There are two major international certification programmes – the Forest Stewardship Council (FSC) and the Program for the Endorsement of Forest Certification (PEFC). The former consists of a generic standard, used when there is no local standard in place, and a wide range of local standards that are used once they have been approved centrally. The latter consists of a number of national standards, again requiring endorsement centrally. With the Forest Stewardship Council, when a country does not have an endorsed standard, an auditor can assess a management unit in relation to the generic standards of the Forest Stewardship Council. This is intended to be an interim measure, and generally there is an expectation that once certification is being sought within a country, a locally developed standard will emerge, with subsequent endorsement by the Forest Stewardship Council. With the PEFC, there is no interim stage, and a national scheme cannot use the PEFC logo until the scheme has been endorsed by the PEFC.

The requirements associated with different forest certification schemes were initially quite diverse, but in recent years they have become progressively more similar. This is not always apparent because of the intense rivalry between standards, which leads to differences being emphasized. However, steps taken by one scheme to improve its standard are usually quickly adopted by other schemes, resulting in the overall improvement of certification standards. This has not stopped the individual certification schemes from being challenged, and all schemes, because they represent the compromises necessarily associated with land management, have been subject to question (e.g. Johansson, 2012).

Forest certification was intended to be market driven, in that buyers were expected to pay a premium for certified forest products. Forest managers have found this premium to be elusive. It is sometimes present, particularly for niche products sold in specific markets, but the premiums are rarely transferred back to the initial producer. This is a common problem in commodity markets, and has given rise to concepts such as 'fair trade' coffee. However, as yet, there is no such equivalent for wood.

Forest certification should not be confused with 'chain of custody' certification. Chain of custody provides an assurance that a product has come from a particular source. In theory it means that a product sold in the market can be traced back to its source. It requires the source (i.e. forest) to be certified, and provides the customer with an assurance that the forest product being purchased has come from that forest.

Further developments

Over the last 20 years, it has been increasingly recognized that forests cannot be managed in isolation. The term 'sustainable forest management' in itself focuses on only one form of land use, but, today, it is recognized that forests interact with other forms of land use, and cannot be considered in isolation. This has led to the emergence of a number of concepts, such as forest quality, which examines the authenticity of a forest, the environmental benefits and the social and economic benefits (Dudley *et al.*, 2006). Another approach is ecosystem-based management, defined by the Coast Information Team (2004) as

> an adaptive approach to managing human activities that seeks to ensure the coexistence of healthy, fully functioning ecosystems and human communities. The intent is to maintain those spatial and temporal characteristics of ecosystems such that component species and ecological processes can be sustained and human well-being supported and improved.

Ecosystem-based management has been applied in a number of areas, but it is perhaps best illustrated in the forests of the Central Coast region of British Columbia, Canada.

As the definition of ecosystem-based management (EBM) includes human well-being, there is a clear link between the land and the people that live on that land. This solves some of the questions posed earlier, where the links between forest management and communities were not clear. EBM is clearly linked to social, economic and cultural issues such as education, equity, economic development and health. For the case of Central Coast, British Columbia, a number of guiding principles were defined, specific to the situation. These included:

- Ecological integrity is maintained;
- Human well-being is promoted;
- Cultures, communities and economies are sustained within the context of healthy ecosystems;
- Aboriginal rights and title are recognized and accommodated;
- The precautionary principle is applied;
- EBM is collaborative; and
- People have a fair share of the benefits from the ecosystems in which they live.

These guiding principles have been elaborated by a statement of EBM goals and objectives, reproduced in Table 7.3.

Table 7.3. Ecosystem-based management goals and objectives for the Central Coast of British Columbia, Canada. (From Coast Information Team, 2004.)

Maintain the ecological integrity of the terrestrial, marine, and freshwater ecosystems	Represent the biological diversity of the region in a system of protected areas according to the principles of conservation biology
	Maintain the natural diversity of species, ecosystems, seral stages and ecosystem functions, including biological legacies (e.g. bear dens, wildlife trees, snags, coarse woody debris)
	Restore damaged or degraded ecosystems
	Ensure that streamflow, channel characteristics and water quality are within the range of natural variability
	Protect or restore red- and blue-listed species and their habitats
	Protect red- and blue-listed and regionally rare ecosystems
	Maintain viable populations of all native species, including genetic variants, across their range
	Conserve soil productivity and maintain slope failures within natural rates
Achieve high levels of human well-being	Achieve the health, wealth and education status required for a high-quality and secure life for both aboriginal and non-aboriginal people
	Build stable, resilient, well-serviced and peaceful communities in coastal British Columbia
	Create a strong and diverse mix of businesses and overall economy within communities and across the region
	Create a strong and diverse mix of non-profit and voluntary organizations and a vibrant set of traditional, cultural and non-market activities within communities and across the region
	Ensure a fair distribution of benefits, costs and risks across all parts of coastal British Columbia, including aboriginal and non-aboriginal people

Sustainable forest management and climate change

Perhaps the greatest challenge facing sustainable forest management is climate change. Many of the criteria that define sustainable forest management refer to the maintenance of particular values. This is appropriate in a stable world, but there are numerous reports that indicate that the world is changing rapidly. Consequently, sustainable forest management will need to be increasingly adaptable in the future, especially given that the failure to control emissions of greenhouse gases means that climate change is occurring and that further changes are inevitable.

Increasingly, forest managers are realizing that many of the principles involved in sustainable forest management are also suitable for ensuring that forests and forest-dependent communities will be able to adapt more readily to climate change (Ogden and Innes, 2007). At the same time, the major uncertainties associated with climate change mean that forest managers will have to be much more flexible than they have been in the past. Adaptive management is a technique that has been proposed to deal with this uncertainty. It involves a sequence of planning, acting, reviewing and evaluating, such that new knowledge is constantly incorporated into management actions. This approach to management is still evolving, and when the management is done together with the communities, as has been strongly recommended in this chapter, the result is adaptive co-management (Pierce Colfer, 2005b; Armitage *et al.*, 2007).

Conclusions

Sustainable forest management is a complex subject that involves drawing skills from many different areas. A professional forester is expected to be able to draw on many different sources of information, to listen to and accommodate a diverse range of opinions about how a forest should be managed, and to implement management practices in such a way that all expectations are met. There have been many attempts to develop suitable decision support tools (e.g. Buongiorno and Gilless, 2003; Kangas *et al.*, 2008), and these can be very helpful. However, many require substantial amounts of data and, as indicated in this chapter, a manager may have less information than would be desirable for effective management decision-making. In such situations, a collaborative adaptive approach is likely to be the most productive, but requires that managers be as effective at working with people as they are at working with trees.

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8 Forestry and Climate Change

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Introduction

Forests affect climate change in a variety of ways: as sources of greenhouse gases (GHGs), as reservoirs of potential GHGs, as sinks that sequester GHGs, and through directly influencing energy dynamics on a landscape scale. In addition, climate change influences forests. National forest policies can therefore greatly influence climate change, and some nations have attempted to implement legislation designed to promote climate-friendly forestry activities while discouraging climate-adverse ones.

A section of this chapter is devoted to each of these aspects of forestry and climate change.

Dimensions of Interactions between Forests and the Atmosphere

More than twice as much carbon (C) is stored in the Earth's plants and soil organic matter than is stored in the atmosphere (Fig. 8.1), and estimates of storage in plant matter range from the 500 gigatonnes (Gt) shown in Fig. 8.1 (Mahli, 2002) to 650 Gt in forest biomass alone (FAO, 2010). Some atmospheric carbon is essential for maintaining liveable temperatures in the biosphere, but a rise in carbon dioxide (CO_2) concentration from 280 ppm in 1800 to 395 ppm today is promoting changes to the Earth's climate that will be deleterious (IPCC, 2007).

The scale of annual interactions between forests and the atmosphere is well shown by measurements of atmospheric CO_2 concentrations at Mauna Loa (Fig. 8.2). Annual fluctuations are due to northern hemisphere forests' seasonal uptake and emission of CO_2.

Assessments of global carbon balances have indicated that there is a large terrestrial sink, and recent research has identified that this sink is in forests. A combination of forest inventory and long-term ecosystem carbon studies have revealed that established forests absorbed an estimated 2.4 ± 0.4 Gt of carbon each year between 1990 and 2007. Forest regrowth absorbed 1.64 ± 0.52 Gt, and so the gross forestry-related sink was 4.05 ± 0.67 Gt/year. This was offset by forestry carbon emissions of 2.94 ± 0.47 Gt/year from deforestation, representing a net forestry sink of 1.1 ± 0.8 Gt/year, which is about the magnitude of the previously unidentified terrestrial sink (Pan *et al.*, 2011).

Climate Change Influences Forests

GHGs and climate change can influence tree growth rates, ranges of species and their susceptibilities to pests, and climatic risks such as windthrow.

A prevailing view among scientists has been that climate change will promote growth of forests, at least in the short term. The argument is straightforward: plants need CO_2 to undergo photosynthesis so as to produce food and oxygen (O_2). But with factories and cars emitting ever-more CO_2 into the atmosphere, this will result in crops and trees growing bigger and faster.

However, this scenario is challenged by results from large-scale field experiments at Duke University (2004) and Stanford University (2002). At Duke University, after exposing lobolly pine to enhanced levels of CO_2 for 7 years, a complex pattern of results has emerged. While annual growth rates have increased by 10–25%, most of these have occurred only in dry years. Given normal or wet years, responses have been a lot less and may be the effect of inadequate nutrition. At Stanford, a major finding has been that plant growth has only been stimulated with higher CO_2 when nitrogen, water and temperature were kept at normal (current) levels. When the latter factors were also elevated, plant growth was suppressed. Studies of impacts of elevated CO_2 on growth of radiata pine in New Zealand (Griffin *et al.*, 2000) found that growth with CO_2 at 650 ppm was elevated during the first

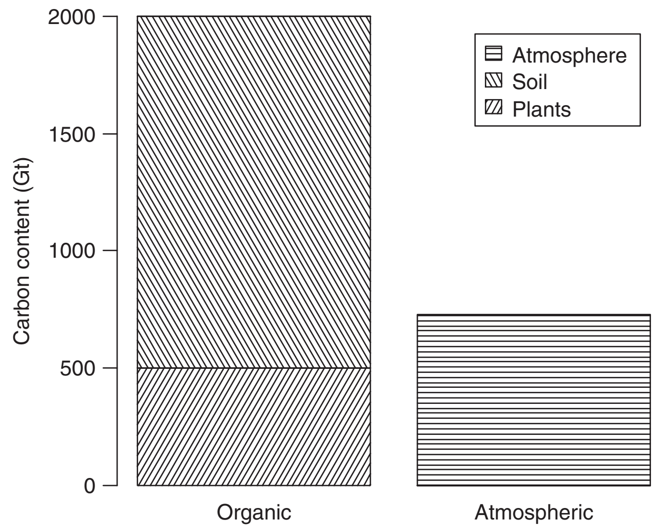

Fig. 8.1. Carbon stored in biomass compared with that in the atmosphere. (According to data reported by Mahli, 2002.)

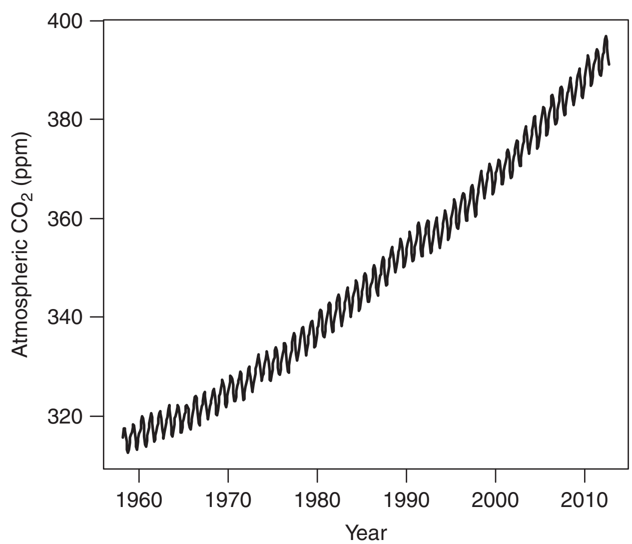

Fig. 8.2. Atmospheric CO_2 concentrations measured at Mauna Loa. (Data courtesy of the Scripps Institution of Oceanography and the US National Oceanic and Atmospheric Administration, Earth System Research Laboratory.)

2 years of the experiment compared with growth with CO_2 at 360 ppm, but then trees gradually 'acclimated', reducing stomatal conductance and thereby increasing water use efficiency. This increase in water use efficiency may explain the results at Duke University.

We can conclude that responses of forests to elevated CO_2 are expected to be positive, but that uncertainty is high. Acclimation appears to be more likely when nitrogen is limited, and greater water use efficiency may mean that production would be more enhanced on dry sites. Measured responses to elevated CO_2 are large enough, however, that we cannot dismiss them, and more research is needed so that they might be better quantified.

Pests may extend their ranges as a result of climate change, influencing forests in new ways. The range of mountain pine beetle in British Columbia has been greatly extended by a combination of warmer winters and warmer and drier summers than usual (Kurz *et al.*, 2008). Coupled with a large, susceptible forest resource, the outbreak of the pest is estimated to be at least 10 times larger than any previous outbreak (Plate 3). Net emissions from the forest resulting from the pest are calculated to average 20 Mt C/year between 2000 and 2020, demonstrating a synergy between climate change and pest influences.

Deforestation

Forests are important sources of GHGs. The world's forests occupy just over 4 billion hectares (FAO, 2010), about half the estimated area of primeval forestland that existed before we began to clear it. Deforestation was estimated to contribute 17% of anthropogenic GHG emissions in 2004 (Fig. 8.3). Deforestation has occurred primarily in East Asian and South American tropical countries, although in recent years Australia and North America have also contributed a significant proportion of these emissions through large-scale forest fires.

Global emissions of GHGs were estimated to be 49 Gt CO_2-e (the 'e' stands for 'equivalents' because gases have different impacts, tonne for tonne, as greenhouse gases and so all are converted to equivalent impacts of tonnes of CO_2) in 2004 (IPCC, 2007), and it is clear that much of the extra carbon entering the atmosphere is from reservoirs that were created through photosynthesis. Photosynthetic assimilation of CO_2 occurs with the preferential uptake of CO_2 containing the lighter stable isotope of carbon, ^{12}C, over the heavier isotope, ^{13}C. As so many sources of CO_2 entering the atmosphere are likely to be biomass or biomass derivatives such as fossil fuels, and therefore a result of photosynthesis, the relative amount of ^{13}C with respect to ^{12}C (expressed using the delta notation as $\delta^{13}C = (((^{13}C/^{12}C)_{atmospheric\ CO^2})/((^{13}C/^{12}C)_{reference}) - 1)*1000)$ decreases, while the CO_2 concentration increases (Fig 8.4). For further details see Allison and Francey (2007).

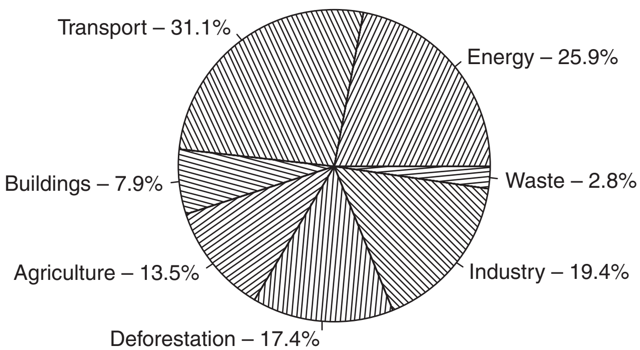

Fig. 8.3. Percentage GHG emissions by sector in 2004. Global GHG emissions were 49 Gt CO_2-e in that year. (From IPCC, 2007.)

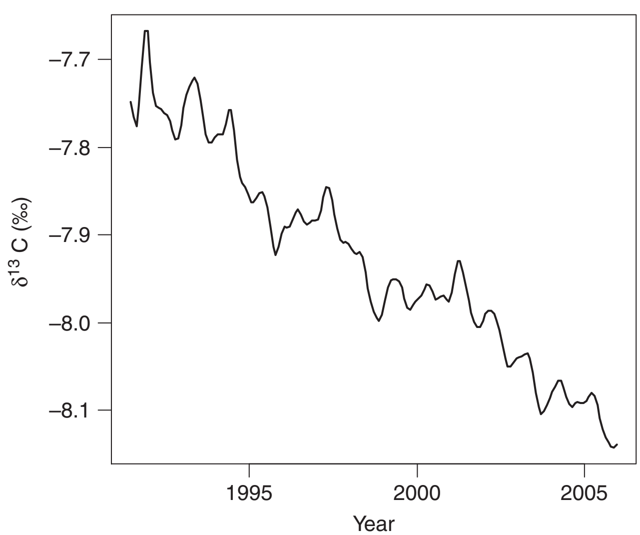

Fig. 8.4. Ratios of stable isotopes of carbon, ^{13}C and ^{12}C, in the atmosphere measured at Cape Grim in Australia. (Data courtesy of Dr Colin Allison and Dr Roger Francey, Commonwealth Scientific and Industrial Research Organisation, Australia.)

Energy dynamics

If only GHGs are considered, then CO_2 sequestration benefits from new forest establishment are overwhelmingly positive, but afforestation can impact on global temperatures in an adverse way. The albedo (proportion of incident radiation reflected from a surface) of grassland is typically 0.24 to 0.27 compared to approximately 0.12 for pine plantations (Moore, 1976). This means that replacement of grassland by plantation results in greater short-wave absorption and this can contribute to increasing temperatures through increases in long-wave radiation emitted from the landscape. In an Australian study, Moore (1976) observed that long-wave radiation above radiata pine forest land exceeded that above grassland by 15% and 25% during winter and summer respectively.

On a global scale, it has been estimated that up to 40% of the sequestration benefits of replacing grassland with forest might be offset by this effect (Gibbard *et al*., 2005). Bala *et al.* (2007) went further, suggesting that afforestation of boreal regions should result in a net increase in global temperature, tree planting in temperate regions should be neutral, while only afforestation of tropical zones would significantly mitigate climate change. However, Pontgratz *et al.* (2011) pointed out that past deforestation occurred on productive land, less subject to snow than normal at any given latitude, and so afforestation of most temperate grasslands is deemed to be beneficial. Snow has a very high albedo, and covering of foliage by snow can greatly impact on energy absorption in the landscape. Moreover, plantations are likely to contribute proportionally more to climate change mitigation because they are very highly productive and also because they are established in areas where snow is either infrequent or where snow never falls. Kirschbaum *et al.* (2011) estimated that the albedo effect would reduce the climate change mitigation potential of radiata pine plantations in New Zealand by approximately 10–20%.

Contributions of forestry to GHG mitigation

The global forestry sector makes large direct and indirect contributions to the mitigation of GHG emissions, and its contribution might be even larger if we set the right policies. Forests are a major store of carbon. As mentioned above, standing trees and the organic layer of forest soils are both significant carbon reservoirs. If the area under forest increases, then the size of this reservoir also increases. New forests sequester extra carbon from the atmosphere as they grow and are therefore carbon sinks. Given the relative dimensions of carbon storage in plants versus the atmosphere mentioned above, it is likely that extra storage in new forests could sequester all the troublesome carbon emissions that humans have added to the atmosphere during the last 150 years if we chose to expand the forest area sufficiently. If the FAO's estimates of total forest storage and forest area (FAO, 2010) are accurate, implying an average forest storage of CO_2-e of 596 t/ha, then we would need approximately 1.4 billion hectares of new forest to return atmospheric CO_2 concentrations to 280 ppm. Current global forest area is just over 4 billion hectares (FAO, 2010).

The rate of carbon sequestration by forests depends on growth rates of trees, but planting of new forest, rehabilitation of existing native forest, or allowing scrub or uneconomic farmland to revert to forest are all mechanisms by which sequestration will occur. Establishment of forest on pastureland also reduces agriculture's conversion of CO_2 to methane (CH_4) and CH_4 is 23 times worse than CO_2 as a greenhouse gas. Radiata pine plantations in New Zealand, for example, typically sequester between 25 and 35 tonnes of CO_2/ha/year, and forests planted on marginal farmland will store additional carbon that would otherwise be in the atmosphere.

Replacement of grassland by forest is almost insignificant on a global scale, but is hugely important in some countries, such as New Zealand, and potentially important in many developing nations. The recent publication of *New Zealand Energy Greenhouse Gas Emissions* by the Ministry of Economic Development (MED, 2008) highlights the important role that forestry plays in reducing net emissions of CO_2-e. In 2007 New Zealand's total national GHG emissions were estimated to be just over 75 Mt CO_2-e, while net absorption of CO_2 by forests reduced net national emissions to just under 52 Mt CO_2-e. Recent projections of sequestration by 'Kyoto-compliant' forests (planted since 1989 on grassland) for the first Kyoto commitment period (MfE, 2009) implied an average sequestration rate of just under 33 t/ha/year (this high estimate perhaps reflects the current of age of these forests, because sequestration rate is typically lower early in a rotation and most of the forests are middle-aged. Their sites may also be more fertile than usual on average).

This direct contribution to GHG emission mitigation results from previously planted forest. In general, forests in their first rotation will be the major contributor to reduction in net emissions. However, altered management practices on forests planted earlier, which increase the volume of the growing stock, will also contribute. A quick calculation shows the potential magnitude of sequestration by changes in silvicultural practices in old New Zealand forests:

1. Assume sequestration of 25 t/ha of CO_2 or 625 t at a 25-year rotation, this implies an average store of 312 t in a radiata pine forest site.
2. If the rotation age increases from 25 years to 35 years, this would increase the average store of carbon to 437 t.

This is an incremental 125 t/ha average or 181 million tonnes of carbon potentially at steady state, for the 1.45 million hectares planted in New Zealand prior to 1990.

It is not easy to quantify the indirect contribution of forestry, but it is likely to be very large. It arises in the following ways:

1. Land growing forest instead of livestock means emissions of CH_4 and N_2O, two important GHGs, are much reduced.
2. Wood used as a structural material has much less embodied energy than alternative products, and as marginal energy production usually emits GHGs, any reductions in energy use can reduce overall emissions. Air dried wood has an embodied energy footprint of 0.5 MJ/kg, compared to 34 MJ/kg for steel, 90 MJ/kg for plastics and 170 MJ/kg for aluminium (Lawson, 1994). Concrete manufacture produces CO_2 and also has high energy costs.
3. Wood is an important, GHG-neutral, source of energy, and use of wood for energy displaces generation technologies that release GHGs. On a global scale this is a very important contribution, with typically 80% of wood harvested in developing nations being used for fuel.
4. The use of wood in residential construction also acts as a carbon sink, at least for the life of the dwelling.
5. Other wood uses, such as treated roundwood, non-residential construction, also form temporary carbon sinks.

Ford-Robertson (1997) has attempted to estimate potential impacts of establishing 1 hectare of radiata pine on a reasonably productive site in New Zealand while allowing for periodic harvest (Fig. 8.5). The assumption is that this is the average of many hectares in a normal forest.

Policies for Mitigating Climate Change through Forestry

In December 1997 a meeting of the United Nations Framework Convention on Climate Change in Kyoto, Japan, agreed in principle to reduce emissions

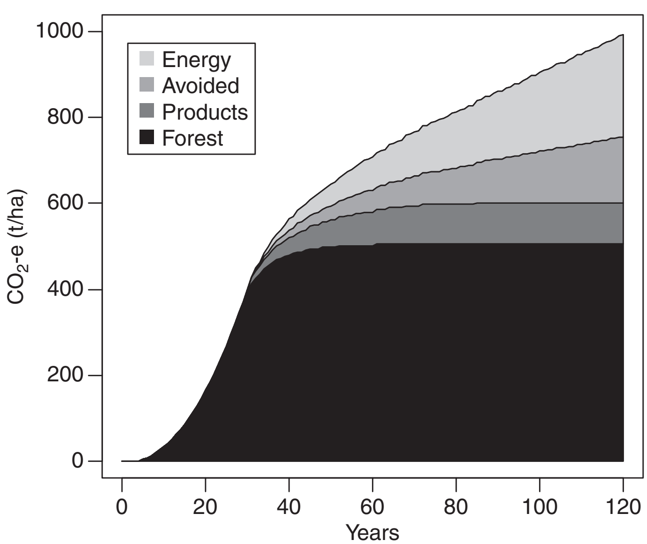

Fig. 8.5. Estimated CO_2 storage benefit from planting 1 hectare of radiata pine in New Zealand. The forest benefit is direct CO_2 sequestration (allowing for periodic harvest), the products area represents storage of C in forest products, avoided emissions are due to the substitution of wood into construction instead of alternative products, and the energy area represents potential energy generation from wood wastes instead of fossil fuels. (Data courtesy of Justin Ford-Robertson, 1997.)

of greenhouse gases. This was an agreement between nations. The Kyoto Protocol establishes the notion of a 'commitment period', during which net emissions are measured. Emissions between 2008 and 2012, the first commitment period, include direct emissions from fossil fuels, emissions of chlorofluorocarbons, nitrous oxide and CH_4 from agriculture, and any net change in carbon reservoirs such as forests. The latter can be positive or negative. All these GHG emissions are converted to CO_2 equivalents because their influences on climate vary. Methane, as previously mentioned, is 23 times worse than CO_2 as a greenhouse gas, and so pastoral farming has GHG emissions despite being mostly carbon neutral because it converts CO_2 to CH_4. A nation that increases its carbon storage in forests during a commitment period can use this to calculate a reduction in net emissions, while another that reduced its forest store of C would increase its emissions during the commitment period.

Forty-one 'Annex I' states agreed to limit their net emissions to varying amounts relative to a base year, which was 1990 for most states. Annex I countries are mostly industrialized ones, although a few, like New Zealand, are merely wealthier than most other nations. New Zealand's emissions profile is more like that of a developing nation because agricultural emissions make up a large proportion of its total. Annex I countries can attempt to limit their emissions by investing in emissions reduction projects in non-annex I countries through a process known as the 'Clean Development Mechanism' (CDM). Annex I countries were given carbon credits, known as Assigned Amount Units (AAUs) equivalent to their agreed emission targets in tonnes of CO_2-e. If they exceeded their emission targets, then they would need to purchase credits, and if their net emissions were less than their targets, then they would have AAUs to sell. The CDM allowed them to earn credits by reducing emissions or by developing in non-polluting ways that involved 'additional' expenditure. The Kyoto Protocol has now been ratified by 191 states. One signatory, the USA, has not ratified the Protocol, and two other nations, Canada and New Zealand, have withdrawn. Given these international commitments, many countries were faced with the need to change their citizens' behaviours, and they often resorted to internal carbon trading schemes, using carbon credits equivalent to 1 tonne of CO_2-e. The basic idea of trading schemes, that a market can determine the most effective way to solve the problem, is attractive because it preserves freedoms to a greater extent than schemes involving authoritarian commands.

Trading schemes fall into two general categories:

1. Compliance schemes, where participants are required to either reduce their emissions or purchase credits to cover them; and
2. Voluntary schemes, where participants voluntarily trade out of either a concern for the environment or to gain some marketing advantage by improving their reputation.

At the time of writing, compliance schemes have all been 'cap and trade', schemes, including the international Kyoto scheme, because such schemes can have relatively slight impacts on behaviour and therefore can be made politically acceptable. Allowable emissions are capped, and participants are required to either reduce emissions to the level of the cap or purchase credits to cover their emissions. Credits can be earned for sale in two ways, either by reducing emissions below the cap or by sequestering GHGs from the atmosphere. Sub-cap credits and sequestration credits are treated the same under such schemes, but this creates problems.

One important problem is that somebody had to decide on the level of the cap. In the Kyoto scheme, each country decided on its own level of cap. Economies in the former Soviet block shrank dramatically in the years following 1990. These newly free market countries, with 'economies in transition' (EITs), agreed to cap emissions at 1990 levels, and consequently have vast reservoirs of credits to sell on the international market (Fig. 8.6). What this means is that these credits, labelled 'hot air' credits by some, could be exported to other countries and led to those countries not having to respond at all to the problem of climate change. It would have been more rational to have a lower cap for EITs, but countries were able to set their own caps. Most internal trading schemes forbid the sale of 'hot air credits' or at least limit them in some way. Europeans justify the exclusion of credits from economies in transition using a concept called 'additionality' to identify acceptable credits generated by behaviour that is 'additional' to normal behaviour and has been taken specifically to mitigate climate change. The Kyoto Protocol allows for 'additionality' at an international level in Articles 3.4, 6.1 and 12.5. Additionality has to be assessed, leading to additional layers of bureaucracy (Valatin, 2012). Despite these efforts, creative people are finding ways to launder hot air credits (Alessi and

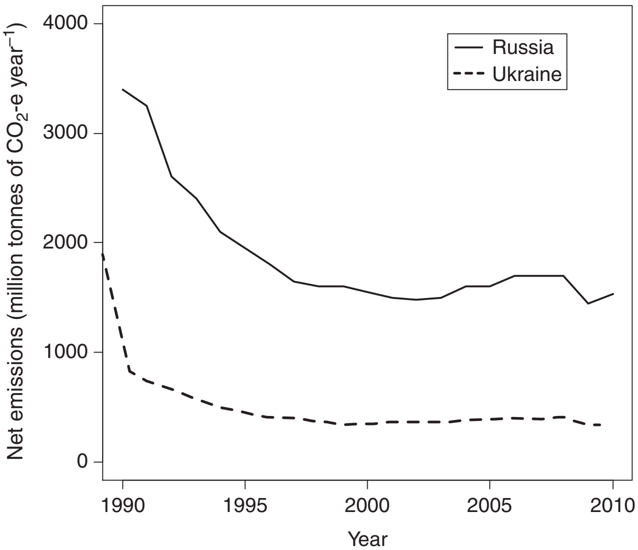

Fig. 8.6. Net greenhouse gas emissions from Russia and the Ukraine versus year. (Source: United Nations Climate Change Secretariat.)

Fujiwara, 2011), undermining attempts to solve the global climate change problem through trading schemes by lowering carbon credit prices.

When credits are awarded to a GHG emitter for emission reductions below a cap in an annex I country, these credits are purchased to offset emissions by other people, who then claim to be 'greenhouse gas neutral', but this is misleading. The credits were initially given to the first emitter as a 'right to pollute' based on historical behaviours, and so purchasers are buying a right to pollute rather than for the sequestration of their GHG emissions.

Emissions trading has resulted in a bewildering array of carbon credits. The following are recognized by the Kyoto Protocol:

AAU: Assigned Amount Units are emission allowances assigned to countries in the Kyoto Protocol for a commitment period. The emission allowances assigned depend on the emission targets that the countries have to meet during the period 2008–2012.
RMU: Removal Units are emission allowances that are generated in addition to AAUs as a result of an increase in national carbon sinks. RMUs expire at the end of a commitment period.
ERU: Emission Reduction Units are created by projects in industrialized countries that are considered to be 'additional'; i.e. they involve extra expenditure to establish non-polluting substitutes for polluting processes. They are generated when one annex I country creates emission reductions in another annex I country.
CER: Certified Emission Reductions are credits derived from CDM projects.
tCER: A temporary CER (tCER) is a credit from a CDM project associated with an afforestation or reforestation project. tCERs expire at the end of the subsequent commitment period and may be renewed if carbon sequestration in forests can be proved by defined methodologies.
lCER: A long-term CER (lCER) is an emission certificate allocated for a CDM project associated with an afforestation or reforestation project. lCERs expire at the end of the completed project period and cannot be renewed. They must be replaced by other emission credits unless proof of carbon sequestration is provided every 5 years.

In developing nations CERs have the potential to undermine emissions trading schemes by inflating carbon credit currency. CERs cause credit inflation because there is no requirement for emitters to account for their emissions, and so emitters are essentially gifted free credits. When credits are awarded for reductions in emissions, the principle of emissions trading, that emitters should pay sequesterers to clean up their pollution, is violated. In order to solve the problem of climate change from anthropogenic GHG emissions, nations should look after their carbon credit values in the same way that they nurture national currency values, but this is not widely recognized. Instead, credits earned through emission reductions are allowed to swamp carbon markets, credits are randomly 'awarded' to people as financial inducements or as compensations that will not impact on national treasuries, and credit values decline to the point where little is accomplished by trading schemes.

RMUs, on the other hand, represent real reductions in atmospheric GHGs, but strangely they are often regarded as lesser credits compared with ERUs or CERs. There is a perception that forest establishment is only a temporary solution, and that the value of the credits is somehow lost. If forest-based credits are measured and accounted for so that people awarded credits need to repay them when their forest becomes an emission source, then RMUs should be highly valued because they represent a genuine cleaning of the atmosphere. If atmospheric cleaning costs become too high, then emitters will adopt emission reduction schemes in order to reduce their credit purchase requirements, and so no gifts of credits should be required for these reductions to occur.

Developing nations can seek rewards for reductions in deforestation via the 'Reducing Emissions via Deforestation and Forest Degradation' (REDD+) mechanism agreed through the United Nations. This programme aims to attach a value to carbon storage, and could see large amounts of money flow from developed nations to developing ones in return for reductions in rates of deforestation and forest degradation. The programme requires verification of emissions reductions, and rewards might be made via carbon credits or through direct financial payments. Clearly the latter is preferable because carbon credit rewards have the potential to undermine carbon trading schemes in developed countries for the reasons outlined above.

Given a high enough credit price in a nation's GHG emissions trading scheme and also the provision for awarding credits for sequestration by forests (essentially domestic RMUs), carbon trading can change the values of forest investments. For instance, the New Zealand scheme allows owners of forests established after 1989 to claim credits for sequestration earned after 2008, but these credits must be repaid if carbon stocks fall below what has been claimed when forests are harvested. It may seem strange that anyone would derive an incentive for new planting from this, but the benefit for forest owners arises from changes in annual cash flows within a forest investment. A typical plantation forestry investment involves large costs for establishment, overheads and tending through the rotation, with one very large revenue stream at the end of a rotation. Carbon cash flows are the reverse of this pattern, with revenue streams from carbon credits throughout the rotation, and then a large carbon credit cost at the time the large harvest revenue is received. Forest investors use interest rates to evaluate these cash flows and early interest on carbon credit revenues adds a lot to the value of an investment.

A carbon trading scheme that rewards owners of forest sinks can lead to changes in silviculture. For instance, at current prices for operations and logs in New Zealand, the relative rankings of alternative silvicultural regimes are much changed if we assume a reward of NZ$20/tonne of sequestered CO_2 (Fig. 8.7).

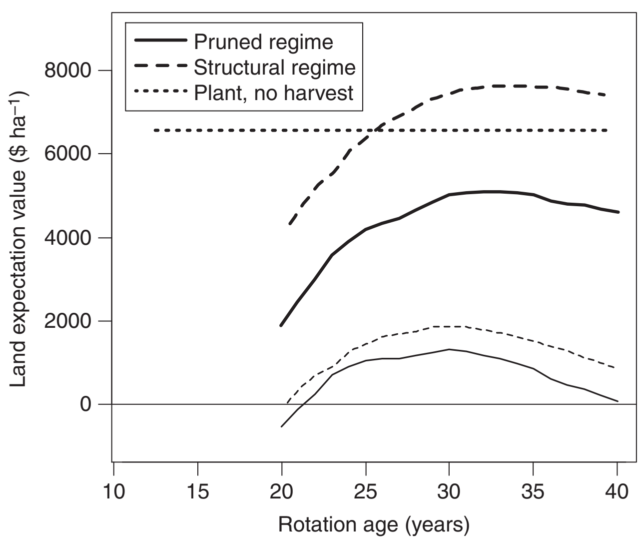

Fig. 8.7. Impacts of carbon trading on land expectation values of alternative silvicultural strategies for radiata pine on an average site in New Zealand. The interest rate used was 8% and the carbon credit price was assumed to be NZ$20/tonne. Thin lines include revenues for wood only and thick lines include revenues for wood and carbon credits, except for the case of planting with no harvest where the LEV is a constant and there is no rotation age. (The analyses were conducted by E.G. Mason using simulations from Atlas Forecaster™ software and a discounted cash-flow spreadsheet. For more details please contact the author.)

Not only are relative values changed to favour structural regimes that maintain higher stockings, but also financially optimum rotation ages are increased because this maintains higher average carbon storage in the landscape. Debris left after harvest is counted as temporary carbon storage, and so forest owners need only repay credits for approximately 75% of the carbon that was in their forest at harvest, so long as they replant.

Summary

Forestry and climate change interact strongly. Changes in atmospheric CO_2 concentrations can increase growth directly or change temperatures, thereby influencing forest productivity. There is some evidence that forests acclimate to higher levels of CO_2 and so their productivity may be directly enhanced only during periods of limited water supply. Climate change can alter distributions of plants, pests and diseases, thereby imposing extra risks for forest owners. Afforestation outside of boreal zones can greatly mitigate anthropogenic climate change by sequestering atmospheric CO_2, but some of the benefit is reduced by changes in landscape albedo. Deforestation in mostly developing nations represents more than 17% of anthropogenic GHG emissions. The Kyoto Protocol set up international GHG trading schemes, and many nations have established domestic carbon trading in order to promote more climate-friendly behaviour. At the time of writing, some of the mechanisms established for carbon credit trading appear to be leading to credit inflation.

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9 Plantations for Wood Production with Environmental Care

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Introduction

Plantation forestry is essentially about renewable and sustainable development of natural resources and their use. This chapter is about plantations for sustainable wood production with due care for the environment. Closely related issues include the global distribution and extent of forest plantations, together with species selection (Chapter 2), as well as the impacts of plantations on water quantity and quality in catchments (Chapter 3), their roles as a source of biomass for bioenergy (Chapter 5) and for sequestering carbon (Chapter 8).

Plantation forests account for less than 2% of global land cover and about 7% of total forest cover, but supply a considerably greater percentage of industrial wood. The share of industrial wood production from plantations has been increasing over the last two decades and undoubtedly will increase in order to meet even the lower estimates of per capita consumption for wood products in the developing countries as their economies grow. An increasing number of developing countries are promoting wood growing and wood products industries to improve their rural economies and export incomes. Plantations are the only source of fuel for many communities in poor regions in some countries.

The focus in this chapter is on forest plantations established with a single species of either native or exotic origin. Emphasis is given to productivity and plantations in the tropics and subtropics where much of the current plantation forest development is occurring.

Plantation forests in the landscape

The concept of sustainable forest management invokes a kaleidoscope of ideas and expectations in people's minds, rooted in our long history of intimate association with forests and overlaid by ever-changing social and political values. Forests for wood production have been, and still are, contentious in many countries. In the past, plantation forestry was often owned and managed as a part of the public sector, to ensure wood supply for regional wood-processing industries. A profit was considered desirable, but not essential, as plantations served the 'public good'. This has changed. Today, most plantation forests and the wood-processing industries are in the hands of private sector, which contributes significantly to regional economies and employment in many countries.

Plantation forestry as a land-use system should comply with the principles of environmental care and regulations governing those principles. This is a challenge to forestry businesses because delivery of each environmental value or benefit from the ecosystem adds management complexity and cost. Some people demand impractical and unnecessary conditions that the structure, composition and function of plantation forests should mimic those of native forests.

A holistic way of viewing the diverse range of land uses, including native forests, woodlands, plantation forests, agro-forests, environmental tree planting and agriculture, is to consider them as inter-linked and partly overlapping components of a land-use continuum, with each entity serving one or more primary purposes. These entities are depicted as links in a chain in Fig. 9.1, which means that the strength of the chain is dependent on the strength of each link. Although all forest types and communities of trees have multiple values, it is unreasonable to expect each link in Fig. 9.1 to serve all values of conservation and production. But the continuum as a whole, together, can deliver economic benefits and ecosystem services including water, biodiversity and carbon sequestration. Ranking of values according to the primary purpose of a particular land use is necessary for judicious and practical management. For plantation forests, objectives may vary from intensive wood production using exotic or native species to plantings of a mixture of diverse species for environmental benefits. It is important to ensure balanced management of all resources in multifunctional landscapes (Fig. 9.1). The scale of an individual entity in Fig. 9.1 may vary, based on the overall landscape functions, economic considerations, informed trade-offs, policies, regulations and community values. The idea of a land-use continuum can promote balanced views on forestry multiple values from the landscape, leading to better outcomes for society. If investments in plantations primarily are aimed for wood production, it is not practical to expect every unit of that enterprise to simultaneously cater for all other ecosystem services. Wood production with environmental care is an essential service to society. Plantation forests can be managed to provide multiple values, including wood production, watershed protection and conservation on the same landscape (Powers, 1999; Brockerhoff *et al.*, 2008).

The size of an individual entity in this continuum may vary, based on the overall landscape functions, economic considerations, informed trade-offs, policies, regulations and community values. Conservation is the primary goal in some forests. The importance given to production goals increases as the intensity of management and investments increase.

Purpose and benefits of plantation forests

Sustained productivity is the foundation on which sustainable plantation forestry and the outcomes from forestry business rest, even when forestry systems are designed to provide environmental benefits, because productivity is a key driver of ecological processes. Sustained productivity is, arguably, the best measure that integrates the functioning of forests and signals the direction of changes in response to management practices and ecological events, including climate change.

Achieving sustainability can be assessed by the degree of alignment between some critical variables: ecological capacity of the site and its interconnection

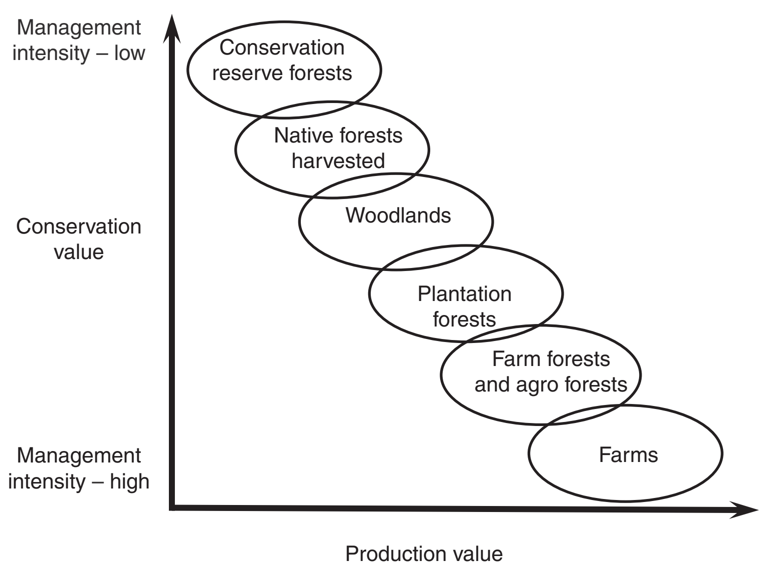

Fig. 9.1. A representation of forest types and land uses as a continuum providing multifunctional landscapes.

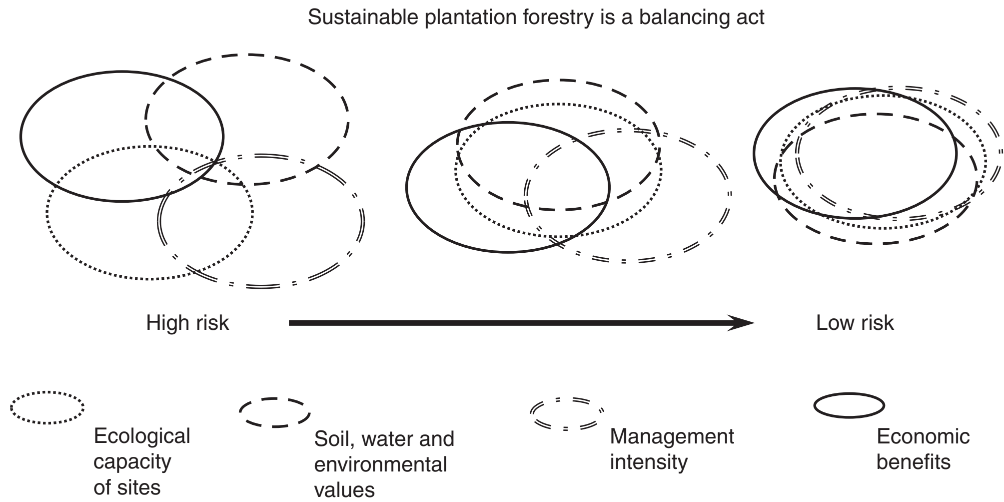

Fig. 9.2. Interactive variables and their alignment governing sustainable plantation forestry.

with the landscape; environmental values including soil, water, biodiversity; investments and management intensity; and economic and social benefits. A conceptual model of this is shown in Fig. 9.2. The nature and degree of risks to sustainability depends on the degree of alignment, weak or strong, between the components (Fig. 9.2). The alignment will not be perfect because it is unlikely there will be full knowledge, tools, investment and social agreement necessary for perfection. For achieving sustainable outcomes, there should be explicit goals for a particular plantation forestry development. Nambiar (1999) described a set of goals appropriate for commercial plantation forestry as follows: (i) ensure the trend in productivity is non-declining or increasing over time; (ii) protect the productive capacity of the soil and off-site values, including water and biodiversity in the landscape; (iii) promote incentive, innovation and profit in growing and utilizing wood; and (iv) improve economic and social benefits to the community. These goals are applicable even if plantations are established for carbon sequestration or production of biomass for conversion to bioenergy. In most circumstances, there will be a need for informed trade-offs among values, none of which can be held supreme on its own.

Management of natural events (e.g. drought) will continuously influence the two-way direction between the high and low risks. The goal of management should be to continuously strive towards the best alignment and judicious management applied at the landscape level (Figs 9.1 and 9.2). Even intensively managed plantation forest estates of a single exotic species managed primarily for wood production are more complex, biodiverse and long-lived than agricultural or horticultural systems. Plantations of introduced and native species can be developed side by side, as seen with *Pinus radiata* and *Eucalyptus globulus* plantations in southern Australia, each managed for different products and hence rotation length. Sustainable management is a balancing act and a continuous challenge.

If a landowner wishes to plant a small area under trees, the decision is relatively simple. It is not so for a large-scale plantation forestry. It involves analysis of complex and interacting variables, including national and regional policies, which need to be for the long-term. Negotiations and consultations are needed on the location, availability, community support, cost and security of land. Also, the intended purpose, suitability of the growing environment, options for processing, markets, investment incentives such as tax concessions, land access, and environmental and social impacts need to be assessed. There are cases in plantation forestry where poor, short-term profit-driven decisions and poorly regulated tax incentives at the start have led to perverse outcomes and failure.

Plantation forestry is expanding as many developing countries use this to improve and diversify their land use and drive regional economic development through growing, processing and marketing wood products. Many governments offer incentives to attract investments from national or international sources. For a number of countries, products based on plantation resources are major sources of export income.

Estimates of the contribution of plantation-grown timber to the global roundwood harvest in 2005 ranged from 30% to 66%, depending on how plantations were defined (Varmola *et al.*, 2005; Seppälä, 2007; Carle and Holmgren, 2008). Clearly plantations are providing a large and increasing proportion of global wood supply. As noted earlier, wood production from plantations is the only solution to meet the growing demand for wood in countries where present per capita wood consumption is low but increasing rapidly as their economies develop. Many plantations managed for timber production achieve growth rates between 10 and 40+ m^3/ha/year in large-scale estates, whereas the average for native forest is somewhere around 2 m^3/ha/year. Seppälä (2007) estimated 73 million ha of effectively and intensively managed planted forest, representing less than 2% of the world forest cover, could meet the current demand for industrial wood, although such a concentration of production is neither desirable nor practical.

Not all plantations are established to grow commercial wood. Kanninen (2010) estimated that about 22% of global plantations are classified as protective rather than productive. Plantations have been extensively used to stabilize sand dunes (*Pinus pinaster* in France; *Acacia* in Africa; *Haloxylon* in Iran; *Tamarix* in Israel; and *Casuarina* in China, Senegal, India and Vietnam). Plantations have been established in upper catchments to arrest erosion and improve water quality and as windbreaks to protect livestock and crops. Plantations are also established for aesthetic and recreational purposes.

Plantations are efficient to manage and therefore more cost-effective than harvesting from multi-species uneven-aged forests. Plantations can be established on land that is less suitable for agriculture and they respond to practices including planting genetically improved stock, soil management, fertilization, weed control and thinning, and they allow efficient product segregation at harvest. Forest operations can be mechanized and carried out at planned intervals. Regulation and control of yield is much easier in a plantation. There are usually one or two major species in a plantation programme, providing uniform and familiar product, enabling economies of scale in processing. Economies of scale can support organized tree breeding programmes and appropriate deployment strategies, including high-quality seedlings and/or clones of improved genetic stock. For example, clones of *Eucalyptus grandis* × *Eucalyptus urophylla* hybrids in plantations in Brazil yield 40–50 m^3/ha/year over a 7-year rotation in deep soils. Similarly, plantations of *Acacia mangium* established with seedlings raised from seed orchards can yield 40–45 m^3/ha/year in 6–7-year rotations in southern Sumatra, Indonesia. Plantations of *Pinus radiata* established with genotypes developed from second- or third-generation genetic improvement programmes managed under sound silviculture can yield 20–35 m^3/ha/year in a 35-year rotation on podzolized sandy soils low in fertility and receiving 650–800 mm annual rainfall and where evaporation exceeds precipitation for 6 months of the year. The adjacent native woodland has a mean annual increment (MAI, m^3 wood/ha/year) of 2–3 m^3/ha/year. In all such cases, genetics of planting stock alone will not provide desirable outcomes. Good site and stand management is equally or more important.

Economic, environmental and social benefits from plantations can be substantial, especially in rural areas. Plantations can be a profitable business and have been managed sustainably for decades in many countries, gaining considerable knowledge about the risks and prospects along the way. For example, *Pinus radiata* plantations in New Zealand can return an average of about 7% on investment. Natural forests cannot provide this (although there are products that plantation forests cannot provide that native forest can) unless they are graded for high-value timber or unless the real value of the forest is not acknowledged as a cost. Wood as a construction material is environmentally superior to its competitors (cement, steel, aluminium) and a source of fuel that is carbon neutral (Chapters 4 and 5). Plantations sequester carbon and contribute to mitigating adverse effects of climate change when established on long-cleared land.

There are several important strategic considerations for sustainable forest resource development. Benefits from plantation forests will be realized only if they are managed towards desired goals and purpose. If not, they may deliver little benefit or fail. At a global scale, there are outstanding examples of sustainable plantation forestry. There have also been failures and some languish without proper management in some developing countries. Many tree-planting programmes, some motivated by short-term political appeal and dedicated to improve environmental values or landscape rehabilitation, are left unmanaged beyond the initial planting, lacking the minimum investments required for ongoing management and care. Woodlots planted and used for fuel wood production are seldom managed well. Failed plantings serve no one and are a lost opportunity. When plantation forestry is focused on commercial wood production with due environmental care, they are usually managed throughout their life cycle.

Clearing of native vegetation for plantation forestry is not permitted or increasingly restricted in many countries. Nevertheless, tropical forests are being cleared, although mostly for agriculture or commodity crops like oil palm and rubber. When plantation forests are established on agricultural land, care must be taken to ensure that they do not, or are not perceived to, compete with food production. This is an emotional public issue, although in terms of scale, plantation forests occupy only a small proportion of the cultivated land in most regions. For large-scale development of plantation forestry, detailed environmental impact assessment is mandatory in several countries and regions (or states) within certain countries.

Management of Plantation Forests

As discussed earlier, the nature and purpose of plantations are very variable and a comprehensive account of their silviculture and management will not be described here. Planted forests and their management are the subject of several books, including Bowen and Nambiar (1984), Maclaren (1993), Nambiar and Brown (1997), Boyle *et al.* (1999), Evans and Turnbull (2004) and West (2006). The challenges in developing 'new forests' in harsh, arid and saline environments are the focus of another book (Nambiar and Ferguson, 2005). When the focus is on silviculture and management of plantations established mainly to grow wood, there is a sequence of events that need to be considered following on a clear understanding of the intended purpose in a given environment. These include: the nature of the land base, species, site selection and preparation, protection of biodiversity, conservation of soil and water, planting (seed collection, raising seedlings or cuttings in nurseries, planting in the field), stocking, weed control, nutritional management, management of pests and pathogens, thinning, pruning, rotation length, the economics of plantations, yield regulation and whole estate planning and harvest planning. For the second or subsequent rotations conservation of site resources (e.g. slash and litter management) is a critical issue. The whole process, seedling to market, should be considered as a continuum.

Species selection

The choice of species and key attributes for their selection include potential growth rates under the environment (physiologically adapted to the climate of the site), their ability to cope with prevailing and new environmental risks (e.g. frost, drought), species and soil matching, susceptibility and vulnerability to pests and diseases, responsiveness to management, and suitability of the wood for intended products. Species, product options and markets determine the rotation length, which range from 5 to 7 years in *Eucalyptus* or *Acacia* grown for pulp wood in subtropical or tropical environments to 60 years or more for species such as *Pseudotsuga menziesii* and *Picea sitchensis* in cold-temperate regions.

Chosen species may be indigenous or exotic species depending on the intended purpose. Economic factors and landscape values also require careful consideration.

Growth rate is important; in operational forestry this may vary from as low as 2 m^3/ha/year in planted pine forests in Scandinavia to as high as 50 m^3/ha/year in eucalypts in parts of Brazil. Faster wood growth rates with appropriate wood quality and freedom from pests and diseases are important. Kanninen (2010) lists the six most commonly planted genera in order as *Pinus*, *Cunninghamia*, *Eucalyptus*, *Populus*, *Larix* and *Acacia*. Several factors determine the choice of species and sometimes native species are suitable (see Chapter 2). There are many examples of where native species meet the physiological requirements and are grown successfully in plantations on land modified substantially from its original features. For example, the USA, Japan and Russia have extensive plantations almost entirely of native species. Other countries either cannot find suitable native species to meet their requirements or have opted for exotics. For example, New Zealand, Chile, Brazil, India, Indonesia, parts of China and South Africa have plantations of almost entirely exotic species. In Australia, both exotic pines and indigenous eucalypts are widely used. The most prominent exotics for wood production are *Eucalyptus*, *Pinus* and *Acacia*. Important exotic pine plantation species are *Pinus taeda*, *Pinus elliottii*, *Pinus radiata* and *Pinus caribaea*. The most important eucalypt plantation species grown in temperate areas are *Eucalyptus globulus* and *Eucalyptus nitens*. Significant species in tropical and subtropical areas are *Eucalyptus grandis* and its hybrids, *Eucalyptus urophylla*, *Eucalyptus saligna*, *Eucalyptus tereticornis*, *Eucalyptus deglupta*, *Eucalyptus camaldulensis* and *Acacia mangium*. Among the high-value timber species grown over the long term, teak (*Tectonia grandis*) is a common candidate planted in parts of Asia, Africa and South America.

The most appropriate species for a region or a sub-region will depend on climate, topography and soil. Available water and drought risks are critical factors. Cold tolerance can be important in some circumstances, especially when exotic species are chosen. All major species vary genetically across their natural distribution and this variation can be exploited through provenance selection and tree breeding (see later). Wood from plantations is used for a range of purposes: pulp and paper, sawnwood, reconstituted timber products (plywood, panels) and energy. Clearly a species that is suitable for all or most of these products is more versatile and better for risk management than one that is more limited in end use. The wood of *Pinus* species is often versatile enough to cover a range of end uses. One most notable is *Pinus radiate*, which, when introduced in Australia and New Zealand, was thought to produce a low-value wood, but has since been developed through breeding, management and 'engineering' the product into an exceptionally versatile timber species. Many plantation forestry programmes are dedicated to one species and one product; for example, *Eucalyptus* plantations in Brazil, *Acacia mangium* plantations in Indonesia and *Eucalyptus globulus* plantations in Australia are all predominantly for chip for pulp and paper production.

Eucalyptus plantations are also used for a range of purposes. They were originally established in some countries for fuelwood and charcoal, and the fast-growing eucalypts quickly gained dominance as a pulpwood resource. They have been difficult to peel, saw and dry because of growth stresses, but improvements in technology and processing practices are resolving these problems. There is an increasing opportunity for more *Eucalyptus* plantations to be established under sawlog regimes. The genus *Eucalyptus* has many hundreds of species, some of which have high-quality timber suited to the most demanding of end uses, but which typically grow more slowly than those species favoured for pulpwood production.

Some species have been grown successfully outside, sometimes far outside, their natural environmental range. There is an ecological risk in straying too far, unless investments are made in research adapting the introduced species to the new environment. Again, *Pinus radiata* is a strong example in this regard. The natural occurrence of this species is restricted to fragments totalling less than 8000 ha in the fog belt of Monterey in California and the adjacent Mexican Pacific Islands of Guadalupe and Cedros, where it is in poor health and of no commercial significance. It is virtually a relic species, facing extinction in its native habitat. However, this has been the seed source for more than 4 million hectares of *Pinus radiata* plantations distributed mainly in New Zealand, Australia, Chile and Spain. Even so, the large areas of occurrence as an exotic are confined to temperate maritime and Mediterranean climates and the species is not successful outside these environments.

Plantation species have a wide range of growth rates (Table 9.1). These are caused by differences between species, climates, soil and site (Fig. 9.3). The productivity of a particular species is determined by soil fertility, water availability and temperature/radiation (which is roughly proportional to latitude). Genetic selection and hybridization has allowed deployment of some species and hybrids to regions with climatic and soil conditions outside those found within the original habitats of their parents.

Tree breeding

Genetic improvement programmes are essential for commercial plantations, where traits determining quantity and quality of wood produced per unit area, resistance to pests and diseases, and adaptation to a changing environment and management inputs are important. In planting programmes where trees are planted essentially for environmental benefits, including aesthetics, growers tend to prefer seedlings raised from seeds collected from locally growing native species adapted to the local environment. There may be considerable variation in the growth characteristics (traits) of a tree species across its range of natural distribution. If these variations have a reasonable degree of heritability, they can be selected and incorporated in the next generation through breeding.

Table 9.1. Indicative rotation length and mean annual increment (MAI) for *Eucalyptus*, *Pinus* and *Acacia* plantations in some countries. (Adapted from various sources.)

Species	Country	Rotation (year)	MAI (m^3/ha/year)
Eucalyptus hybrids	Brazil	6–8	35–45
Eucalyptus hybrids	Congo	8	17–25
Eucalyptus grandis	South Africa	8–10	18–20
Eucalyptus grandis (sawlog)	Uruguay (Rivera)	16	35
Eucalyptus globulus (pulp)	Uruguay	8	20–25
Eucalyptus globulus	Chile	10–12	20–25
Eucalyptus globulus	Portugal	12–15	10–15
Pinus radiata	New Zealand	25	23–35
Pinus radiata	Chile	23	22–25
Pinus patula	South Africa	25	18–20
Pinus patula	South Africa	25	18
Pinus radiata	Australia	25–35	20–30
Pinus caribaea	Latin America	15	15
Pinus caribaea × *elliottii*	South Queensland	25–30	15–20
Pinus taeda, *P. elliottii*	USA	23	13–15
Pinus elliottii	South Africa	30	12
Acacia mangium	Sumatra, Indonesia	6–7	20–35

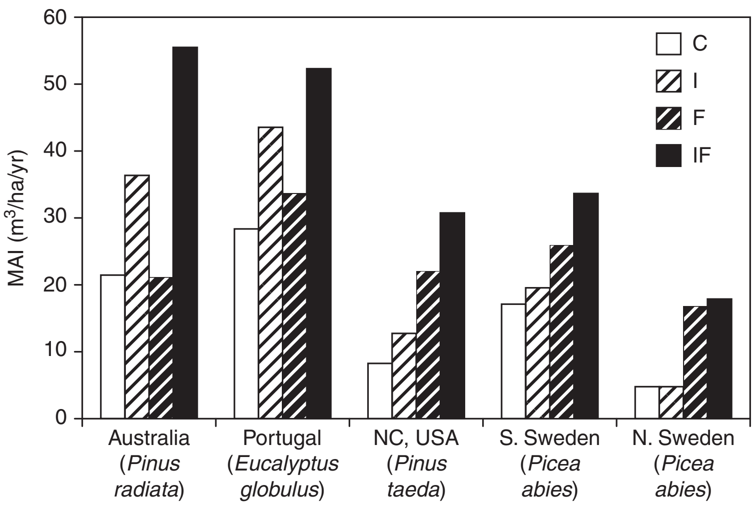

Fig. 9.3. The effect of no irrigation or fertilization (C), irrigation (I), fertilization (F) and irrigation and fertilization in combination (IF) on above-ground volume production of four plantation species from different parts of the world. (From Sune Linder.)

Some of the key terms used in tree improvement are described below (adapted from Arnold *et al.*, 2005; West, 2006).

Base population

All breeding programmes start with the collection of natural populations of a species. It is a gene bank containing the diversity of genotypes available in that species necessary for both gene conservation and breeding purposes. Even in most advanced breeding programmes, breeders may have to go back to base populations in search of genotypes with specific traits. When a species is threatened to extinction in its native habitat (for example, as in the case of remaining native populations of *Pinus* *radiata* in California), urgent measures are required to collect and conserve populations for future use.

- Heritability: The proportion of total variation that is due to genetic effects; the rest is attributable to environmental effects.
- Clones: A set of genetically identical individuals produced by vegetative propagation of selected plant tissues or through technologies including tissue culture.
- Family: Progeny raised from the seed collected from a single mother tree.
- Provenance: The original geographic source of seed from a natural population of a species growing at a location.
- Seed lot: Quantity of seed collected from a particular stand of a species, with a collection date and handling history.
- Seed production area: A planted stand of trees of suitable provenance that has been thinned, leaving the best trees from which seeds are harvested. Parents of individual trees are not known. The seeds from here are usually less improved than those from seed orchards.
- Seed orchard: A seedling seed orchard is developed from a progeny trial designed to test several families raised from known superior mother trees. The trial is thinned to remove poor trees, leaving the best performers to produce seeds. A clonal seed orchard is developed from a set of clones obtained from superior trees.
- Selection intensity: Selection intensity is a measure of selection given in units of standard deviation from the mean. The term is also often used in relation to the proportion of individuals in a population or group that is selected. Thus in 'intensive selection' only a small proportion is selected, and in 'extensive selection' a higher proportion of individuals may be selected.
- Breeding population: This is a repository of individuals with superior genotypes that have been selected over one or more breeding cycles. They provide the genetic base for ongoing selection and breeding and they can be enlarged by introducing new selections from time to time. Poor performing genotypes may be eliminated (or retained elsewhere for any future reference or use) sequentially in breeding populations. As the breeding programme moves through successive generations, the knowledge about the base and breeding populations increase, enabling more targeted selection.
- Genetic gain: The difference between the average of a desired trait in an offspring of each generation of the programme and its average in the individuals in the breeding populations from which the offspring originated.

The fundamental difference between individuals within provenances of a given species is determined by their genetic identity, given by a set of genes inherited from its parents. Each genotype has a specific inherent potential to function and grow, but this potential interacts with the local environment. The environmental and genetic components together determine the appearance and performance (called the phenotype) of an individual. The genetic variability within a species can be exploited to improve traits of interest, providing these traits are sufficiently heritable, and therefore capable of providing a genetic gain between generations of selection.

Genetic evaluation trials should be established over the range of environments expected in the plantation estate, which provides important information about genetic or genotype × environment interaction (commonly described as G × E). Those genotypes that rank best at the widest environmental range are selected. Understanding G × E interactions and the occurrence of this in some individuals can also be profitably exploited if managing that particular environmental variable is important. Despite the occurrence of G × E, the performance rankings of improved genotypes, particularly for wood quality as well as pest and disease resistance, do not change much over a range of site and silviculture. Tree breeding in its simplest form involves selecting superior provenances from natural populations and testing their open or cross-pollinated progenies (families) for traits of interest. This will identify appropriate genotypes that can be deployed in breeding programmes for successive generations of tree improvement. The provenance trials in which the best performers are retained and the poor ones thinned out are often converted to seed orchards.

Genetically improved seed can be raised in seed orchards and/or genetically superior individuals can be clonally propagated as cuttings. In practice, breeding programmes for economically important species become increasingly complex because objectives of the programme are to achieve genetic gain in several economically and physiologically important traits in each generation. For example, if the wood is exclusively for pulp production, growth rates, volume, density and fibre recovery are important. If saw log and solid timber products are sought, traits including log form (straightness, low branching frequency), high density and strength, and sawing and drying properties are given high weighting. Resistance to pests and diseases, drought and cold (frost) tolerance may be given high weighting in some circumstances.

Breeding programmes now are commonly adapted to achieve multiple trait selection, in which case breeders give certain economic weighting to each desirable trait. Genetic correlation between traits may be positive or negative, and negative genetic correlation between two or more traits (e.g. between growth rates and wood density) need to be considered for multiple trait selection and incorporation. In general, the addition of every new trait to breeding objectives adds cost and complexity to the programme.

Tree breeding strategy aims to avoid inbreeding and/or a narrow range of genetic variation so that the subset of genotypes deployed to plantations may not suffer increased vulnerability to various ecosystem stresses. Also reducing genetic variability in the underpinning breeding populations may limit future but as yet unknown options. Tree breeding programmes recognize this and ensure that breeding populations are large and broadly based, and a strategy for infusing new genes is built into the programme.

Tree breeding is a slow process because of the long time between generations. Research aims to find ways to reduce the generation intervals between reliable identification of genotypes, mating and the deployment of the best progenies in operations. For this, the study of early to late age correlations, early flower induction, selection using molecular markers, physiological testing and modelling are applied for improving the gains in desirable traits per generation and shortening the breeding cycle. Single national (or cooperative) breeding programmes have been successful for a range of breeding objectives (Carson, 2002; Wu *et al.*, 2007).

Tree breeding has made major contributions to progress in plantation forestry worldwide. However, it is important to make a realistic assessment of the net value from breeding. Determining the genetic gain achieved in each generation does this. Such gains must be evaluated by an adequate number of field tests under conditions that represent the overall plantation environment and management practices. It is often the case that genetic gains are estimated using statistical models, using early growth data rather than based on measured gains from well-designed field tests managed over a full rotation. This can give rise to erroneous expectations from breeding and lead to incorrect predictions of the potential wood supply to the mill. Examples of this, based on inflated gains predicted from less than robust validation of realized gains in forestry, exist in some tropical countries today with serious consequences, such as a gross mismatch between wood supply and consumption rates required by the mills. Promotion of a single clone for large-scale planting based on overzealous expectations of growth has resulted in serious failure in some environments. In some cases there is a simplistic view that monoclonal forestry provides uniform and high-performing plantation estates. Many field observations suggest that monoclonal plantations should be avoided.

Systematic tree breeding is probably less than 100 years old and populations that are planted today are still relatively less domesticated, partly because of long generation intervals in breeding cycles, compared with some agricultural crops harvested annually, whose genetic range may have been confined through intense breeding over many generations. Sexual reproduction between individuals from different species is usually not possible because the genetic differences are too great. However, the genetic composition is similar enough between some tree species to permit hybridization, which may result in superior performance. Hybrids are also formed naturally if compatible species occur in proximity. Examples of successful hybrids in plantation forestry are *Eucalyptus grandis* × *Eucalyptus urophylla* in Brazil, *Pinus elliottii* variety *elliottii* × *Pinus caribaea* variety *hondurensis* in Queensland, Australia and *Acacia mangium* × *A. auriculiformis* hybrid in Vietnam.

The research in progress into producing transgenic trees (GM trees) indicates a number of potential benefits through genetic modification to provide traits for pest and disease resistance, frost resistance, herbicide resistance and desired wood properties and biofuel. The scope for wider application of this technology and risk assessments are yet to be well developed. Its adoption requires more validation and community engagement. It is being strongly resisted by some environmental organizations, sometimes based on ideology. The way forward for developing and applying this technology is to identify ecosystem- and purpose-specific opportunities, and validate the scientific outcomes under transparent regulations, and with community engagement.

Tree breeding is not a panacea, and the potential production advantage of improved genotypes will not translate to real value unless they are well coupled with appropriate management and maintenance of the productive capacity of soil. Equally, any innovations in site, soil and stand management would not lead to positive outcomes if they are applied to poor genotypes. Gains from tree breeding can be significant, but gains from proper site and stand management are larger and are critical for success (Carson *et al.*, 1999; Boreham and Pallet, 2009). Increasing and sustaining productivity require integrated management.

Site and soil selection

From biological and productivity perspectives, the concept of site is important for all forestry management decisions. One definition of site is 'an area of land which can be managed homogenously and will produce a more or less constant wood yield across it from a particular plantation species under proper management' (West, 2006, p. 48). Thus it involves due consideration of soil, terrain, climate and other potential growth-influencing factors. West also defined site productivity as 'the total stand biomass produced, up to any particular stage of development, of a plantation growing on a particular site, when it uses fully the resources necessary for tree growth which are available from the site' (2006, p. 48). The measure of productivity may be gross or net primary production, net carbon sequestered or stem wood produced, depending on the purpose of that information, and they are all interrelated (for a discussion see Powers, 2001). The wood production may be measured as total volume of stem wood or volume of merchantable wood (above certain minimum diameter at the top of the stem) that can be processed to products.

There are several well-developed methods available for assessing site productivity and then classifying the land in management units in relation to their productive capacity (ranging from high to low or unsuitable). For such a classification, managers use Site Index (SI) or Site Quality (SQ), which are indices of stand-level productivity, and their choice is validated by experience and local information. These are central to all decisions for short-, medium- and long-term production management and for assessing sustainable production (Powers, 2001; West, 2006; O'Hehir and Nambiar, 2010).

Where there has been a long history of plantation forestry, managers would have an understanding of the site productive capacity of the estate and the extent to which productivity can be managed through better management. This experience can be used for continuous improvements for both predicting productivity and for fine-tuning management. The ability to make reliable estimates of current and future trends in growth rates for the different parts of the estate is central for sound planning of harvesting and planting, rotation length, age-class distribution and thus for sustainable management.

Most well-known and commercially planted species have higher flexibility in their capacity for adapting to a range of soils, but less so with growing environment, especially drought and frost. For example, *Eucalyptus globulus*, a species with premium pulpwood quality, can grow in soils ranging in texture from siliceous podzolized sand to soils with 60% or more clay. But because of its particular physiological attributes, it is very sensitive to soil water deficit and prone to drought-induced mortality. Soils low in chemical fertility can be supplemented with fertilizers to improve production, but options for managing available water are limited. Irrigation is not a common practice in forestry, except in some limited cases where industrial or municipal effluents are used.

Productivity is dependent on geology and soil type (which can vary within a short distance), land form (terrain), growing environment (particularly available water), elevation, temperature and factors such as frost and drought. While growth is determined by multiple factors and their interaction, some factors can be more limiting than others. Total annual rainfall may be inadequate to explain production, as the net water available to the stand through the rotation is dependent on factors including frequency and seasonality of rain, evapotranspiration, soil water holding capacity and silviculture.

A striking example of the contrasting impacts of site on productivity of short rotation *Eucalyptus globulus* in Western Australia is shown in Table 9.2. These two sites within a Mediterranean climate were under long-term pasture before conversion to plantations. There is more than a fourfold difference in productivity between the sites over two successive rotations: in this case productivity is largely driven by available water and soil fertility.

Table 9.2. Comparison of productivity of *Eucalyptus globulus* plantations at two contrasting ex-pasture sites during two successive rotations in Western Australia. (From Mendham *et al*., 2008.)

	High-fertility site	Low-fertility site
	Red earth	Grey sand
Rainfall (mm/year)	1023	825
Pan evaporation (mm/year)	524	574
Volume: first rotation – age 8 year (m^3/ha)	366	96
Volume: second rotation – age 10 year (m^3/ha)	324	70

The growth response to management, including fertilizer application through the life of a stand, can be equally influenced by site and soil factors. So also can the capacity of the site to maintain productivity through successive rotations.

The productive capacity of a site is not an immutable reference point: it is a snapshot in time, and can be upgraded by good management or downgraded by poor management. There are many examples of both positive and negative changes in site productivity in practice. Poor harvesting practices leading to loss of organic matter due to slash removal or burning of organic matter, soil compaction, excessive nutrient depletion and soil erosion are examples of factors that can downgrade site productivity. This cannot be overcome by planting genetically improved planting stock. Productivity can also be adversely affected by pests and diseases, unless they are controlled or managed to a lower level of risk. Site preparation practices including ploughing, deep ripping, mounding and various techniques for managing postharvest slash are employed to partly offset the constraints at the site and to maintain gains made over time.

Establishing a Plantation Forest

Plantations are usually planted with one species mostly using genetically improved stock, and planted in lines to a pre-determined planting density (referred to as 'stocking', the number of trees per hectare) achieved by adjusting the distance between rows and/or between trees in a row.

Even when trees are planted for environmental purposes or landscape protection, the predominant way of establishment is through seedlings or cuttings, and this is almost exclusively so for commercial plantations. Sometimes *Eucalyptus* plantations are re-established from coppice. Some species (e.g. *Pinus* and *Acacia*) can establish a following plantation from naturally regenerated seedlings from seed fall, but this is not common. Direct seeding to establish a commercial plantation is rare. However, direct seeding is used for environmental plantings of mixed woody species, for promotion of biodiversity values, for rehabilitation of degraded landscapes damaged by salinity, and for restoration of ex-mine sites or severely damaged land in post-war zones.

When the stand is grown from coppice for products, the number of coppice per stump needs to be controlled to allow an acceptable size (diameter) of coppices. Typically, if the intended use is wood processing, two stems per stump are common. If the wood is for charcoal or directly for cooking, multiple stems are allowed to grow and local communities may repeatedly harvest several coppice rotations over decades. Coppice plantations have an advantage in that they have an established root system enabling water and nutrient uptake. Nevertheless, coppice plantations commonly yield less (and decline with successive coppice rotations) than plantations established from new stock at the same time. Some managers accept this reduction on the basis that they are cheaper to establish than replanting, which requires seedlings or cuttings and some site preparation for planting. Coppice plantations also delay or forego the opportunity for obtaining genetic gain until replanted with improved planting stock.

Planting stock

A successful plantation programme starts with selecting the right sites suitable for forestry. This should be followed by selecting planting stock (seedlings or cuttings, which should be the right genetic selection within a chosen species, healthy and hardy).

Seedlings

Seedling nursery technology is well developed and can produce large numbers of seedlings or cuttings of uniform quality. Large companies require millions of seedlings each year and consequently invest in capital-intensive, mechanized and partly automated nurseries. Smaller, less capital-intensive and perhaps shifting nurseries are more appropriate for smaller enterprises, particularly community-based forestry programmes.

Seedlings to be planted in climates with a pronounced winter season are grown in large beds and lifted as 'bare-rooted' in winter while they are physiologically dormant and can be cold-stored until planting out. It is critical that they have a set of healthy roots, especially first order laterals that arise directly from the main root or cut ends of cuttings. It is important to avoid wilting (water loss) between lifting and planting seedlings. While planting open-rooted stock, there should be adequate contact between the root and the soil; over compaction of the soil will cause root damage and under compaction will cause poor root to soil contact. This can induce water stress in the seedling, even if the soil has adequate water supply and the vapour pressure deficit (a measure of the dryness of the atmosphere) is low (Sands, 1984).

There are various criteria established for assessing planting stock quality to enable seedlings to establish a good root system, cope with transplanting stress and grow well. One critical success factor in establishment is the rate of new root initiation and growth after transplanting and this is strongly related to the number of first order lateral roots transplanted. Their vigour determines the 'root regeneration potential'. Periodic severing of roots (root wrenching) at a depth of 10–15 cm below soil surface can promote a multi-branched root system and this is a common practice in pine nurseries. Well-managed nurseries aim to produce seedlings that are vigorous and uniform in size with an optimal ratio between shoot and root. For this, optimal supplies (amounts and timing) of water and nutrients are critical. Seedlings need to be 'conditioned' by a programmed withdrawal of water and nutrients before lifting, so that they are 'hardened' and capable of withstanding transplanting stresses that inevitably follow out-planting, particularly in stress-prone and unpredictable environments.

For some species, notably those planted in subtropical and tropical environments, container-grown seedlings are the norm. They also need to be conditioned by the progressive reduction in supply of water and nutrients and increase in sunlight. Because the roots are confined within containers, it is necessary to ensure that shoot growth does not become excessive. It is more expensive, but reduced transplanting risks, economies of scale and flexibility in management make containerized seedlings the better option under certain circumstances.

For all types of planting stock, the root systems should not be deformed when transplanting because these distortions remain for life and may harm tree growth. Root deformation and strangulation between roots affect tree stability and increase vulnerability to windthrow. Planting stock can be inoculated with mycorrhizas in the nursery, if necessary. Mycorrhizas may be endemic in many forest sites.

Plantation programmes should achieve at least 80% survival of seedlings planted in the field by the end of the establishment period, but this can only be achieved with good site preparation, careful planting and post planting management, especially weed control. Loss of trees tends to be high in the first year after planting and tends to stabilize beyond this. But if the planted species is susceptible to pests and diseases, mortality may continue through the rotation and this can be a serious problem in short rotation forestry. If all aspects are well managed, and if the growing environment is not too stress-prone, some organizations target and achieve more than 90% survival and establishment. Access to good-quality planting stock is an essential prerequisite for any tree planting, even in home gardens.

Cuttings and clones

Rooted cuttings have been used for plant propagation for thousands of years. Cuttings from portions of shoot, stem, root or sprout can root in soil, depending on the species. Some species root very easily and some poorly. Cuttings from eucalypts root most easily on young material in warmer climates. For example, it is extremely difficult to root cuttings of the cool montane *Eucalyptus nitens*, difficult but manageable for the temperate *Eucalyptus globulus* and easy for the tropical *Eucalyptus grandis*. There can also be large genetic variation in rooting within a species. Usually cuttings are set in a nursery (in which case they are sometimes called stecklings) for rooting and subsequently transplanted into the field. They are more expensive to produce than seedlings, but the extra costs are justified by managers on the basis that stands have greater uniformity and allow them to match genotypes more precisely (as clones) to site.

For clonal forestry, one or more elite genotypes are vegetatively reproduced and multiplied through rooted cuttings and planted extensively. Clonal forestry has become prominent in the subtropics and tropics, particularly with *Eucalyptus* and *Acacia*. There are extensive clonal plantations of fast-grown eucalypt pulp plantations, well-known and successful examples being the highly productive clonal plantations of the *Eucalyptus grandis* × *Eucalyptus urophylla* hybrid in Brazil. Tissue culture and somatic embryogenesis are other forms of vegetative production and a basis for clonal forestry. Their application at an operational scale to plantation forestry is increasing for tissue culture, but is negligible for somatic embryogenesis.

Weed control (vegetation management)

Tree growers consider the native and introduced vegetation that competes with planted trees for water, nutrients and light to be weeds. Successful plantation establishment is not possible without good weed control anywhere in the world. Competition by weeds for available soil water will result in tree mortality in environments where water deficits are common (e.g. Australia, India, China, South Africa, southern USA) and commercial plantations in such areas will not be viable without weed control. Weed control is equally critical in the humid tropics (e.g. Sumatra, Sabah), which may receive more than 2500 mm rainfall per year or on sites with plenty of nutrients in the soil. Weed control can greatly increase tree productivity (Table 9.3). In areas where competition for resources is not acute, contemporary views of forestry advocate optimal vegetation management. Vegetation management, rather than outright elimination of all weeds, seeks to provide judicious control of vegetation to allow the establishment and early growth of trees to a stage when they can dominate the weeds, which then becomes an understorey. This strategy can promote biodiversity in the landscape. If trees can close canopy in 1 year (e.g. *Acacia mangium* in Sumatra), weed growth is fully suppressed after this age and will remain so until the canopy is opened by thinning or clear felling. In contrast, in eucalypt plantations that generally maintain small crowns allowing more light on the forest floor, understorey vegetation can grow throughout the rotation. Weeds may be herbaceous or woody, native or exotic.

Table 9.3. Above-ground biomass (Mg/ha) of 6-year-old *Pinus elliottii* and *Pinus taeda* in Florida. (Abridged from Dalla-Tea and Jokela, 1991.)

Treatment	*Pinus elliottii*	*Pinus taeda*
Control	11.9	7.1
Weeded	26.2	35.2
Fertilized	26.0	38.6
Weeded and fertilized	34.2	57.6

During the establishment period of young plantations, rooting density and the physiology of the weed types can have a strong influence in determining the degree of competition for water. Many grass weeds have a rooting density in the top soil layer 10–50 or more times higher than those of most commercial trees and this would give a clear advantage to the weeds. On the other hand, such weeds are shallower rooted than trees, and as the tree roots grow deeper in the soil profile, their competitiveness to overcome the weeds increases. Some weeds dry off during late spring and summer months, transpiring little water, whereas some transpire throughout the summer months causing severe water stress in young trees. An understanding of the nature and underpinning processes of the tree–weed interaction in an ecosystem enables greater efficiency in weed management. For example, in some cases it is not necessary to continually adopt a zero weed-tolerance strategy. Even in environments where adequate water availability is seasonal, good control of weeds in a 1–1.5-m wide strip along the tree row, rather than complete removal of all vegetation throughout, may be sufficient for adequate tree growth beyond the first few months or a year after planting.

Weeding is most effective in increasing plantation growth if it is carried out just before planting and in the first year or two after planting. Fertilizing soon after planting may be ineffective unless the weeds are controlled as well, as this will also fertilize the weeds and increase their competitiveness. In sites where the amount of available water is low, such competition will be detrimental to young trees. Weed removal is often no longer necessary after the first couple of years. In most cases, where industrial plantation forestry is well developed, weeds are mainly controlled by herbicides. Manual weed control is common in places where labour is relatively cheap and adoption of herbicide technology remains in its infancy. The appropriate timing and intensity of weed control depends on the particular circumstances (tree and weed species, climate and soil). Another control option when water is not the major limiting resource is to replace the weeds with N-fixing legumes. This could increase soil nitrogen, protect the soil from erosion and provide an aesthetically attractive understorey. Oversowing with legumes has been routinely practised when establishing radiata pine plantations in sandy areas in New Zealand and this has significantly increased tree growth. However, some N-fixing plants left to proliferate in plantations can impose severe water stress in trees in water-limited environments (e.g. *Ulex europaeus* (gorse) in New Zealand) and in some areas make access to plantations difficult.

Weed control can increase productivity considerably. Table 9.3 shows the effect of weed control and fertilization, singly and in combination. The desirable degree of weed control (intensity, spatial coverage and frequency) is best determined if the competing process (typically water, nutrients and/or light) and the canopy dynamics of the trees are well understood so that a balance can be found (Nambiar and Sands, 1993). Some weeds are said to have allelopathic effects on trees but scientific evidence for this is not strong.

Management of nutrition and available water

Availability of water and nutrients in soil for trees is regulated through highly interrelated processes. Management of water (mostly by weed control or in special cases by irrigation) influences the supply of nutrients. Similarly management of nutrition (with fertilizer) influences availability of water (through root growth) and water use efficiency. Productivity is often determined by their interaction where deficiency of either will limit the response to the other. For example, application of fertilizers to improve production will be of little value if trees are water stressed. Conversely, water use efficiency will be low if deficiency of one or more nutrients is limiting growth. Best silvicultural practices improve the availability of both. Site management practices such as ripping and other controlled disturbances in compacted soil allow water infiltration, help root growth and thus provide better access to water and nutrients. When weeds are well managed, both nutrient and water availability to trees are improved. When a stand is thinned and the canopy is opened, it increases the infiltration of water and the remaining trees benefit from both increased availability of water and nutrients released from thinning residues left on the forest floor. In water-limited environments, when a stand is clear cut, during the inter-rotation phase the soil profile is recharged with water and the rapidly growing new plantation benefits from stored water. Beyond canopy closure, if stand growth rates are determined by water availability and light interception by foliage, there is little chance for response to added nutrients even if they are experiencing marginal nutrient deficiency, but may well do so if they are thinned. Stands that are chronically nutrient deficient will seldom close canopy and this will stimulate weed growth and competition for site resources between trees and weeds.

After harvesting, if slash and litter are retained at the site, it acts as a mulch and minimizes evaporative losses (conserves water) in addition to serving as a rich source of organic matter and nutrients. If the soil is wet, nutrient mineralization will increase rapidly, sometimes by many fold. Mineralization rates can drop to zero when the soil is dry or too cold. Recent work in Brazil shows that the emerging problem of potassium deficiency in large areas of fast-growing eucalypt hybrids impairs stomatal regulation in leaves, resulting in loss of growth (Raposo *et al.*, 2010). So it is important to understand the interaction between water and nutrients for specific ecosystems for designing sound management practices. For a recent discussion on the ecophysiology of water and nutrient interaction in plantation forest see Binkley *et al.* (2010).

For a healthy and fast-growing plantation, the soil needs to supply adequate levels of essential nutrients, both major (N, P, K, Ca Mg, S, Si) and micro (Zn, Cu, Fe, B, Mn, Ni, Mo). Recent studies with eucalypts in Brazil show that sodium (Na) can partly meet the physiological functions of potassium in trees in potassium-deficient soils (Raposo *et al.*, 2010). No plantation will grow and yield well if its foliage is deficient in one or more nutrients. Ideally, rates of nutrient supply from the soil should be commensurate with the uptake rate required by trees for maintaining good growth rates. Trees take up and accumulate more nutrients than required for growth in biomass if nutrients are continually available in soil. Therefore caution is needed not to interpret the nutrient contents in biomass, at a given time, as a measure representing nutrient requirements for growth in a physiological sense.

These need to be determined by local research and appropriate methodologies, and these are well developed (Goncalves and Benedetti, 2000; Nambiar, 2008; Rodrigues and Alvarez, 2010).

Managing the availability of nutrients for improving the productivity of plantations requires an understanding of several factors that determine nutrient budgets, transformations and cycling through the ecosystem. Key variables include nutrient stock and availability in soil (generally related to parent material, soil type and management), rate of growth and nutrient uptake rates (dependent on the stage of stand development), nutrient retranslocation within trees (a process through which mobile nutrients are withdrawn from mature and senescing tissues, translocated and re-used for supporting new growth), nutrient return through litter fall, decomposition of organic matter and mineralization and nutrient released from soil for uptake. Small amounts of nutrients will be released by weathering of parent rock, but these are unlikely to be important for plantation cycles. Contributions from weathering are important over centuries.

The amount of roots, their configuration and distribution, have a strong influence on nutrient uptake, especially phosphorus (and micro nutrients), which is largely immobile in soils and does not exist in the soil solution phase; hence fine roots have to reach them (adsorbed to soil particles) for uptake. Roots can absorb phosphorus ions only from the pool accessible within 2–3 mm radial zone of root filaments. For nitrogen, which is found in the soil solution, uptake by roots is enabled partly through water flow to the root. Rooting patterns and the factors that determine rooting intensity in the surface horizons have a strong influence on nutrient uptake. Since most nutrients are found in the top 0–30 cm soil layer, trees are very dependent on rooting density (root length (cm) per unit soil volume (cm^3)) in upper soil horizons for nutrient uptake. Soil properties that influence root growth include soil penetration strength (determined by soil bulk density, texture and water content), porosity, aeration and presence or absence of salinity and or acidity. Rooting density is predominantly due to fine roots less than 2 mm in diameter, which undergo reasonably fast turnover in soils, adding to both carbon and nutrients pools from which further uptake takes place. In contrast to nutrients, water uptake by roots can occur from deeper parts of the soil, sometimes several metres deep, depending on the features of the soil profile and if deeper layers are re-charged with water received and infiltrated from rain. Rooting density is almost always very low in deeper parts of the soil profile, but a few deep roots can be critical for water uptake and for survival and growth during dry periods.

If plantation forests are managed with due recognition of nutrient inputs and export, avoiding extreme perturbations, nutrient cycles can be managed in a closed loop (cycle) within the ecosystem with little loss. When nutrient mineralization is much higher than uptake by trees and associated vegetation and if there is abundant water flow, nutrient leaching can occur. Risk of this is moderate to high soon after harvest and during and immediately after site preparation, but very low or non-existent once trees are established and trees and understorey dominate the site. If the terrain is steep and exposed to surface runoff following high-intensity rainfall, then nutrients may well be transported offsite with water flow. Judicious management of weeds can be used to improve nutrient retention at the site. Fertilizer can be added in the weed-free zone, where weed control is restricted to weed-free rows of predetermined width. In this case, the weed-free zone should be sufficient to avoid water and nutrient stress in trees. This approach reduces cost and allows the inter-row vegetation to act as a sink for nutrients to be released later when trees close canopy and control the weeds. Good management during the early stage of stand development is crucial for success later and requires an understanding of the site-specific interaction between planted trees, vegetation, water and nutrients and a holistic approach to management.

Globally, increases in plantation productivity from applying nitrogen are common. Phosphorus has been a major limiting nutrient in many places and a variety of other deficiencies are known. Deficiencies can usually be corrected by adding mineral fertilizers. Nitrogen-fixing plants can sometimes improve nitrogen supply. Experimental studies have shown use of lupins and other annual legumes, eucalypt and *Acacia* mixed plantings can benefit tree growth. Despite the potential benefits from biological nitrogen fixation and the rising price of nitrogen fertilizers, these approaches have not yet been adopted by commercial forestry, mainly because of the silvicultural difficulties in planting and managing multiple species and the competition between them. Composted municipal waste, treated sewage sludge, fire ash from wood-processing plants and effluents from pulp mills and municipalities are also occasionally used as nutrient supplements.

Fertilizers can greatly improve productivity on infertile soils (Table 9.3). Indeed most successful cases of plantation forestry in the world would not have been possible without the use of fertilizers containing one or more nutrients. The use of relatively small amounts (compared with those applied to agriculture or horticulture in the same environment) of fertilizer containing phosphorus, zinc and copper has enabled establishment of good plantation forests in infertile soils in Australia, New Zealand and South Africa, transforming the value of land to society. Application of nitrogen and phosphorus benefited slow-growing species in Scotland and Sweden, until the post-war industrialization increased atmospheric deposition of these and other elements, including sulphur (which has created another set of environmental challenges). There are many instances (e.g. *Pinus radiata* plantations on poorly drained, heavy soils in New Zealand; Will and Ballard, 1976) where fertilization has resulted in permanent improvement in not only soil nutritional status, but on other soil properties such as structure, water infiltration and aeration over a rotation period of two decades.

Visual deficiency symptoms can be used as a guide to diagnose the particular nutrient deficiency, if that deficiency is acute. The most common visual symptoms are yellowing (chlorosis) or dying (necrosis) of foliage. These symptoms can be similar to symptoms of disease or of water stress and local knowledge and experience is required to distinguish between these. Other diagnostics such as sampling foliage for critical levels of nutrients and soil survey are used to determine whether or not a plantation will respond to fertilizer application. They are useful only if good locally applicable calibrations are developed first. Non-symptomatic deficiency (that is, no obvious deficiency symptom but the crop will respond profitably to addition of nutrients) is now more widespread in established forestry areas where fertilizers have been applied to the previous crop. Management for addressing these situations uses more sophisticated techniques, including knowledge of soils, water availability, targeted growth rates and an array of sound field experiments in representative sites/soils. Information from these can be integrated into appropriate models that can forecast likely increases in production, wood quality for end use and economic returns from such investments. Application of fertilizers in plantations of temperate species is common in southern USA, Chile, South Africa, Australia and New Zealand, where the most common deficiencies have been nitrogen, phosphorus, zinc, copper and boron. Routine application of fertilizers is increasingly common in subtropical and tropical regions, including Brazil, China, Indonesia and Vietnam where fast-growing short-rotation plantations are being established.

Fertilization should consider the intended use of the wood and the stages of plantation development. For short-rotation pulp plantations (4–8 years), application at planting is all that may be required. Some of these, for example *Acacia mangium* in Indonesia, close canopy at age 1 year and significant litter fall and nutrient cycling commence from that age and there is little scope for a growth response from further additions of fertilizers. For longer rotations, fertilizer can be applied at various stages, starting at the beginning of a rotation and later (later-age fertilization), particularly with nitrogen and phosphorus, and after thinning. This benefits the plantation ecosystem, promoting higher productivity (adding value to the standing resource) and is profitable. By coupling with appropriate thinning, the manager can select the trees that can be fertilized to yield the best commercial outcome. Efficiency of nutrient uptake from later age fertilizer application is higher than that applied at planting and there is virtually no risk of nutrient loss as the plantation nutrient and water cycles are well coupled with stand development.

Increasing productivity with fertilizers depends on availability of other resources, particularly water, being present in sufficient quantity to support the increased growth rate. Figure 9.3 shows the effect of irrigation and fertilization, together and in combination, for four different plantation species in four different environments. When water and/or nutrients are applied to a soil deficient in water and/or nutrients, increased growth usually is preferentially directed towards above-ground at the expense of below-ground. Fertilizer responses are a combination of increased total biomass and an increased proportion above-ground (Table 9.4).

Nutritional management based on empirical nutrient (fertilizer) trials that have a combination of nutrients and rates are useful. They alone, however, are a 'shot gun' approach, with the chance

Table 9.4. Distribution of above- and below-ground biomass (t/ha/year) of 20-year-old *Pinus sylvestris* in Sweden after 6 years of irrigation and nutrient addition. (Derived from Linder and Axelsson, 1982.)

	Control	Fertilized and irrigated
Above-ground	4.7	15.3
Below-ground	6.9	6.9
Total	11.6	22.2
Above/below	0.7	2.2

to be inefficient and wasteful. There has been considerable research into the nutritional physiology of plantation species and of soil management to improve production efficiency. Knowledge-based and integrated site and stand management underpins sustainable management applicable to local situations (Bowen and Nambiar, 1984; Nambiar and Brown, 1997; Goncalves and Benedetti, 2000; Rodriguez and Alvarez, 2010).

Stand dynamics

Stand density, thinning and pruning

A detailed discussion on stocking, thinning and pruning is given in West (2006). In a native forest harvested or opened by natural cause or burnt in wild fire, dense regeneration may develop. Trees at an initial high stand density (number of stems per hectare) compete with each other for water, nutrients and light, the stronger persisting while the weaker trees may die prematurely owing to lack of growing space. The plantation manager can choose to plant at densities low enough to preclude competition-induced mortality, but often will plant at higher densities to compensate for survival loss in transplanting, to promote early height growth and to 'site capture' through canopy closure. If the primary objective is to produce biomass (bioenergy plantations), then the optimum stand density at harvest is the highest that the site can support without causing mortality from competition. For pulpwood production, higher stockings can be an advantage because stems up to a top-end diameter as low as 5–7 cm can be used. Stand densities of around 1600 stems/ha are common for pulpwood regimes.

If the plantations are designed for multiple and higher value products such as sawn timber, higher initial stocking is used to improve stem straightness, inhibit the development of large side branches, and to provide sufficient stock from which to select the most commercially valuable trees to retain at each thinning. A stand can also be thinned to pre-empt mortality if drought is a risk in order to increase access to available soil water for selected trees. Trees under stress, as in unthinned plantations, may be vulnerable to pest attack. Thinning promotes diameter growth on fewer stems. One critical factor for successful thinning is the decision on which trees are to be removed and which ones should be retained. The general objective is to identify those trees with the best growth potential and the best form in terms of straightness and small branch size, attributes that provide high value to sawlogs. In sequential thinning, this decision needs to be made at each stage based on an understanding of stand dynamics of the species, rotation length, product option and market. Thinning also creates a different geometry in a stand, as in the case of row thinning at nominated distances to suit mechanical operations and cost efficiency. All thinning is at the expense of total productivity per hectare, but this loss in productivity is more than made up by product value. Initial stand densities for high-quality sawlog regimes from high-productivity plantations are typically in the range of 1200–1500 stems/ha, depending on species and circumstances. For sawlog regimes there is usually at least one and often a series of thinnings with the objective of concentrating the growth onto fewer straighter larger trees at rotation age. In a few cases the first thinning may be a non-commercial thinning, where the thinned stems are left on the ground to decay. But in majority of cases the stem wood from first thinnings is used for pulp and some for poles and fence posts. Subsequent thinnings can be used for pulp and for small round timber and for sawn wood. The number and timing of thinnings varies between species and product profile. Typically a stand at the end of rotation age of 30 years will have about 200–400 stems/ha. There are many thinning regimes, depending on the species, growing environment and the management objectives; the figures given here provide a rough guide.

Light penetrates a thinned stand and illuminates the lower branches. This stimulates the photosynthesis of the lower live branches, which can become quite thick. Some species, such as *Eucalyptus globulus*, are self-pruning and do not produce large branches unless they are grown in the open. Others, for example *Eucalyptus nitens*, retain heavy branches leading to a large and unsightly knot in the sawn timber and loss of recovery of high-value products. The lower branches can periodically be pruned to confine the knots to a 'knotty core', with clear knot-free wood being produced outside of this core (Chapter 4). Clearly pruning and thinning should be considered together in planning. Pruning large-sized branches leads to wounds that become entry points for fungi, causing stem wood decay. When to prune, which stems to prune, how high to prune and how many pruning lifts are required depend on species, site and market. Whether or not to prune will depend on the nature of the product and whether it can receive a higher price to cover the cost of the pruning. Thinning and pruning both reduce total tree volume per hectare. Thinning and pruning regimes are subjects of great debate and passion among foresters.

Rotation length

The rotation length is the age of the trees from planting to final harvest. Rotation ages vary between 3 years for some firewood crops in the tropics to 80–100 years for some slow-growing species in cold climates as in Scandinavia. Usually the faster the growth rate of a species, the shorter is the optimal rotation. Pulpwood and fuelwood can be grown on shorter rotations than sawlogs (typically <8 years). Temperate pines are usually grown at rotation lengths of 15–40 years (Table 9.1). Typically, the MAI of a plantation increases with stand age relatively rapidly to a maximum value, after which it slowly declines (Fig. 9.4). If volume production was the only criterion, the age at maximum MAI would be the logical rotation age. Figure 9.4 shows that *Pseudsotsuga menziesii* is potentially more productive than *Pinus radiate*, providing you wait long enough. The reason why *Pinus radiata* and some eucalypts and tropical pines are high-productivity plantation species is that they grow quickly early, which means they can be grown over shorter rotations and still have acceptable wood quality for processing into a range of products. This is important from an economic perspective. The costs of establishment and maintenance have to be carried with interest over the length of the rotation. High interest rates usually necessitate shorter rotations. Also longer rotations carry greater risk of catastrophic damage from fire, pests, wind or changes in investment criteria and markets. However, the lower wood quality from short-rotation grown logs has limited use and utility, but advances in timber technology are changing this. Species and logs considered unsuitable for peeling and reconstituted timber products a few years ago are now being processed into high-value products in some countries.

Typically wood quality changes with tree age: wood density and stiffness increase with distance from the centre of the tree (the pith) and the outer wood is of better quality than the younger inner wood (juvenile wood). The market determines the size and nature of product required. Sawmills may have a minimum and maximum log size that they can handle. In long-rotation forestry, rotation age needs to be flexible enough to meet the

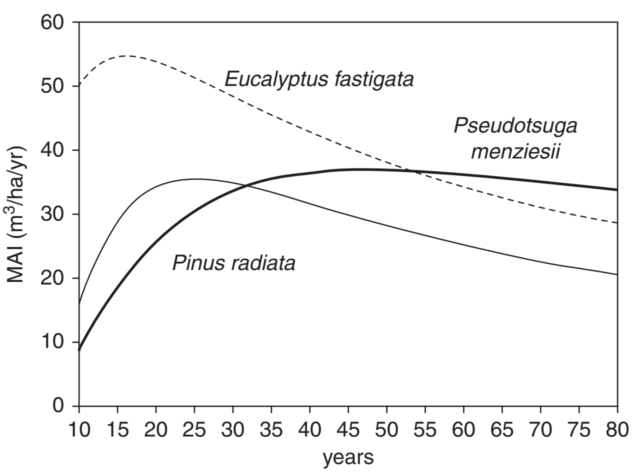

Fig. 9.4. MAI versus age for *Eucalyptus fastigata*, *Pinus radiata* and *Pseudotsuga menziesii* grown under similar climate on fertile well-watered sites in New Zealand. Stands were planted at 1000–1200 stems per hectare and were unthinned. (Compiled from permanent sample plot data by Richard Woollons.).

changing real world market conditions. A plantation enterprise does not have evenly distributed age classes across the estate. A mosaic of age classes needs to be created to allow continuous production.

In the past, rotation length was decided not only by the growth rates of the species, but also based on principles of sustainable harvest. Thus, in any given year the amount of wood harvested from an estate should not exceed the amount grown by the total estate during that year. A manager should harvest only the accrued interest and not deplete the capital. If the harvest exceeded the 'interest accrued', it was labelled 'overcutting' and questioned. The advent of short-rotation forestry and building of very large processing capacity (e.g. large pulp mills built relying on uncertain wood resource supply) seem to have disregarded this concept of sustainable harvests to the detriment of the plantation sector in some countries. A harvesting strategy designed simply to cope with the urgency of immediate wood supply by overcutting or reducing the rotation length is fraught with high risks. Rotation length determines the frequency of harvests and the concomitant major disturbances and this does have a strong impact on sustainability. The shorter the rotation lengths (more frequent and intensive harvests), the greater are the impacts on the site over time. Overcutting simply postpones the problem of wood supply to the next year or after.

Plantation Protection and Maintenance

After establishment, plantations face many hazards, biotic and abiotic, anthropogenic and natural, such as insect attack, browsing by vertebrates, diseases, destruction by fire, damage by wind or flood, air pollution and climate change. Sometimes plantations can be insured against some of these hazards, but this a costly matter.

Regrettably there are many instances globally where plantations have been established and essentially abandoned, either because of the lack of a coherent forestry policy, lack of investments or under the mistaken impression that once planted nature will take over and the plantation will look after itself. Plantations need to be actively managed and to be tended and cared for over their rotation length. All too often plantations are thinned too late or not at all. Poorly managed or failed plantations represent a loss of financial and natural resources.

A discussion of the many and diverse insect pests and diseases, their impacts and management are outside the scope of this book. References that provide integrated views of the challenges include Harrington and Wingfield (1998), Wingfield *et al.* (2008, 2010), Edmonds *et al.* (2010) and Garnas and Hurley (2012). Plantations are a long-term investment that carries considerable risk. Therefore systematic monitoring of plantation health, introduction of biological control wherever possible, and coordinated prevention and risk management actions in an increasing globalised economy are important for sustainability.

Sustaining productivity

Sustainable forestry (the application of the science, technology and the art of forest management; Fig. 9.2) should be pursued regardless of whether plantations are established for production, land and water protection or environmental services. Multiple values, diverse expectations, the need to achieve high production and the economic realities of managing a commercially-driven land-use system all impact on the pursuit of sustainability in forestry (Fig. 9.1). Forestry is a long-term business, and can be viable and successful only if the fundamentals of sustainable production over the long term are understood and managed. If productivity fails, the objective of forestry will be lost with it. Long-term productivity is a central issue, whether plantations are managed by large industrial companies or by individual, small-scale growers.

There are several historical reports of productivity decline in plantations. Examples include *Picea* and *Populus* plantations in Europe, *Pinus radiata* plantations in Australia, *Cunninghamia* plantations in China and *Eucalyptus* plantations in India. There are other anecdotal and non-verified cases. Sometimes the yield decline arguments have become confused with the misconceptions of exotics and monocultures, when in fact the reason for the decline can be traced back to factors including site degradation due to poor harvesting practices, subsequent site management that depleted the site resources, poor management of weeds or poor choice of species or genetic material.

How are plantation forests managed for sustainable production over several rotations, extending to decades? Plantation management operations should ensure that the soil base is protected and disruptions to ecological processes (carbon, nutrients and water cycles) are managed within known boundaries of resilience and the capacity of amelioration of a particular ecosystem to support long-term productivity beyond the current rotation. This is particularly important for short-rotation forestry because risks are higher with increasing frequency of harvests and intensity of interventions. General principles of management have been discussed already. Here the focus is on the one critical phase that in some cases may have an overriding influence on sustainable production, the phase between harvest and establishment of the next rotation stands. This period of inter-rotational management is a window of considerable risk to the site, but also a time of opportunity to correct past mistakes and set the course for sustainable management. Furthermore, this is the phase of high risk that can induce off-site impacts and when scientifically based management offers the best way to minimize or avoid them.

Clear cutting a plantation is a major disturbance event that exposes the site to impacts including loss or displacement of organic matter, potential erosion on sloped land, exposure to intense rainfall, higher soil temperature and invasion by weeds. The amounts of nutrients removed from the site depend on the volume of wood removed, age of trees and the type of harvests practised. For example, Nambiar and Kallio (2008) found that the amount of phosphorus removed when harvesting a short rotation of an *Acacia mangium* plantation growing at an MAI of 30 m^3/ha/year was (kg/ha): merchantable stem wood, 12.2; wood + bark, 14.0; whole tree (wood + bark + slash), 24.8; total biomass (whole tree + litter + dead trees), 28.6. Since *Acacia* fixes atmospheric nitrogen, export of nitrogen is not critical in *Acacia* plantations. In the same report they also demonstrated a similar pattern with eucalypt plantations harvested in Brazil, in which case export of nitrogen is a critical factor. A progressive increase in nutrient removal in relation to intensity of harvest would apply to other elements. The impacts of nutrient removal on future productivity would depend on the fertility of the soil and the frequency of removal. All soils do not contain all nutrients in amounts adequate for good growth. Some nutrients are more limiting than the other and it is important to assess the rate of depletion of each nutrient in relation to the reserve capacity of the soil. Impacts of such removal on successive productivity would depend on the capital of available pool of nutrients in the soil and this needs to be evaluated at the local level. The methods for estimating biomass and nutrient export for a range of plantation systems and for assessing their impacts on productivity of short-rotation, fast-growing plantations are available (Nambiar, 2008).

Export of nutrients in wood and bark may not be the main cause of site degradation in many cases. Displacement or loss of organic matter due to practices including windrowing to 'clean the site' and slash burning can inflict a heavy penalty on site productivity (as examples, see Powers, 1999; O'Hehir and Nambiar, 2010). There is a considerable literature on the effect of plantation management on soil properties and in most instances increasing the tree productivity enriches the soil rather than the opposite, providing site organic matter (litter and harvest residues) are retained. Impacts of harvesting and site management on productivity tend to be strong in soils low in fertility. This is well demonstrated in a short rotation eucalypt hybrid plantation in the Congo (Fig. 9.5).

Here in a second-rotation stand, wood volume at the end of the rotation was reduced to half when all the organic matter (slash + litter from the first rotation) was removed at the start of the second rotation. Productivity increased linearly as the amount of organic matter (and nutrients) retained increased with various site management practices. Another good example of long-term impacts over a century comes from changes in production over three rotations of *Pinus radiata* planted over a period from 1932 (first rotation) to 1984 (third rotation) established on sandy soils in South Australia, where marked declines in the productivity of the second rotation were noted in the 1960s (Plate 4). The cause of this was found mainly to be the postharvest loss of organic matter and nutrients caused by high-intensity burning of residual biomass either left lying across the site, or heaped into windrows, an operation that often carries some surface soil along with the slash and litter to the heaps. Ploughing sometimes followed this action, which would have caused further loss of soil organic matter, accelerated mineralization and losses due to leaching in winter planting of seedlings for the next rotation. Current management employs a research-based package of practices, including conservation of site organic matter and nutrients, minimum cultivation, improved genotypes and judicious

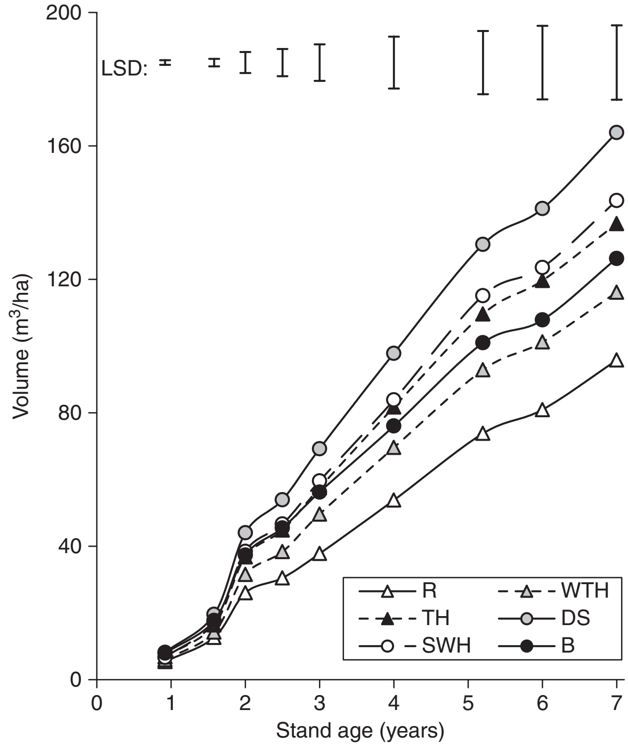

Fig. 9.5. Effect of harvesting and inter-rotation management on productivity of eucalypt hybrids on a sandy soil in Congo. All above-ground biomass including litter removed (R); whole-tree harvest (WTH); all residues burned (B); only merchantable wood and bark harvested (TH); wood alone removed debarked at stump (SWH); and double slash – slash from WTH plot added on top of the in situ slash (DS). LSD is least significant difference. (From Laclau *et al.*, 2010.)

weed and stand management to hasten 'site capture' by the trees. Effective implementation of these practices has underpinned large-scale improvements of site quality and higher productivity in third-rotation stands across the entire estate (Nambiar, 1996; O'Hehir and Nambiar, 2010).

In the absence of major disturbances, nutrients are tightly cycled within biogeochemical pathways in forested ecosystems. Any management that breaks this cycle and removes significant amounts of nutrients off-site (as biomass removed from the site, leachate or eroded soil) has the potential to reduce soil fertility and therefore productivity. Arguably the most important silvicultural practice, especially in soils low in fertility, at the time of site preparation from both productivity and environmental perspectives is the conservation of site organic matter through retention of slash (harvest residue) and litter on the forest floor (see Nambiar, 2008). Wood in logs from long-rotation forestry is relatively low in nutrients and their removal in harvesting has a small impact on nutrient capital. But wood and bark from fast-growing short rotation plantations would be richer in nutrients and cumulative removal over a 5–7-year cycle may add up to large amounts. Twigs, leaves and other litter on the forest floor have a higher nutrient content and their removal should be avoided. De-barking at stump in the forest is highly desirable. Practices such as windrowing and burning might be attractive for establishing an easy planting site, but the impacts through nutrient loss and displacement and soil damage can be severe in the long term.

Sites can be cleared of vegetation by hand, mechanically, by burning, by grazing or by using herbicides. As with minimum tillage systems in agriculture, clearing with herbicides will minimize soil disturbance and prevent erosion. Site preparation between rotations is more challenging. Burning is a cheap and easy (although highly risky) way to clear the site of debris (non-merchantable wood, dead trees and slash). Burning between rotations has been prevented in many plantation management regimes, but is still used extensively in some regions. Fire is also sometimes used for fuel reduction within the stand during the rotation and this can have adverse consequences on soil fertility. Nitrogen will be lost even at a temperature of 100°C and this is detrimental to non-nitrogen-fixing plantation species such as pines. Slash and litter burns also cause carbon emissions. Burning during and between rotations should be avoided, unless there are exceptional circumstances.

Intensive harvesting practices that remove a wide range of material, such as in biomass plantations and whole-tree harvesting, will reduce soil fertility. Whole-tree harvesting is justified by some managers on the grounds of economic efficiency, delivering higher pulp wood recovery and efficiency in harvesting. Where the trees are processed at the roadside leaving heaps of biomass outside the site, large-scale displacement of organic matter and nutrients is the end result. Total biomass harvesting for bioenergy is another growing business. Both practices can cause site deterioration and this should be carefully weighed against short-term benefits. Loss in fertility cannot necessarily be compensated for by addition of fertilizers. The efficiency of uptake of nitrogen by young trees may be 10–20% of nitrogen added. Replacement of say 300–500 kg N/ha, sequestered in organic matter and typically lost in total biomass harvest or postharvest burn, would require significant fertilizer application to even partly compensate for the loss. In fact, it is not possible to add such high rates of fertilizers without potential adverse effects on the ecosystem, nor is it economically sensible. Removal of organic matter and decoupling of the mineral cycle and cation balance have more profound impacts on soil and sustainable land use. Continued judicious use of fertilizers has a role in sustainable forestry, but forestry will be better served in the long term by adopting and perfecting management that enhances conservative use of site resources.

Sustainable production can be achieved, not by any single action, but through the conservation of site resources and integration of all aspects of management from selection of genotypes through all practices of plantation management to harvest and then replanting, taking care to ensure minimum disturbance to site for the next cycle.

Monocultures and Exotics

There is no evidence to support the view that single species plantations are inherently less sustainable than natural forests (Powers, 1999). Many natural forests are dominated by one species (e.g. pine forests in Scandinavia and spruce in Canada). Sometimes forests regenerated after wildfires are largely even aged, as is the case, for example, with *Eucalyptus regnans* foregts in Australia. Pests and diseases can inflict severe damage on native forests. For example, bark beetles (*Dendroctonus* spp.) have over the last two decades ravaged pine forests in western North America, probably aided by climate change (Halter, 2011).

Most plantation species are out breeders (i.e. individuals tend to breed with individuals from different populations) and if plantations are established from seed from well-designed breeding programmes, there will be significant genetic diversity within the stands, which reduces the risk of large-scale pest damage. On the other hand, clonal propagation of one or few genotypes can narrow the genetic base in the forest and increase the risk of losses due to pests and diseases, especially if those clones are particularly susceptible to pests. Deploying a reasonable number of clones and the configuration of that deployment are critical issues with clonal forestry. Pre-deployment testing of clones for their susceptibility to known pests and diseases and their adaptability to variable site conditions are also important. These are time consuming and costly processes, but cannot be ignored if sustainable forestry is the aim.

The impacts of pest attacks will be expected to differ within monocultures and in multi-species forests. This is the case for both natural monocultures as well as planted forests. If pest attack seriously affects a forest dominated by one species, this may be an ecological disaster, as has happened with the pine bark beetle in Canadian forests during the last decade (Halter, 2011). In plantations, epidemic or chronic pest attack may slow growth rates, reduce the value of living trees through pests such as stem borers or kill trees outright with consequent commercial losses. If disease or insect attack affects just one species of many in a multi-species forest, the overall damage is proportionately less or may not even be obvious.

Plantation managers are often prepared to take the risk of using one species across their estate in the reduced timescales of plantation forestry if this species shows superior growth and performance and provides the product they need. They justify this on the basis that economies of scale, proven technologies of risk management, continuous genetic improvement in planting stock, more focused research and careful investment in pest management can balance out the extra risk associated with having to trial, manage and market a number of species. Some plantations of exotic species have been successfully managed for more than 130 years (e.g. *Pinus radiata* in New Zealand and Australia), and even longer (e.g. *Tectona grandis* in Java and India).

There are, of course, examples of pest and disease attacks in established plantations, but there are many examples of large-scale plantation programmes that, up until the present, have been remarkably free of disease. Nair (2001) compared a range of native and exotic tropical plantation species and concluded that monocultures caused an increase in pest problems, but that there was no evidence to suggest that the exotics as a group were any more or less prone to pests than the natives. Gadgil and Bain (1999) argue that the health of intensively managed plantations of proven successful plantation species is better than the health of trees in natural forests. Trees that are water and/or nutrient stressed, over stocked or neglected may be rendered vulnerable to pest attack. Good management and hygiene can reduce the risk significantly. Despite the success of exotic species in plantations world-wide, potential future threats cannot be ignored and careful monitoring is warranted. Recently, the spread of root rot fungi (*Ganoderma* spp.) and stem dieback diseases caused by *Ceratoystis* species are posing a threat to the sustainable production of *Acacia mangium* plantations in Sumatra, and practical control measures are not in sight. In this case, *Acacia* sites may have to be gradually converted to eucalypts, which seem less susceptible but not immune to root rot. Crop rotations may become important in such cases.

Some argue that monocultural plantations degrade the soil through processes of acidification and podzolization. However, providing plantations are managed well, site resources and especially organic matter conserved on the site, and fertilizers judiciously applied, monocultures will not degrade the soil. In fact evidence from *Pinus radiata* plantations established on poor podzolized sandy soils shows the site productivity can be maintained or upgraded over a long period and over consecutive rotations (O'Hehir and Nambiar, 2010). Certainly there are examples where a particular species planted on infertile soils with a history of ongoing organic matter removal have resulted in deterioration of soil properties. These effects have little to do with monocultures per se and are more than compensated for by examples of well-managed plantations enriching the soil.

Some exotics species have the potential to be invasive and out-compete native vegetation. The weediness of some species has caused considerable difficulties in land management in various parts of the world where an introduced species has invaded the surrounding landscape (e.g. *Acacia melanoxylon* in South Africa, *Cinnamomum camphora* in Australia, *Melaleuca quinquenervia* in Florida and *Pinus contorta* in New Zealand). Invasion of exotic plantation species into the adjoining native vegetation requires regular monitoring and control. On the other hand, exotic species can be used as a nurse tree for promoting the growth of planted or seed-regenerated native species for ecosystem restoration. For example, *Acacia mangium* planted in rows can serve as an effective nurse tree for the establishment of several native *Dipterocarpus* species for plantations in Indonesia and Malaysia. Similarly tropical exotic pines have been used for restoring native species in Costa Rica.

Plantations and biodiversity

When considering biodiversity, there are a number of aspects to examine. One arises from clearing and conversion of native forests, woodland or native grass lands to plantations. The second concerns the conversion of agricultural land to new plantation forests. The third aspect is the protection of native vegetation within the plantation landscape and areas adjoining them.

Clearing of remaining native forests is a risk to biodiversity and other ecological values (Chapter 3), but our economic and social development, historically, would not have been possible without clearing forests. Economic and social drivers for forest clearing, which continues at the current global rate of about 10–12 million ha/year, are well known. They include expansion of agriculture, grazing and commodity crops such as oil palm and rubber, as well as other activities related to bioenergy, mining and the expansion of infrastructure associated with economic development. Clearing of native forests for plantation forestry per se has been a contributor in the past, but is now a relatively minor cause of deforestation. The policy that legitimizes the conversion of so-called secondary degraded forests remains questionable, as are the criteria applied for such demarcation in some countries. The challenge today is to reduce clearing native forests for whatever purpose.

Plantations can contribute to biodiversity in several ways within stands and at the landscape level. Commercially managed plantation stands can provide habitats for a wide range of native plants, animals and fungi in diverse environments (Carnus *et al.*, 2006; Brockerhoff *et al.*, 2008). In New Zealand, plantations of *Pinus radiata* provide a habitat for about 118 native species some classified as threatened, or vulnerable or sparse (Pawson *et al.*, 2010). Several studies from Australia, Argentina, the UK and elsewhere provide evidence that single species plantations can and do serve as habitats of animal and plant diversity. There has also been much progress in our understanding of how a plantation can support biodiversity at the landscape level (e.g. Fischer and Lindenmayer, 2006). Several management options can enhance the environmental values of plantation forests (Bauhus *et al.*, 2010).

Plantation forests are commonly referred to as 'even aged', which is misleading. A reasonably significant area under plantation estate is never of the same age. Each year a proportion of the area will be harvested and an equivalent area from the previous harvest will be replanted with the same species, but mostly with different sets of genotypes. Thus a plantation area of say 100,000 ha (mostly interspersed in a larger area with other land uses), managed on a sustainable harvest regime over a 30-year rotation cycle, may well have 30 age classes of 3000 ha (non-contiguous) each, some areas of which would have been thinned sequentially (creating a different habitat), interspersed as a mosaic through the estate. In addition, the plantation often contains protected riparian zones (rich in biodiversity), native forest edges and small to medium size patches of native vegetation, which can be protected. These age classes of varying stand structure and protected native vegetation provide continuous and diverse environments – habitats for flora and fauna, including soil fauna and fungi (Carnus *et al.*, 2006). When crop rotations are short, as in pulpwood plantations, age-class distributions reduce accordingly. It is not possible from both ecological and economic perspectives to grow and manage plantation forests that mimic native forests in all their diversity and function.

Plantations established on already cleared land and on degraded lands will be an environmental gain. If the objective is to maximize the chance of restoration and enhancing biodiversity, plantation establishment may be the best option. Restoration of degraded lands comes at a cost and one of the reasons plantation managers sometimes avoid degraded lands is that of the additional cost. Planted forests can make a major contribution to ecological restoration and landscape protection (e.g. Maginnis and Jackson, 2003).

There are many cases where plantation forestry has added to the gain in forest cover. In countries with low or no native forest cover, plantations can comprise most or all of forest cover (e.g. Egypt 100%). Several European countries report large areas of plantation cover (e.g. Czech Republic 99%, Hungary 79%, although European countries have a more liberal definition of planted forests than in many other countries). Plantations of mainly *Eucalyptus* and *Acacia* comprise a significant and growing proportion of the total forest estate in some relatively forest-rich countries in South-east Asia (e.g. 21% in Thailand and 25% in Vietnam) (FAO, 2010). Many major industrial plantation enterprises now devote and protect significant areas of native vegetation within their estate for environmental and related biodiversity values. In Brazil, some companies allocate nearly 30% of their land base for such purposes and the plantation industry collectively is making major contributions to biodiversity conservation goals in that country. There are similar trends in other countries, including Chile and Uruguay, but managers cannot be expected to maintain the entire local biodiversity within each of their production compartments. A landscape approach to total land use (Fig. 9.1) can play an important role here. Every additional desired environmental outcome adds to the complexity and cost of management. Therefore expectations to deliver environmental services need to be tempered with realities of management and economic imperatives (Brockerhoff *et al.*, 2008; Bauhus *et al.*, 2010).

Plantation forests reduce the dependence for wood from native forests. In addition, there are many ideas on the potential additional role of plantations in the 'green economy'– ranging from direct carbon sequestration to a renewable resource for bioenergy and biochar production. How these ideas may eventuate is an open question. Leach *et al*. (2012) discussed the ideas of various proponents of the 'green economy' and pointed out that some are advocating the prospects for tree plantations for biochar production ranging from 200 million to 1 billion hectares. As argued by the authors, if this was to occur, even partly by clearing native forests or savannah woodlands in Africa, what would be the net outcomes to conservation and environment? Environmental impacts of past clearing of native forests for plantation establishment cannot be undone. The question now is to explore how investments in plantation forestry can enhance biodiversity without penalizing productivity and recognizing the economic realities and the purpose of those investments.

Summary

Native forests, woodlands, industrial plantation forests, woodlots for bioenergy, farm forests and farms should be seen and managed in a continuum of systems of sustainable land use. Planted forests established primarily for wood production can also deliver environmental benefits (land rehabilitation, biodiversity rejuvenation or catchment protection). Several types of plantation development to suit one or more land use objectives are possible and are in vogue. There are many examples of sustainable and successful plantation forestry operations in diverse environments and countries of the world. There are, of course, controversies and some failures. Many forestry debates and some protests about the expansion of plantation forestry have been driven by the opposition to: land-use change; the impact on the livelihoods of rural people and communities; 'exotic monocultures'; international investments; or the establishment of pulp mills alleged to have caused negative environmental impacts. Arguments against plantations have been eroded over time, and the need for and benefits from further development of plantation forests are now well-recognized worldwide. About 5 million ha/year of plantations were established between 2005 and 2010 (FAO, 2010), mainly in tropical countries, and there is scope for further growth.

Government approval in most countries for almost all recent or new major plantation development programmes is subject to satisfactory outcomes from either an independent and comprehensive environmental impact assessment or local regulations, which include codes of forest practice that are legally enforceable. There has been rapid progress in several certification programmes that aim to demonstrate the implementation of sustainable forest management practices. Plantation forests reduce the pressure for wood harvests from native forests. They are a renewable natural resource and should be recognized as a part of the 'green economy'. Global demands and need for wood are increasing in response to economic growth and wood-products consumption in several countries. Plantations are the most productive way to grow, efficiently, large amounts of wood of uniform and specified quality from a relatively small land base in an environmentally sustainable manner.

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10 Social Forestry

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What is Social Forestry?

Since the World Forestry Conference in Jakarta, organized by the FAO in 1978 with the theme 'Forestry for People', the concept of social forestry has become general. Especially at the end of the 20th century, this term was used to reflect concerns that forestry should give more attention towards socio-economic welfare of rural communities in tropical countries, and that explicit attention should be given to the contribution of forests to local livelihoods and poverty alleviation. This requires new arrangements for forest access and benefit-sharing by indigenous and rural communities. There is no robust definition for 'social forestry'. The idea of social forestry arose in response to the traditional focus of forest management that was based on the principle of state custody over forests, with management being the responsibility of a professional forest service and being focused predominantly on commercial timber production and national interests. In many tropical countries, this approach was not as effective as anticipated (Westoby, 1989). The state forest organizations proved to be bad managers of the forests, either overexploiting themselves or issuing concessions to private companies or public enterprises without effective monitoring and control. In many places they were absent as managers or controllers, leaving the forests open to uncontrolled use. Moreover, they were mainly focused on commercial timber exploitation and the role of forest in the national economy, and neglected or even outlawed the use of forests by local people. Big forestry with a power and policy base remote from the forest often was detrimental to subsistence farmers. It mostly alienated the very forest the rural farmers needed for their livelihood and reallocated the forests to serve industry. It also attracted big investors with little interest in the plight of the peasant farmer. In reaction to these negative aspects of public forest management, social forestry was characterized as indicating that 'forests are more about people than about trees' (a well-known quote attributed to Jack Westoby).

In the 1980s, the notion of the need for more local participation in forest and nature conservation became further strengthened as a result of the publication of the World Conservation Strategy published in 1980 (IUCN, 1980) (see also Chapter 11). This document indicated the need for a change in nature conservation by adapting the prevailing preservation approach focused on establishing wilderness conservation reserves devoid of people to a more socially conscious approach. The strategy indicated that conservation is also needed outside official nature reserves and that more attention should be given to grass-root developments of communities living in or near conservation areas. In this last context, much attention became focused on the rights of indigenous people on ancestral lands.

In the early 21th century, the term social forestry became less commonly used and other terms became fashionable, such as community-based forest management (CBFM) or participatory forest management. This does not mean that the notion of social forestry is less relevant. It forms an important issue in most global forest policies (Chapter 11). Also in the industrialized countries new socially oriented approaches to forest management were developed. These often concerned novel approaches towards the amenity functions that increasingly urbanized people expected from the forests. Consequently, the notion of social forestry has gradually evolved. The original idea behind social forestry was to assist the poor rural communities in developing countries to sustainably use the forests in their vicinity as a livelihood asset. This idea is now often referred to as community forestry. But the concept has been broadened to include other forms of participatory and 'small-scale' forestry in both rural and urban areas in developed and developing countries. For convenience, social forestry will be sub-divided in this chapter into community forestry, farm forestry and agroforestry, and urban forestry, although the boundaries are not always distinct. But first the basic social issues that inform social forestry are elaborated.

Forests, Human Rights and Poverty Alleviation

Forestry as a profession developed out of scientific disciplines where it was assumed that science and technology could solve all forestry problems, providing that people behaved in predictable, rational ways. The notion of social forestry reflects that such rationality is grounded in normative considerations on how human society can best be organized. The traditional approach to professional forestry, especially in tropical countries, was based on a vision of states being best able to manage forests as a public resource. National agencies could best represent public interests, had the power to protect these interests and had the appropriate knowledge to do so. But different people may have different rationalities, and the rationalities of professional foresters engaged in the national services and the inhabitants of (rural) communities are not necessarily similar. The notion of social forestry is based on the understanding that sustainable forestry requires attention to the multiple rationalities in forest–people interactions (FAO, 1978; Arnold, 2001). It is based on three main notions. In the first place, it emphasizes human rights of indigenous people and rural communities in using the forest resources on their ancestral or traditional lands and highlights the democratic principle of local participation in decision making and implementation of location-specific forms of forest use and management. In the second place, it assigns much importance to the principle of equity in benefit sharing, with due attention to the forest-related needs of groups of people who depend on forest resources for their daily livelihoods. In the third place, it is also based on the notion that sustainable forest management is best assured if it involves the stakeholders that directly depend on those forest resources (see also Chapter 7). Ideally, social forestry aims at safeguarding the environment (arresting deforestation and conserving soil, water and biodiversity), improving economic welfare (increasing natural, physical, financial, human and social capital) and enhancing the social fabric of the community. This is no easy task, especially as different people may have different opinions about the relevance of these objectives.

Human rights

When, at the end of the 1970s, the notion of community forestry was introduced, it was primarily based on concerns regarding the rights of local communities to have access to forest products needed for their daily livelihoods. In the 1980s, human rights concerns also became focused on the rights of indigenous people on ancestral lands and their own cultural identity. The global recognition of indigenous people's rights to land brought with it an important change in scale in community forestry. Originally, the concept was based on the idea of communities as small settlements, with community forests having a size of some tens or hundreds of hectares. But as a result of the increased attention given in the late 20th century to the rights of indigenous people, the concept of community also became related to groups of tribal people. Notably in South America, but also in Asia and countries such as Canada, the USA, Australia and New Zealand, the ancestral land rights of tribal people became legally acknowledged as well as the rights of self-determination of indigenous people over these lands. Box 10.1 illustrates this process in respect of the Maoris in New Zealand. The legal transfer of tribal lands to indigenous people brought much larger tracts of forests (up to thousands of hectares) under local control than in the earlier small-scale community schemes (Molnar *et al.*, 2004). These extensive areas of forests provided good scope for income earning through the sale of forest products. Human rights of citizenship mean that indigenous people are not only entitled to rights over lands and rights to maintain traditional culture, but also to rights to become engaged in modern society, including in commercial enterprises. Consequently, whereas originally access to forest resources was a basic tenet of community forestry, this tenet became extended to rights of access to markets. The basic question of social forestry was no longer how local communities could use forests for basic needs, but also how they could be connected to

Box 10.1. Justice for New Zealand Maori – by Nora Devoe

Ten separate purchases transferred New Zealand's South Island land from its native Maori inhabitants to the Queen of England, 'the Crown', or the New Zealand government. The Treaty of Waitangi (1840) established the conditions for these purchases. The Treaty gave the Queen 'the rights and powers of Sovereignty' that Maori chiefs had held. It also 'guaranteed' Maori 'full and undisturbed possession' of resources they declined to sell, and granted Maori the rights of British subjects, including property rights. Within the boundaries of the land purchases were Maori settlements, camps, food-gathering sites, and in some cases, unspecified reserves, for which continued Maori ownership was guaranteed. These guarantees were mostly immediately abrogated (Evison, 1998).

By 1891, Maori owned less than 20% of their 1840 holdings (Te Puni Kokiri, Ministry of Maori Development, 1996); 50% of South Island Maori were landless. A further 40% had insufficient land for their sustenance. Abject poverty marked their overall condition (Waitangi Tribunal, 1991). As partial compensation for the much more valuable lands promised in the deeds of purchase, the 1906 South Island Landless Natives Act (SILNA) granted 57,498 ha to 4064 Maori who had no or inadequate land. SILNA lands were to provide for the owners' livelihoods, but they were and remain rugged, largely forested, without access, infertile and non-arable.

Between 1840 and 1993, forests throughout New Zealand were cleared to create farms and plantations. In 1993, the Forest Act 1949 was amended to require what the government deemed 'sustainable management', which precluded natural forest clearfelling except in small patches or when the wood was not milled. Export of native timber was prohibited unless it was sustainably produced. Some SILNA owners were clearfelling to export chipwood.

Because of likely Treaty of Waitangi compensation claims, SILNA lands were exempted from the Forests Amendment Act 1993 (FAA). Successive governments sought to bring SILNA lands under this law. SILNA owners argued, and independent research confirmed, that compliance with the FAA would reduce forest value by some 90% of clearfell value (Griffiths, 1998). SILNA owners viewed the FAA as an affront to their self-determination and the loss of the option to clearfell and export as a theft of many millions of dollars. Non-SILNA forest owners also protested abridgement of their property rights (Heath, 1992; Federated Farmers of New Zealand Inc., 1999). The SILNA owners' argument with the Crown waxed and waned. The Crown purchased conservation settlements over the most valuable SILNA softwood forests. The owners in these settlements relinquished their Treaty of Waitangi claims.

Under a 2004 amendment to the Forest Act 1949, the Crown further reduced its exposure to compensation claims by construing compliance with its rules as voluntary. However, the SILNA exemption to export prohibitions was repealed. Other environmental legislation was cited within the 2004 Act, giving it force over SILNA land. The 2004 Act made non-sustainable management unlikely and uneconomic. If sustainable management was voluntary, refraining from non-sustainable management was not. Without payment for the foregone market values of clearfelling, the Crown effectively coerced private landowners to finance a public good, forest conservation. Treaty of Waitangi claims against the Crown are pending. The Crown offset some of the SILNA owners' economic loss by offering limited forestry services to support sustainable management. So far, hardwood management under the Crown's terms has proven unprofitable for any forest owner.

Justice is a necessary foundation for sustainable forest management. Even when laws dictating sustainable management are enacted, they are not fully effective without forest users' cooperation. Illegal logging in New Zealand has increased with rising values of selected native timbers and the sense among landowners that they have been treated unfairly.

markets for forest products and services and thus to forest-related consumption patterns of urbanized people (Colchester, 2008).

Poverty alleviation

The World Bank estimates that 410 million people (including 60 million indigenous people) live in or near tropical forest areas and depend on these forests for their subsistence and survival needs. As illustrated by the Millennium Development Goals (Chapter 11), global forest policies strongly emphasize the need to reduce such poverty. The fact that so many poor people live in and near forest areas suggests that there is an intrinsic relation between forests and poverty. Historically, forest areas have been regarded as being underdeveloped; in order to eradicate poverty they needed conversion to more lucrative forms of land use. At present there is a much more nuanced view on the linkages between forests and poverty (Wunder, 2001; Sunderlin *et al.*, 2005; Shackleton *et al.*, 2007).

In the first place, there is better understanding of the different roles of forests in poverty alleviation. Originally, poverty was interpreted as concerning a lack of employment and income, and poverty alleviation was considered to be synonymous with increased employment and income generation. More recently, poverty is also conceived of in terms of vulnerability and a lack of ability to withstand adverse conditions, and poverty alleviation is interpreted as also including prevention of greater vulnerability. Hence, poverty alleviation is now interpreted as involving either poverty mitigation or avoidance, or poverty reduction or elimination. Forests can play a role in both processes. In the case of poverty mitigation and avoidance, people use forests as a resource to meet subsistence needs such as wood, food, fibre, medicinal plants and energy, or as a 'safety net' to meet occasional shortfalls in production or income. The access to forest resources thus protects them from economic decline and serves to cope with emergencies such as periodic droughts limiting agricultural production. In the case of poverty reduction or elimination, people use forests as a means to provide products and services that can be traded (sometimes after further manufacturing), thus providing possibilities to generate cash income. When such products or services permit the accumulation of savings and assets, they may lead to lasting improvements in income and well-being and hence to the reduction or even elimination of poverty. These two processes involve different types of rural household strategies (Table 10.1). For households engaged in a survival or a coping strategy, forests mainly serve as a means of poverty mitigation, while for households following a diversification or accumulation strategy, forests serve primarily as a means of poverty reduction.

In the second place, the role of forests as a livelihood asset is better understood. In the mid 20th century, attention for the role of forests in economic development was exclusively focused on timber production. Since the end of the 1980s, it has been acknowledged that forests also provide a large variety of non-timber forest products, such as food, medicinal plants and fibres. Furthermore, forests are often also a sociocultural asset because they are perceived as ancestral lands or a living environment, providing indigenous people with cultural identity. In addition to the recognition that forests provide multiple livelihood assets (and not only productive ones), it is now also acknowledged that forest-based livelihood activities usually form part of multiple component livelihood strategies. Because of seasonality and the low densities in which non-timber forest products generally

Table 10.1. Household strategies in using forest products. (Adapted from Shackleton *et al.*, 2007.)

Strategy	Characteristics
Accumulation or specialized strategy	Households endeavour to increase the stock of assets and income flows from forest products. The objective of this strategy is to increase income and it often involves specialization in forest product manufacturing and trade, which then become the most important sources of household income. The main prerequisites for this proactive livelihood strategy are access to capital and access to markets.
Diversification strategy	Households endeavour to diversify their livelihoods by supplementing (subsistence) agriculture and sometimes petty trading with the sale of forest products. This pro-active supplementary livelihood activity is mostly undertaken by households with a low to intermediate income and often serves to generate additional income that can be used for special household expenditures.
Coping strategy	Households with few other opportunities respond to adverse impacts of livelihood shocks or by using forest products for food security or for the provision of cash for essential livelihood costs such as school fees. This reactive and defensive livelihood strategy mitigates poverty rather than reducing it.
Survival strategy	Households revert to forest products as a last resort to secure food and prevent destitution. This reactive and defensive livelihood strategy acts as a safety net for households that have no other choice than to rely on this and other similar safety nets and survival activities.

occur, the options for forest-based poverty alleviation will rarely concern specialized full-time activities, but are usually combined with other sources of income.

In the third place, since the late 20th century new opportunities for trading forest products and services emerged. As a result of the worldwide decrease in forest areas and the increased demand for forest products and services of increasingly affluent urban populations, several forest products and services are acquiring a financial value. In the past, wood was considered to be the main commercial forest product, but at present markets for non-timber forest products have also developed. During the last decade, experience has also been gained with payments for the aesthetic and experiential values of forests, for instance through (eco)tourism. Several initiatives have been started to develop payment schemes for environmental services, such as the provision of regular water supplies for domestic needs or CO_2 sequestration. These developments brought increased attention to options for making markets work for forest-dependent communities (Scherr *et al.*, 2003). As a result, the original focus of social forestry on the importance of subsistence forest products used in survival or coping strategies has been widened to include the role of commercial forest products in diversified or specialized livelihood strategies.

Community Forestry

FAO (1978) defined community forestry as 'any situation that intimately involves local people in forestry activity'. In a more formal way, it can be defined as the use and conservation of forest resources on the basis of controlled use and management by local communities, with decision making on management organization and practices as well as on benefit sharing being primarily based on the shared norms and interests of local people. Although this definition includes farm forestry (to be discussed below), the term community forestry is mostly used for referring to community involvement in managing forests as common property (see below). The term does not only apply to forest management practices of communities that live in the forest but also to forest-related practices of communities living adjacent to forests or in forest mosaic landscapes. These practices do not just concern the use and management of timber trees, but a large range of other forestry activities as well: managing woodlots for fuel; growing multi-purpose trees; providing fodder for livestock; hunting for bushmeat; gathering and marketing of non-wood forest products and medicinal plants; and providing mulch, shade and windbreaks for agriculture. As elaborated above, such forest activities may be critical to rural farmers in supplementing their agricultural activities and incomes; they may also act as an emergency source of food in times of famine or crop failures.

The concept of community forestry originally arose in the context of searching for new approaches to stimulate forestry development in tropical countries. Within this context, the term community forestry is sometimes not just used to denote the forest use and management practices of local communities, but also the forestry development programmes stimulating the local involvement in forestry. This is confusing because the objectives of local people in using and managing forests as parts of their livelihood strategies are distinct from the policy objectives of community forestry development programmes. As discussed above, the overarching principle in community forestry (or community-based forest management, CBFM) development programmes is involving people at the local community level in the management of the trees and forests in their vicinity and in sharing the benefits. The ultimate aim is not only to reduce deforestation and stimulate sustainable forest management, but also to reach social goals such as stimulating rural development, alleviating rural poverty, assisting the landless, empowering women, and achieving social justice for the marginalized and the disadvantaged. Some of these aims may not necessarily be similar to the local norms for using and managing forest resources, e.g. where they are based on community relations giving landowners power over landless people or favouring owners of large animal herds. Because of the multifaceted and locally sometimes non-consistent development aims, it is no wonder that there is a history of community forestry programmes that were criticized for not fulfilling all expectations.

Initially community forestry development programmes were often based on a top-down approach aimed at encouraging local communities to stop destructive practices, such as short fallow shifting agriculture and deforestation of upland catchments. This was followed by top-down village woodlot programmes to arrest the so-called fuelwood crisis (see Chapter 5). Most of the first phase development projects were based on a single policy goal, such as stopping forest degradation, improving erosion control or producing fuelwood. It was gradually recognized that such a single-objective approach does not suit the multifaceted livelihood strategies of rural households. Moreover, it became recognized that many programmes had ignored local practices in using and managing a diversity of forest products. Also the relation between community forestry and professional 'big' forestry became clearer. Historically, some forest areas previously used as common property by local communities were appropriated by government and managed as timber reserves to support industry. This reduced access to common forest land and weakened and confused the local arrangements of local communities for managing the common forested land they relied on. This was further complicated by private tenure rights being given to privileged individuals and a greater proportion of the rural poor relying on paid employment for their livelihood. These lessons from the first generation of community forestry development projects resulted in the recognition that community forestry would only work if it addressed specific needs of the locals and built on their already existing forest-related practices. The stimulation of community forestry essentially requires a location-specific approach of multipurpose forestry and incorporation of local knowledge and experiences rather than just the facilitation of professional forestry practices through extension and communication.

The initial community forestry programmes were mostly focused on the provision of essential forest products to local people within the framework of their subsistence economies. But gradually more attention was given to the role of forest products for providing an additional income supplementing agricultural food production. This reflected the growing understanding that, for poor people living in or at the edge of forests, forest products often form a better option for earning an income than agriculture. Moreover, from an empowerment point of view, it was considered that access to markets is an essential element in raising income and living standards (Scherr *et al.*, 2003). Consequently, community forestry development programmes evolved from meeting the subsistence needs of the community to community forestry being a significant income earner and a means of raising the living standard of the whole community.

Basic principles of community forest management

The term community is sometimes interpreted as referring to a local settlement with a small and bounded spatial unit with a homogeneous population of people sharing the same values. In reality, however, most rural communities are not homogeneous and do not act as a cohesive group (Agrawal and Gibson, 1999). There often exist social and economical hierarchies; differentiations in gendered roles and responsibilities, and inequities in land tenure and in wealth. Examples of such heterogeneity are caste differences in South Asia or the differentiation between pastoral people and crop cultivators in the African Sahel region. Communities may also involve co-existence of landowners and tenant farmers, or seasonal presence of people who are part-time employed in other, often more urbanized, regions. Due to such socio-economic differences, there is always the chance that community management will reflect existing community power structures that may favour the wealthy over the poor, the landed over the landless, mainstream over marginalized and men over women. Women are frequently disadvantaged in rural poor communities. Women are the collectors of fuelwood and the gatherers of forest products. If a community forestry programme is able to materially improve the plight of women, it is more likely to be a success. However, social structures often make this difficult to achieve. Not everybody will operate in the community's best interests and community power structures may be well entrenched. Hence, it is naïve to think that people living in a rural community always share the same values and that they cooperate in meeting their daily livelihood needs. None the less, factors such as trust and social dependencies stimulate cooperation and communal action, and many forest-dependent communities have established arrangements for maintaining forest resources that are essential in their daily livelihoods.

Forests as common property

The specific characteristics of community forestry were not recognized in the past. Rather, there was widespread doubt about the capacity of local communities to manage their forest resources. Hardin

(1968) introduced the theory of the 'tragedy of the commons', which claims that it is inevitable that property held in common will be overused. Such common resources are characterized as being non-exclusive in the sense that all users have access to the resources, although their use is subject to rivalry because consumption of the resource by one user makes consumption by other users impossible. The argument is that it is human nature for individuals to take more than their fair share at the expense of others if they can get away with it. This argument greatly stimulated the forest policies favouring either state control or privatization. However, in the 1980s researchers started to challenge this theory by pointing at the many manifestations of existing community forestry (FAO, 1985; Poffenberger, 1990). They argued that many examples used to demonstrate the tragedy of the commons referred to situations where no commonly agreed rules and regulations on forest use existed, with the result of forest resources being subject to uncontrolled use. However, there are many examples of local cooperation that reflect common interests of community members and that work very well in maintaining forest resources that are essential for local livelihoods. These local systems are often not only directed at timber trees, but also include all kind of arrangements for preventing overexploitation of non-timber forest products used in the local livelihoods.

Hardin's theory became not only disputed on these empirical grounds, but also on theoretical grounds. Notably the work of the later Nobel laureate in economy, Elinor Ostrom, contributed to the replacement of Hardin's theory by the theory of common property resource management (Ostrom, 1990). The theory argues that it is incorrect to consider local forest users just as individualistic profit maximizers, as is the case in Hardin's theory. Much attention was given to the factors enabling local communities to manage their own natural resources. The theory highlights the importance of clearly defined boundaries of the resource, a proper local organization for looking after the resource that enable resource users in decision making, a set of locally agreed regulations for controlled use, monitoring of rule compliance, a graduated set of sanctions against non-compliance and local mechanisms for conflict resolution.

The identification of these so-called design criteria for common property forest management has greatly contributed to the recognition of its scope and potential. But it had its limitations in stressing the own autonomy of local communities in managing forest resources, because it gave less attention to the impact of external factors (Agrawal, 2001).

Indigenous knowledge

The presence of traditional systems for common property forest management demonstrates that many local communities recognize the value of forest resources and they have developed indigenous management practices (Wiersum, 1997). These practices reflect the indigenous knowledge regarding both conservation and enrichment of forests as well as their use. Typical examples of indigenous practices for conserving forests are sacred forests. In several cultures forests are consciously preserved as resting places for forefathers, religious sanctuaries or ceremonial places. Conservationists have heralded such sacred forests as ancient examples of conservation and repositories of biodiversity (Posey, 1999). Other examples of indigenous forest-related knowledge concern knowledge on specific forms of forest use, such as for medicinal purposes. The recognition of the relevance of such knowledge is reflected in ethno-botanical research by pharmaceutical companies, who expect that indigenous knowledge (e.g. of local healers) may contribute towards the development of new medicines. Indigenous knowledge is not restricted to conservation and use of forest resources, but also includes knowledge for using the ecological services of forests in agricultural production or enriching forests with valuable species. Such practices may result in anthropogenic forests types that maintain many features of natural forests, but that have been adapted by humans. Typical examples are secondary forests created by shifting cultivation practices and multi-storeyed cropping systems such as homegardens and forest gardens. In the past, shifting cultivation systems were often condemned by foresters as slash-and-burn systems wasting good timber, but at present they are understood as agroforestry systems with rotating trees and agricultural crops. Provided that the tree fallows do not last too short a time, these systems can be sustainable under low population pressure conditions. When cutting the forests, valuable trees (e.g. fruit trees or trees harbouring honey bees) are often not cut. During the period of agricultural cultivation, regeneration of valuable species may be protected, or even planted. In this way, the secondary forest fallow may become enriched in valuable species, and gradually develop into forest gardens. In the past, such forest gardens were often not recognized, but (as will be elaborated in the section of agroforestry) their presence in many tropical regions is now acknowledged. For examples, see Chapter 6.

Of course, in addition to the examples of such indigenous knowledge of sustainable use and management of forest resources, there are as many examples of indigenous land-use practices that were not ecologically stable and resulted in ecological degradation. This is often attributed to the fact that these practices were not adjusted to modern conditions, such as population growth and agricultural modernization. But such examples should not be interpreted as indicating that indigenous practices are never able to deal with rural dynamics and are just relics. As demonstrated by the continued presence of indigenous agroforestry practices (see later), many indigenous practices are good examples of adaptable management (Berkes *et al.*, 2000). They provide a good basis for learning from local forest users (Lawrence, 2000). The International Convention on Biodiversity Conservation (see Chapter 11) explicitly recognizes the need to respect, preserve and maintain the knowledge and practices of indigenous and local people regarding biodiversity. The use of such indigenous knowledge should be promoted, and the benefits arising from the utilization of this knowledge should be equitably shared.

Land and tree tenure

In traditional forest management, the ownership of land and trees and the rights of their exploitation are often rather straightforward. The rights on land and trees often coincide, and the forest owner can either harvest timber trees himself or contract it to a harvesting concessionaire. In community forestry the situation is often much more complex, with different rights on lands, trees and tree products. These rights are often not formally registered, but are locally recognized. They concern an informal bundle of rights concerning the ownership and use of both lands and tree resources (Fortmann and Bruce, 1988). As demonstrated by the legal prohibition in some countries of harvesting valuable timber trees growing on private lands without permit by the forest department, ownership of trees does not automatically mean use rights. Similarly, a farmer leasing land from another farmer for growing agricultural crops may not be allowed to grow trees on these leased lands, because it may be considered that the planting of perennial crops provides a long-term right to use the lands in contrast to the short-term nature of an agricultural lease. Alternatively, a forest land-owner may give a permit to other people to harvest certain tree products such as fodder or fruits from his land, but may not allow those people to cut trees. Hence, property rights do not simply refer to ownership, but to a diverse set of rights to maintain trees, use trees and sell tree products, to loan or lease lands or trees to other people, or to give away or bequeath lands or trees to other people. In addition to such endowments, because of property rights there are also entitlements in the form of use rights (Leach *et al.*, 1999). The use rights may depend on the type of use of a product (e.g. people may have the right to collect tree products for own use, but not for commercial purposes), the location of trees (private lands, communal lands, state lands) and the nature of the product (e.g. collection of dead wood versus cutting of live trees).

The tenure complexity in community forestry, with differentiation in endowments and entitlements, is further compounded by the fact that the mostly informal tenure rights at community level are supplemented by the national rules and regulations on forest ownership and use. These legal regimes are often of a much less refined nature than traditional local tenure arrangements. They mostly focus on timber trees and forbid use practices such as grazing that are considered detrimental to forests. Local arrangements often also involve regulations on the collection of non-timber forest products or the controlled access of livestock to forests, e.g. by herder-supervised rotational grazing. A clear and locally accepted system of tenure arrangements is crucial for community forestry and differentiates open-access forest use from community-controlled forest use. In spite of all efforts to decentralize and devolve rights to local communities and groups of forest users, insecure tenure arrangements and conflicts over forest land because of the coexistence of formal legal and informal local tenure systems often still prevail. The crucial question in community forestry is not whether the tenure systems are *de jure* formalized, but whether they are *de facto* locally recognized.

Basic principles of community forestry development

Since the recognition of community forestry as a feasible strategy in forest conservation and management in the late 1970s, many forestry development programmes have been initiated to stimulate this management regime (Arnold, 2001; Charnley and Poe, 2007). Initially, many programmes were based on a rather conventional, albeit down-sized, professional forestry approach. It concerned top-down, aid-driven approaches that were established with all the best intentions. Many of these initial programmes had limited success or even failed. Rural folk were suspicious of technical forestry experts who told them what they needed for their own good. The rural subsistence farmers proved to have their own way of life handed down to them through the generations and they were reluctant to take part in new practices that did not fit well within their traditional livelihood strategies, often conflicted with their traditional practices and did not acknowledge the value of various indigenous practices. If a project does not identify with a community and considers local people as subjects who need to be taught principles of professional forestry without acknowledging local knowledge and practices, then it will probably fail. Most successful community forestry development projects are those where ideas are generated in interaction between development officers and local people. Sometimes more advanced technologies are inappropriate in a community forestry project and simpler local practices proven over many decades or centuries may be better suited. Often, however, the local practices need to be further adapted and better related to the present ecological and socioeconomic conditions; this needs to be done with care and respect. To successfully stimulate community forestry, several of the traditional tenets of professional forestry need reconsideration. It requires new approaches of multifunctional forestry that respect the location- and livelihood-specific forms of forest use and that incorporate the positive elements of indigenous practices of forest resource production. Arguably, the key principle is greater self-determination at community level. To accomplish this, three issues need careful consideration: participation, decentralization and the growing importance of markets.

Participation

As illustrated by the term participatory forestry, the notion of participation forms an essential component in many community forestry development programmes. This notion is based on both normative and practical considerations. The basic principle is that all stakeholders share the power and responsibility and actively participate in the planning and implementation of forestry-related activities and share in the rewards. A more pragmatic consideration is that local communities who live in close proximity to the forest and who depend on the forest for part of their livelihood are better positioned to care for the forest. They observe the forest every day. They require a range of products from the forest and it is in their immediate best interests to ensure that these products are sustainably managed. The local community is therefore likely to conserve forests and its biodiversity better than a single-interest industrial forest enterprise with its head office in a distant city. Moreover, if the local community becomes involved in the management of their local forests, this should decrease the cost to the state in conservation and management. Because of their intimate involvement with the forest, it makes good common sense to include locals in its management. If the locals are not involved in management, they are likely to ignore or even frustrate the efforts of central management even when central management believes they are acting in the best interests of the local community.

There are not only different aims for stimulating participation, but participation can also take many forms. Within the context of forestry development programmes, participation involves at least two main groups of stakeholders, i.e. the local community and the external forestry development agents. Often, other stakeholders also are involved such as non-government organizations facilitating the process. The various groups of participants have different roles and responsibilities. In planning participation, the three basic questions are who participates, in what activities and with what intensity (Cohen and Uphoff, 1980). In respect of the question of who are considered relevant stakeholders, different criteria may be used, e.g. direct dependency on forests, existing rights to land and trees, unique knowledge to manage forests, level of investment in management, or historic or cultural relationship with the forests (Borrini-Feyerabend *et al.*, 2004). The different stakeholders may be engaged in the appraisal and planning of management schemes (including decision making on the basic question of what the objectives of a specific community forestry project should be), the implementation of management activities, and/or the monitoring and evaluation of the activities. And the intensity of participation may range from passive, to exchange of information and consultation, to provision and use of material incentives, to interactive decision making. Self-mobilization of community groups for autonomous decision making and action is often considered as the ultimate form of participation. This demonstrates that the notion of participation is often related to the role of local communities, and that the role of external partners is often given less attention. Such an interpretation leaves little scope for acknowledging that the external partners may have their own specific aims in stimulating community forestry. For instance, whereas conservation organizations specifically focus on the role of local community in biodiversity conservation, social movement organizations often focus more strongly on community rights for self-determination. This reflects that the notion of participation always needs to be assessed within the context of whose knowledge and power counts most, and that this question should not only be addressed at the level of local communities, but also of external facilitators of community forestry (Lebel *et al.*, 2004).

Participation in community forestry need not be restricted to interaction between communities and forestry authorities and/or development organizations. In the early 21st century new partnerships between communities, commercial enterprises and civil society organizations have emerged. The respective partners bring in labour, technical knowledge and skills, financial means, economic power or communication skills, and share risks, responsibilities and rewards. Examples of such partnerships include local communities, timber enterprises and timber retailers cooperating in getting community-produced timber certified as sustainably produced and marketing it as a fair trade product; pharmaceutical industries cooperating with local communities in testing the traditional knowledge of medicinal plants for commercial use; or international and national travel organizations cooperating with local communities in developing and advertising community-based ecotourism projects (Ros-Tonen *et al.*, 2008). Such partnerships are often facilitated by civil society organizations that stimulate and facilitate environmentally sound and socially responsible development. Hecht (2012) describes how new ideologies on combining environmental conservation and development, and the advent of new social movements involving partnerships between local communities and civil society organizations, significantly contributed to a decrease in deforestation in the Amazon region (see Box 6.1 , Chapter 6).

Decentralization and devolution

In reaction to the centralized approach of traditional state forestry, community forestry often is characterized as decentralized forest management. But similar to participation, this notion is open to multiple interpretations. For instance, it can take the form of bureaucratic decentralization (or deconcentration). In this approach, administrative authority over forests is transferred from the national level to lower levels of bureaucracy. In several countries such bureaucratic decentralization has resulted in the appointment of district forest organizations that fall under the authority of district governments rather than being responsible to the national forest service. For instance, district forest officers may have the responsibility to oversee the local forest resources; they may co-exist with national foresters holding responsibility over the nationally proclaimed forest reserves. The idea is that such local forest officers will be better able to look after forest resources that are of local interest and can more easily communicate with local forest owners than the foresters of centralized forest bureaucracies. But alternatively, it has been argued that such decentralization of power and responsibility may in fact result in a recentralization, in the sense that the government strengthens its grip on rural areas (Ribot *et al.*, 2006). Much depends on the motivation and skills of the local foresters acting as 'frontline bureaucrats' in dealing with the conflicting pressures of local communities using forest resources in a relatively autonomous manner as an essential livelihood resource and the government regulations on proper use of essential environmental resources in the public interest. This means forest agents require good social and communication skills in addition to their traditional technical skills.

An alternative form of decentralization is democratic decentralization. This approach may take the form of delegation by transferring forest policy or management responsibilities to non-governmental organizations, or of devolution by transferring these responsibilities to local actors. In this last case the decisions, responsibilities and rewards are shifted from the forestry service to the community or subunits in the community. Although devolution is often considered as a key principle in community-based forest management, there are relatively few examples where it has actually been achieved (Edmunds and Wollenberg, 2003; Larson and Soto, 2008). All too often, central authorities will devolve the responsibility but not the power. This demonstrates the difficulty of actually transferring power and decision making from the bureaucratic forestry organizations to local communities. But it also reflects that community forestry not only concerns subsistence use of forests, but also commercial forest production. In the last case, community forestry cannot be considered as an autonomous activity, but it becomes incorporated in external networks. These networks do not only involve economic networks related to forest product marketing, but also policy arrangements for controlling compliance with general standards for commercial timber production. The meaning of devolution of forest management authority should therefore not be interpreted as referring to local autonomy in using forest resources for local use, but rather as referring to local decision making on the objectives for managing local forests and on appropriate forms of benefit-sharing from local forest products, including formation of partnerships with external stakeholders other than the national forest service.

Growing importance of markets

The notions of participation and decentralization are often related to issues of forest access and ownership and of sustainable forest management. But in order to be able to profit optimally from forest resources, local communities should not only have the ability to manage forest resources and use them for their household needs, but also to capitalize these resources through selling the resources (Scherr *et al.*, 2003). At present most community-derived forest products are marketed at informal artisanal markets, where they often fetch a low price. Special measures are required to improve the access of poor rural communities to markets, such as debureaucratizing exploitation and transport regulations, strengthening producers' organizations, stimulating small-scale forest-based enterprises, and forging public–private and company–community partnerships and other alliances that may enhance poor people's access to lucrative (niche) markets for timber, non-timber forest products and environmental services. In addition to external markets, more attention needs to be paid to the role of local markets and the way in which performance on these markets (which absorb the lion's share of the forest-based products sold by poor households) can be improved. The increasing importance of trading traditionally non-marketable forest products and services offers an excellent opportunity to forge new partnerships for forest-based income generation. Care must be taken that the benefits of developing new market opportunities for forest goods and services, such as ecotourism and non-timber forest products, are equally distributed and will not lead to disrupted income distribution within communities, nor to the creation of new elites and the exclusion of, or negative effects on, other groups.

Co-management

During the development of community forestry, it was gradually recognized that it should not just be considered as relating to community autonomy in managing common forest resources, but also as indicating scope for greater community participation in public forest management. Co-management (in some countries also termed joint management) is where local forest-use groups and formal forestry (or conservation) organizations collaborate in joint management and control over formally gazetted forest reserves. The idea is that both need each other to achieve a mutually satisfactory outcome. The central authority working alone often cannot ensure sustainable forest management, and the local community acting alone often cannot fulfil the national or global objectives of forest conservation. A collaborative and decentralized structure for forest management is becoming increasingly favoured in international forest policies as a means of meeting both global and national forest concerns and contributing to rural development and poverty alleviation. In order to promote such collaboration, in several countries socially oriented development organizations have been recruited to facilitate the collaboration. Hence, co-management forms a good example of the emergence of new partnerships in forest management.

A prerequisite of joint forest management is that the local community acts within the policy framework of the region or nation and gets as much help and support from the centre as possible. Ideally the centre should support and encourage rather than subjugate, although the centre will still have to regulate and control to a greater or lesser extent.

In principle, this may include social issues, such as inclusion of poor people in joint management. In the case of community forestry, where local communities have a degree of autonomy, local power relations may prevent poor people from benefitting (e.g. richer farmers with a large number of cattle may profit from communal forest grazing arrangements, but poor people owning only small livestock may not profit). Providing social security was formally a task of governments; a forest service taking this idea seriously can specifically target poor people in joint management schemes. An example of such socially conscious practice is the selection of landless people in programmes for temporary agricultural intercropping in reforestation programmes. This taungya system is elaborated later in this chapter. The foresters may also act as a conciliator in the case of disputes and be an important agent in conflict resolution. He (still only in few cases, she) is also in a good position to coordinate state or even international involvement and the provision of technical expertise.

Notwithstanding the potentially positive features, the implementation of many joint management programmes is still beset by many of the difficulties that are also encountered in community forestry development. For instance, the forestry agencies may adhere too strictly to professional standards (e.g. the requirement for professionally formulated forest management plans that neglect the more informal community arrangements), they make take more than their locally acceptable share of the forest benefits (income) and disperse these elsewhere. Such practices that neglect local values and practices will stop local initiative and involvement. Also restrictions placed on collaborative forestry schemes in order to promote national or even global goals such as conservation of biodiversity, protection of downstream areas from flooding or mitigation of climate change can act as a disincentive (Arnold, 2001). Such national objectives are, of course, essential issues in sustainable forest management, but they need to be incorporated into collaborative forestry programmes in such a way that they do not clash, but rather support or at least complement community concerns. Governments are rightly concerned with rehabilitating degraded lands, but sometimes expect the rural farmer to be the instrument of this even when it is of little economic benefit to the farmer. It is all very well to be concerned with afforestation of upland water catchments, with erosion control and with arresting short-fallow shifting cultivation, but unless the rural farmers can reap tangible benefits from it, they are unlikely to cooperate. This is not to say that rural communities are not concerned with forest degradation and conservation issues. Rural communities are concerned because they see this as contributing to scarcity of forest resources that are important to them. Accordingly, some indigenous forest management systems have been very successful at afforestation and forest conservation. Rural communities should not, however, be expected to subsidize rehabilitation and conservation programmes.

Experiences with Community Forestry and Co-management

Since its initiation in the early 1980s, community forestry has won much acclaim. After the initial discussions at the World Forestry Conference of 1978, the development of community forestry was included in several global forest policies (see Chapter 11) and within the framework of both environmental and development programmes many efforts were directed at stimulating community forestry. The general acceptance of community forestry as a feasible arrangement for forest management is demonstrated by the fact that at the beginning of the 21st century about 20% of the tropical forests were under some form of community management. It was most widespread in Latin America, and in Asia a considerable area of forests was also under community forestry. In contrast, in Africa only a relatively small proportion of the forest lands were under community management (Table 10.2). The status

Table 10.2. Regional status of forest management. (After Sunderlin *et al.*, 2008.)

Management regime	Africa	Asia & Pacific	Latin America
Public administration by government	97.9%	68%	36%
Public administration for use by communities and indigenous people	1.6%	3%	7%
Owned by communities and indigenous people	0.4%	25%	25%
Owned by individuals and firms	0.1%	4%	32%

of community forestry programmes not only varies between continents, but also within continents. Boxes 10.2 and 10.3 give case studies of community forestry programmes in Nepal and joint forest management in India, each written by an expert who has been intimately involved in the programme. These countries were among the first to systematically stimulate community forestry (see also Hobley, 1996; Poffenberger and McGean, 1996). These examples demonstrate the

Box 10.2. Community forestry in Nepal – by Bob Fisher

In the 1970s and 1980s, Nepal was commonly presented as the prototypical example of a case where pressure from a rapidly growing population seeking firewood and timber was leading to a disastrously high rate of deforestation.

It was increasingly recognized in the 1970s that the Forest Department's real capacity to manage state forests was limited (most forests were state forests). At the same time, it was recognized that some local communities had been taking successful action to protect forests and the concept of seeking community participation in forest conservation was born. Initially, the emphasis was placed on seeking local contributions to plantation and protection (with considerable success), but, by the mid-1980s, there was increasing recognition that community forestry was more likely to attract local support if it contributed to the needs of local people for forest products. There was a shift (in rhetoric, if not so much in practice) towards forest management rather than forest conservation. This shift was motivated by the recognition that forests were a legitimate and significant source of products needed for local livelihoods. There was, at the same time, growing awareness that indigenous forest management arrangements were quite common in various parts of the country and were frequently very successful in protecting forests and restoring forest cover. These arrangements existed in parallel with the official system and had no legal status. Research showed that they were typically based on groups of people with mutually recognized (but unofficial) rights to clearly identified areas of forests.

The practice of community forestry evolved to focus on such user groups rather than on official local government boundaries. Legislation was passed in 1993 that formally allowed the Forest Department to hand over rights to use and manage forests to formally established Forest User Groups (FUGs), subject to a management plan approved by the Forest Department. The programme was immensely popular and, by 2003, over 12,000 FUGs had been registered, over 1 million ha of forest land were managed by these groups and more than 1 million households were involved. This growth was demand driven – a good indicator of the programme's popularity. The programme is internationally regarded as a good (and rare) example of a large-scale programme with a sound legal basis. Among the programme strengths are the recognition of local use rights and the focus on groups with shared interests in a forest ('natural users') rather than on formal local government areas.

In terms of biophysical outcomes, the programme is generally recognized as having contributed to improved forest cover in areas under community forests. (Community forestry has been largely implemented in the Middle Hill region.) Although the biodiversity of these forests is less than that in relatively untouched natural forests, it is frequently far better than the degraded areas that often existed previously. It is probably true to say that community forestry has been less successful in providing economic benefits to individual users, although limited funds generated from sale of products have been used for community development purposes such as schools and roads. In many cases forest products, especially firewood, leaf litter (for fodder and animal bedding) and some timber are distributed, but there is a strong perception that management plans in general are much more conservation oriented than they need to be and that more could be provided. The Forest Department seems unwilling to step back from maintaining a greater level of control than is apparently intended in the legislation. A related issue is the emerging recognition that the poor have not benefited particularly and may indeed have less access to forest products than previously. The FUGs seem generally to be dominated by local elites.

The programme emerged through a combination of the initiative and leadership of a number of Nepali foresters and support from the international donor community. The strength of the movement within the Forest Department during the 1980s and 1990s was exemplary. However, some elements of the Forest Department are currently attempting to wind back some of the more progressive elements of the programme. (This is being resisted by civil society, including networks of user groups). Nevertheless, the programme remains one of the few large-scale international examples of community-level forest supported by legislation.

Box 10.3. Joint forest management in Tripura, India – by J.P. Yadav

Tripura is a hilly state, densely populated by Bengalis and tribal people. Sixty per cent of the livestock population of 1.5 million graze in the forest, which occupies 52% of the state and of which 67% is controlled by communities (village councils, district councils and private individuals) rather than government. Joint Forest Management (JFM) was introduced in 1991 to try to reverse deforestation due to development activities, over-exploitation, mismanagement, human-induced disasters, political instability and floods. Forest Protection and Regeneration Committees (FPRCs) are formed at the village regional level and the committees are encouraged to register under the Societies Registration Act, 1860. They work in close coordination with Panchayati Raj Institutions and government departments.

The first attempt, a Forest Department project involving rural families living in four villages surrounding a plot of 100 ha of a proposed forest reserve, was mostly successful. By the end of 1999, 165 FPRCs had been formed, covering 18,566 ha of forest. The main activities of the committees are: encouraging natural regeneration of sal and teak; establishing bamboo plantations; under-planting of canes; establishing and maintaining medicinal plants; and soil and water conservation. The community forests also contribute to livelihood by supplying bamboo, fuelwood, small timber, thatch, sand, tubers, leaves, honey as well as employment. The timber is yet to be harvested. If the plantations and natural forests are protected by the FPRCs, the gain will be substantial.

There are some difficulties. The JFM Committees (JFMCs) are formed by government resolutions and have no legal standing like the Panchayats. This makes them vulnerable at law. The cultivation of some minor forest products (fruits, tubers, palms, fishery, oil yielding and medicinal plants, spices, stones, bajri, fibre) is crucial for motivating people to support JFM, but this is not recognized as an acceptable forest activity by the Forest Conservation Act, 1980. Members of JFMC understandably object if non-member families receive their share of the common benefit, and if these families are denied it, they can gain the benefit illegally. There is no provision to deal with offenders in JFM areas, except the Indian Forest Act. (Smuggling of forest products between India and Bangladesh is a concern in border areas of the state. The problem may be so acute that even small twigs and dry leaves are removed from forest areas and the local people are not in a position to prevent it.) Other reasons for poor response and low participation of local communities in JFM are: paucity and lateness of funding; bureaucratic inflexibility; inappropriate and unmotivated staff; poor monitoring and evaluation; inconsistent regulations; poor marketing of forest products; and better opportunities (and less manual work) offered to villagers by other agencies and departments. Sometimes forest adjacent to a village has traditionally been used by a more-distant community. This and other incompatibilities in territorial boundaries of the Forest Department and the Civil Administration sometimes create confusion. Also, lack of personal security may be a problem for staff.

Experience so far indicates that JFM is not an easy task. Most, but probably not all, of these can be resolved. The concept of JFM is still evolving and most forest personnel are not familiar with it. Planners need to proceed gradually and at first give full attention to a few selected sites. When positive results are available, more areas can be progressively added until all degraded forest areas come under participatory management regimes, which would confirm JFM as a powerful tool for forest improvement and rural development. This requires staff with the right attitude and aptitude.

JFM is an integrated holistic management approach and both peoples' representatives and influential leaders (legislators, Panchayat members, local community leaders and religious heads) should be involved. Continuous flow of information from bottom-to-top and vice versa is essential to achieve joint forest management. This will not only keep all informed, but will be a tool for regular monitoring and evaluation of programmes and a vehicle for promoting JFM globally.

variation in community forestry programmes and the different degrees of success. They also demonstrate how specific models of community forestry have gradually emerged (Molnar *et al.*, 2004). In Latin America and some Asian countries, community forests include large areas of natural forests (often over 1000 ha in size) on lands with formally recognized ancestral tribal rights. These forests are communally managed by indigenous tribes as part of their cultural identity. In other regions it mostly concerns smaller forest plots of some 100 ha located in fragmented forested landscape mosaics, where the forests supplement agricultural cultivation and/or animal husbandry. In these cases the forests have often been adapted to local needs through agroforestry practices (see below).

Critical issues

Community forestry has become an established component in the national forest strategies of many countries. There is increasing evidence that community forestry has in many cases been more successful in forest conservation than conventional state forestry. The success of both community forestry and professional forestry depends on the presence and local acceptance of regulations for controlled use and management. In a meta-study comparing the relation between vegetation density and presence of rules in 76 publicly managed parks areas and 87 community-managed non-parks areas, Hayes (2006) found that in the publicly managed parks 30% had identified rules on all forest products and that 22% had specific user-group defined forest rules. In non-park areas these percentages were higher: 60% and 70% respectively. In 30% of the parks the vegetation density was abundant, in 36% average and in 44% (very) sparse. In the non-park areas, tree cover was abundant in 29% of the cases, average in 43% and (very) sparse in 28%. A similar trend was observed in another meta-study comparing the forest cover change in 40 publicly protected areas and 33 community-managed areas (Porter-Bolland *et al.*, 2011). In the publicly protected areas the mean annual forest cover change was −1.47%, with a maximum rate of recovery of +0.40% and a maximum rate of deforestation of −19.40%. In the community-managed areas the mean range of forest cover change was −0.24%, with a maximum rate of recovery of +0.63% and a maximum rate of deforestation of −1.99%. Although the lack of consistent data means that these findings can only be considered indicative, they do suggest that community forestry is no less and probably more effective in conserving forest resources than public forest management. In both cases the success depends on a proper management organization with sufficient ability to install and control a location-specific system of regulations on the conservation and use of forest resources and on distribution of forest benefits to the various categories of stakeholders.

But other assessments are more critical about the success of community forestry, and the approach is still under heavy debate. The claim of community forestry serving the multiple objectives of ensuring ecological integrity, social justice and material well-being has often proven to be elusive (e.g. Arnold, 2001; Fisher, 2001; Charnley and Poe, 2007; Dressler *et al.*, 2010). Some criticisms of community forestry focus on ecological issues. Some forest conservationists, who emphasize the need to conserve as much as possible undisturbed wilderness forests and threatened species because of their intrinsic value, argue that community forestry has proven not to be able to deal with such conservation issues, and that the forests managed by them are often degraded with a loss of biodiversity. Consequently, the merits of community forest management versus strict forest conservation remain hotly debated (Wilshusen *et al.*, 2002). In these discussions often much attention is focused on animal species rather than on vegetation properties. Whereas community forestry programmes are mostly focused on conserving forest vegetation for local needs, other community-based conservation projects are focused on wildlife conservation or on nature preservation. The balancing of global and local interests in such integrated conservation and development projects has proven to be more elusive than the balancing of global and local interests regarding sustainable forest management in community forestry. For instance, community-based management of mobile animals, especially larger species roaming the territories of several rural communities, is more challenging than community management of immobile resources such as trees.

Community forestry projects have also been criticized for not fulfilling social objectives in respect to empowering local decision making or improving the livelihoods of disadvantaged people. Such criticisms are often based on a specific normative interpretation of the social aims of community forestry. For instance, in several studies it was demonstrated how community forestry development projects resulted in elite capture with village leaders or better educated or more powerful people reaping most of the benefits. If community forestry activities are focused on subsistence use, they may well be based on traditional community arrangements for autonomous decision making on common property forest resources. But if it concerns commercial use, management requires negotiation skills to deal with external actors, including staff of forestry development organizations and traders in forest products, as well as administrative skills in proper bookkeeping of commercial transactions and distribution of costs and benefits for individual households. Such specific skills may bring delegated authority and diversification in community forestry activities. Hence, opinions on whether the social aims of community forestry development are reached may depend on whether community forestry is basically conceived as involving an autonomous activity based on equal participation of all community members, or as involving a process of local delegation of management organization to respected local representatives who are skilled in dealing with actors from external social and economic networks. Other critical assessments reflect differences in opinion of whether community forestry has been able to fulfil the claims of democratic decentralization and devolution in managing forest resources, or whether it has involved a process of embedding communities in external relations. This last process might involve a process of recentralization with national governments extending legal and management control over forests that formerly fell outside the national forest reserve (Ribot *et al.*, 2006).

Community Forestry: Component of a Dual Forest Economy or Embedded in Forestry Sector?

Community forestry and co-management originally evolved in reaction against traditional centralized forestry. The specific merits of this approach are now well recognized in many regions. Originally it was proposed that a dual forestry economy should be developed in which community forestry and conventional state-controlled forestry coexisted. But as demonstrated by co-management, increasingly new approaches towards linking community forestry and forestry are evolving. Whereas community forestry was originally suggested as a means to provide disadvantaged rural communities with locally needed forest products, it is now recognized that it also can involve production of commercial forest products. Consequently, programmes such as forest certification (see Chapters 7 and 11) that were established to encourage sustainable forest management by commercial forestry enterprises are now giving attention to adapting the programmes to the conditions of community forestry. Hence, community forestry is increasingly considered not as one of the components of a dualistic forestry sector, but as a specific management regime within the overall forestry sector. The embedding of community forestry in the overall forestry sector is clearly reflected in the policies on Reduced Emissions from Deforestation and Forest Degradation in Developing Countries (Chapter 8). The explicit attention given in this policy to including community forestry indicates that, 40 years after its initial identification, this approach to sustainable and socially conscious forest management is now well established. This has important repercussions for professional foresters. The professional forester in a community forestry development and collaborative forestry programme may have quite a different perspective from that of the local community on what is important. The forester will have a different background and culture and very different skills, knowledge and institutional allegiances to the locals. A key to success in stimulating the new forestry approaches is the ability of the professional forester to understand and accommodate community perspectives on forest management. Professional foresters have in the past largely been trained to operate in a non-pluralistic framework, one where single and often large institutions can determine policy and practice. This is no longer the case.

Farm Forestry and Agroforestry

Within community forestry, forest use and management is organized as a collective activity. But individual farmers may also use and manage tree resources as part of their multi-enterprise farming activities. Farm forestry can be considered as any activity that incorporates forestry-related activities and the use of trees in and around the farm. This includes planting of woodlots for fuel and wood products, planting trees for windbreaks, planting trees for shelter and shade for livestock, planting trees for beautification and for conservation of biodiversity, planting trees to control soil erosion and to safeguard water quality, planting trees to lower saline water tables, and planting trees to improve soil properties and to conserve soil moisture. In many tropical areas, agroforestry, farm forestry and community forestry coexist; this illustrates the important role forest resources have for the millions of people living live in or near tropical forest areas.

The terms farm forestry and agroforestry are sometimes used interchangeably, but they may better be differentiated as regarding organizational and technical issues of forest management respectively. Farm forestry relates to a specific organizational arrangement for managing woody vegetation, i.e. management by private farmers as part of their farming strategy. Agroforestry relates to specific management techniques in the form of simultaneous management of tree and agricultural resources. Such practices are not only common in farm forestry, but such practices may also be used in community forestry. Both terms reflect that the notion of agricultural cultivation involving the relentless clearing of forests for agricultural crops is not correct. Traditionally many farmers have maintained trees in their rural agricultural landscape, for both livelihood products and environmental protection (FAO, 1985; Leakey, 2012). Farming does not just involve the growing of staple food crops, but also the production of supplementary crops such as fruits providing nutrient requirements, medicinal products for treating health conditions and a variety of wood products for energy (fuelwood) and shelter (construction material). The tree products are not only directly consumed by the farmer and his family, but can also be used as inputs to other farming activities, e.g. as fodder for animals, as shelter or climbing support for agricultural crops or as manure. Hence, trees in farming systems do not only provide timber and other wood products, but also a large variety of non-timber forest products. Some products provide the opportunity to obtain income by selling them, e.g. in dry periods when no agricultural crops can be cultivated or in times of necessity such as illness or marriage. When farmers live near forests, this array of livelihood products may be gathered in the forests. But in the case of valuable tree products, it may be more efficient to incorporate the trees in the farming system because this allows better control over access and production capacity. This is also the case for disappearance of the original forest cover. In rural areas with good marketing conditions, farmers and small investment syndicates are becoming increasingly aware of the potential of tree growing as a means to provide wood and non-wood products to (urban) markets (Arnold and Dewees, 1995). Because of the important role of trees in rural livelihoods, in several parts of the tropics former forest areas have been transformed into forested landscape mosaics in which remnants of natural forests, domesticated forests, agroforestry systems and agricultural fields coexist (see Chapter 6).

Within forestry development programmes, the potential of trees to complement agricultural production as a means to improve livelihood and living standards is now well recognized. As a result, programmes to stimulate small-scale forestry are becoming more significant. These programmes not only stimulate new forestry and tree-growing practices, but also the adaptation of traditional tree-growing strategies to modern conditions (Arnold and Dewees, 1995). As was the case for community forestry, the forestry profession has had to adapt the professional knowledge and management systems to meet the needs of this groundswell movement. It meant a change in attitude and practice, where the forester has had to change from being a silvicultural technician and land regulator to a facilitator. It required more understanding of the role of non-timber forest products in rural households, and a reconsideration of the notion of forestry and agriculture as being at odds. It also required new knowledge on social processes enabling or stimulating farmer tree-growing, notably in respect to the intricacies of land and tree tenure or stimulation of new partnerships such as forest-owner cooperatives.

What is Agroforestry?

Agroforestry, in its strictest sense, can be defined as a land-use practice where woody species are grown intentionally on the same land and in combination with agricultural crops and/or livestock, either simultaneously or in sequence, so that there are both ecological and economical interactions between the different components (Nair, 1993). There are many possible combinations of interacting components: agrisilviculture (crops and trees); silvopastoral (pasture/animals and trees); agrosilvopastoral (crops, pasture/animals and trees) and more, but it is simpler and less confusing to use the generic term agroforestry. The trees may be more or less equally spaced within the other components or planted as strips, or around boundaries of agricultural fields, and/or may overlap or be separate from the other components in time. Most attention has been given to agroforestry in the tropics. However, agroforestry as well as the broader aspects of farm forestry are also important in the temperate developed world. The main agroforestry practices in the tropics are summarized in Table 10.3. There are other equally respectable ways of classifying (and spelling) the various

Table 10.3. The main agroforestry practices in the tropics (w = woody; h = herbaceous; f = fodder for grazing; a = animals). (Adapted from Nair, 1993.)

Agroforestry practice	Arrangement of components	Groups of components
Agrisilvicultural		
Improved fallow	Woody species planted and left to grow during the fallow phase	w: fast, preferably leguminous h: common agricultural crops
Taungya	Combined woody and agricultural during early plantation establishment	w: plantation species h: common agricultural crops
Alley cropping	Agricultural species between woody hedges	w: fast coppicing leguminous h: common agricultural crops
Multilayer tree gardens	Dense multispecies, multilayered with no organized planting arrangement	w: varying in form and growth habits h: usually absent
Multipurpose trees on crop lands	Trees random, or systematic on bunds, terraces or plot/field boundaries	w: multipurpose and fruit trees h: common agricultural crops
Plantation crop combinations	(i) Integrated multistorey (mixed, dense) (ii) Mixtures in regular arrangement (iii) Shade trees for plantation crops (iv) Intercrop with agricultural crops	w: coffee, cacao, coconut, fruit esp. in (i), fuel and fodder esp. in (iii) h: present in (iv), sometimes shade-tolerant species in (i)
Homegardens	Intimate multistorey combination of trees and crops around homestead	w: fruit trees, vines h: shade-tolerant agricultural crops
Trees in soil conservation and reclamation	Trees on bunds, raises, terraces +/– grass strips, and for soil reclamation	w: multipurpose and/or fruit trees h: common agricultural crops
Shelterbelts, windbreaks, live hedges	Trees around farmland/plots	w: variety of tall spreading types h: local agricultural crops
Fuelwood production	Interplanting firewood species on or around agricultural land	w: firewood species h: local agricultural crops
Silvopastoral		
Trees on rangeland or pastures	Trees scattered or systematic	w: multipurpose fodder f: present, a: present
Protein banks	Protein-rich tree fodder for cut and carry fodder production	w: leguminous fodder trees h: present, f: present
Plantation crops with pastures and animals	Example: cattle under coconuts in South-east Asia and the South Pacific	w: plantation crops f: present, a: present
Agrosilvopastoral		
Homegardens involving animals	Intimate multistorey combination of trees, crops and animals around home	w: fruit trees, other woody species a: present
Multipurpose woody hedgerows	Woody hedges for browse, mulch, green manure and soil conservation	w: fast-coppicing fodder trees, shrubs h: common agricultural crops
Apiculture with trees	Trees for honey production	w: honey-producing trees
Aquaforestry	Trees lining fish ponds, leaves as forage for fish	w: trees and shrubs preferred by fish
Multipurpose woodlots	For wood, fodder, soil protection, soil reclamation, etc.	Multipurpose species

agroforestry systems and practices (e.g. Young, 1997; Huxley, 1999). It is counterproductive to try to limit the definition of agroforestry. In this chapter any growing of trees within the context of farming systems, no matter how loosely defined, is eligible for discussion.

What Are the Advantages of Agroforestry?

Plants require light, water and nutrients. If plants are separated in space or time, they can access these resources independently. As they approach each other in space and time, they will compete with each other for these resources. In agricultural and forestry monocultures, the individuals compete with each other for these resources in much the same zones (leaves in the air and roots in the soil) and at the same time. Agroforestry systems introduce the possibility of improving the competitive efficiency of the total system by exploiting the zone and time differences between the competing species in capturing water, nutrients and light. Consequently, it is possible for the total productivity of the trees plus agricultural crops to be greater than any one of them would be alone on the same site. Competition in agroforestry systems is discussed in more detail by Huxley (1999) and Wojtkowski (2002). Plants may also impair the growth of other plants through allelopathic effects. But between different plants not only competition, but also synergy may take place. This is the case if one crop improves the growth of another, e.g. tree legumes may provide nitrogen to crops. Trees may also act as filters or buffers against the loss of nutrients as a result of deep root systems taking up nutrients leached beyond the more superficial root zones of annual crops or by protecting soils against water and wind erosion. This may also prevent degradation of soil hydrological properties. Hence, agroforestry has three potential advantages over agricultural monocropping: it may either increase or diversify productivity and it may enhance resource conservation. There are many examples of agroforestry systems with trees and annual crops together being more productive than annual crops alone (Ong and Huxley, 1996). Annual crops alone do not occupy the site for all of the year, and trees may provide additional production in the agricultural off-season. However, a more diversified (tree plus crop) productivity will not necessarily please the farmer if the yield of the marketable annual crop is lower. If the tree component is for environmental purposes only or for long-term site enhancement, the farmer may not see this as a useful gain. Thus, the potential advantages of agroforestry depend not only on the specific types of agroforestry practices, but also on the nature of the farmer's strategy (Table 10.1).

The combination of competitive and synergetic interactions between components of agroforestry systems are complex and each agroforestry system needs to be evaluated on its merits. Sometimes agroforestry systems may increase the productivity of the system as a whole, but in other systems trees may prevent loss of soil productivity. Many interacting physiological and ecological processes need to be considered. Trees will shade ground crops and this will have the effect of reducing the amount of radiation intercepted by the ground crop. Usually reduced intercepted radiation will reduce canopy photosynthesis and productivity of the ground crop. However, some species are tolerant of shade and some even prefer it. Tree shade may increase the proportion of legumes in pasture and thereby improve pasture quality under the trees (Huxley, 1999). Crops that prefer shade are well suited to agroforestry systems. Trees may increase the humidity under their canopies, causing a decrease in the vapour pressure deficit. Depending on circumstances, trees may increase or decrease the temperature under their canopies, resulting in an increase or decrease in the vapour pressure deficit. Any increase in vapour pressure deficit (a measure of the dryness of the atmosphere) may decrease photosynthesis (and therefore growth) and increase the rate of water use relative to biomass production. Tree shade may reduce soil temperatures, resulting in increased or decreased growth of ground crops, depending on the circumstances. The foliage of trees may intercept a proportion of rainfall and prevent this from reaching the ground. Trees may also preferentially direct rainfall to flow down their stems or drip from their canopies, while tree litter protects the soil from the erosive force of rainstorms. The decomposition of tree litter contributes towards soil organic material; this enhances soil fauna and flora and assists in good soil aeration and water conductivity. These processes decrease erosion hazards and provide good hydrological functioning. Trees may alter (usually reduce) the wind speed over ground crops, which may both increase or decrease their productivity, depending on the circumstances and wind speed. Wind can promote carbon dioxide entry into leaves and thereby increase photosynthesis, but too much wind can unduly increase the rate of transpiration (which can hasten the onset of water stress) at the expense of photosynthesis. Strong winds can cause damage to crops and wind erosion; trees diminish this hazard. Often the main competition in agroforestry systems is below ground. Roots compete for water and nutrients and there can be both spatial and temporal segregation of roots of competing species in agroforestry systems, which may enhance their competitive efficiency. There is a common assumption that the roots of agricultural crop or pasture species do not compete greatly with tree roots for water and nutrients because crops and pasture have their roots near the surface and tree species have their roots at depth. Sometimes this may be the case, for a time at least. However, sometimes competition between tree roots and herbaceous species can be intense, particularly when soils are shallow or when the trees are small and have not established root systems at depth. The deep roots of trees, however, are important to their long-term survival during intermittent periods when the surface soil is dry. Deep rooting is an adaptation required by woody perennials but unnecessary for annual crops and pastures. Tree roots are more opportunistic than the roots of annuals because they are there all the time, and because their fine roots can quickly regenerate from an already established extensive root framework to exploit new soil resources. An annual, on the other hand, has to start from zero. Understanding and managing competition between roots of interacting species in agroforestry systems is complex and a challenge for research (Schroth, 1999).

The final competitive outcome depends on how all of the physiological variables mentioned above interact for a given climate, site, plant and tree species, and their configurations in space and time. Agroforestry systems can sometimes, but not always, optimize competition and increase the productivity of the total system.

An agroforestry system is more complex than an agricultural monoculture and is likely to be more biodiverse. Because of the diversity in species, agroforestry systems can provide a variety of products. This increases the diversity of consumables and market opportunities, and reduces the risk of catastrophic single-crop failure. Agroforestry spreads risk over time and may allow the rural farmer to survive bleak times. The different species may also positively influence production. The tree component of agroforestry systems can provide shade to livestock and protection to livestock and crops from wind. Alternatively, in tree plantations weeds can be serious competitors with tree crops for water, nutrients and light (Chapter 9) and their control can be time consuming and costly. An agroforestry option would be to replace the weeds with crops of commercial value, particularly legumes. Because of their biodiverse nature, agroforestry systems also offer options for biodiversity conservation (Schroth *et al.*, 2004).

Trees in an agricultural setting may, over time, improve the fertility, physical properties and organic matter content of soil under their canopies (Young, 1997). Nitrogen-fixing tree species can improve soil nitrogen status on a continuing basis. This is well demonstrated in alley cropping (see below), where continual pruning of the foliage of the leguminous hedges increases the amount of light received by the crop in the alley while providing a continuous source of green nitrogen-rich manure to the soil. Agroforestry systems have the capacity to better recover, recycle and utilize nutrients than agricultural systems alone. Trees in an agroforestry setting provide more closed (less leaky) nutrient cycling. Trees can capture nutrients leached below the root zone of agricultural annuals and recycle them back into the system rather than having them leached off-site. If, however, a more productive agroforestry system replaces a less productive traditional system, such as long-fallow shifting agriculture on an infertile site, the soil is likely to become less fertile and nutrients may need to be added to the systems to maintain fertility (Szott *et al.*, 1991). Trees may also protect the soils from erosion. Soil erosion depends on the amount of exposed mineral soil and the time it is exposed. Annual agricultural monocultures may expose the soil for a considerable period of time. Agroforestry systems offer the opportunity to keep soil exposure to a minimum and therefore conserve soil and improve water quality. Trees contribute to a more persistent, complete and complex protective litter layer on the surface of the soil. Contour hedgerows of woody species can be particularly effective at arresting soil erosion. Shelterbelts and windbreaks also protect the soil against erosion. Agroforestry systems may have a range of different intermeshing root types, which are more effective at holding soil against wind and water than a monoculture, where all the root systems are alike (Chapter 3).

Agroforestry was scientifically identified as a promising land-use system for tropical countries in the 1970s. Its emergence was based on great concerns on the increasing presence of wasted lands, where the prevailing agricultural practices had resulted in land degradation, as well as the recognition of different types of traditional agroforestry systems that demonstrated options for structurally and functionally combining crop and tree production. Initially, much attention focused on the scope of agroforestry as a low-input practice for improving wasted lands. For instance, one of the claimed benefits of agroforestry is to arrest shifting cultivation. Shifting cultivation can be considered as the first and most tested form of agroforestry and, if fallow periods are long enough, it can be an environmentally acceptable option. But if fallows become too short, soils may become exhausted. Much attention focused on improving shifting cultivation systems by growing crops in alleys between trees or by improving fallows by planting trees to improve soil fertility. But since its early years, the scope of agroforestry has been expanded and it is now understood that agroforestry is pluralistic and integrative, and that the various processes of trees increasing productivity, diversifying productivity or assisting in resource conservation depend on ecological conditions (e.g. wet versus dry environments, fertile versus poor soils), specific agroforestry systems and actual management practices. Originally, there was a tendency to expect agroforestry to deliver more than it is capable of doing (Huxley, 1999), but with the advance of scientific research in agroforestry (Sanchez, 1995; Nair, 2007) it became clear that it may provide an excellent option, but not always. For example, in New Zealand, where there has been extensive research into grazing animals under widely spaced *Pinus radiata*, the consensus is now that it is more sensible for farmers to separate tree growing and animal grazing on their properties and manage them as individual and unconnected activities (Box 10.6).

Examples of Tropical Agroforestry Systems

Agroforestry is a generic term. As shown in Table 10.3, a wide array of possible agroforestry systems exists. Taungya, alley cropping and homegardens will be used as examples to illustrate the multiple manifestations of the nature of agroforestry systems and their development. These three agroforestry systems differ in origin. Taungya cultivation was developed as a specific form for forest rejuvenation within professional forestry. It demonstrates that agroforestry was already applied in professional forestry long before the concept was officially formulated. Alley cropping demonstrates how the emergence of the concept of agroforestry resulted in the identification of new types of integrated tree/crop cultivation and how this new cultivation technique was developed through a process of research and dissemination. In contrast, homegardens form an example of how farmers have traditionally developed their own agroforestry systems, and of how these traditional systems are now recognized as important examples of integrated land-use systems that transcend the forestry–agriculture dichotomy.

Taungya

Generally, the focus in agroforestry is on agricultural crops, the trees having a supporting role for producing food, fuel, fodder and/or providing environmental protection. In taungya, the emphasis is turned the other way around and the primary objective is the establishment of commercial plantations for wood production (see Chapter 9). Taungya is a tree regeneration system that originally was developed in South-east Asia (mainly Myanmar and Thailand). Here the government promoted the establishment of plantation trees (traditionally teak, *Tectona grandis*) by recruiting peasant labour to plant and tend the plantations. In return, the peasants were allowed to grow their crops between the rows of the trees for the first few years of the rotation. Taungya is now a widely practised technique for rejuvenation of timber plantations (e.g. in Thailand, Myanmar, India, China, Philippines, Sierra Leone, Ghana, Nigeria, Sri Lanka, Costa Rica, Trinidad and Tobago) (Jordan *et al.*, 1992). The system has the advantage that it can re-establish plantations at minimal cost and that it can provide rotating agricultural land to the rural peasants, thereby arresting land degradation from shifting agriculture. The plantations are owned by the government or by remote private enterprises. The taungya farmers do not gain permanent land-use rights, but may intercrop young plantations during the first 2–3 years of establishment. In this way taungya has the capacity to provide food and labour to the peasant community.

From a biological perspective, taungya is an efficient agroforestry system. Plantations in the first few years do not completely occupy the site and there is the potential for ground crops to exploit water, nutrients and light that would otherwise not be utilized by the plantation crop. Weeds are a big problem in plantation establishment (which confirms that the site is not fully occupied). If an agricultural crop replaces the weeds, this may be a win–win situation. In dry areas, competition for water between weeds and newly transplanted tree seedlings can be intense. Growing crops at the early stage of plantation establishment may reduce the growth of the trees compared with a weed-free situation, but the benefits of reduced establishment costs may well outweigh this disadvantage.

Traditional taungya is an agroforestry success story from the biological, ecological and environmental perspective. Due to the short cultivation periods and strict contractual obligations, with restricted options of crop cultivation, it was originally not very socially conscious. The peasants do not gain permanent land-use rights and originally did not get any of the financial rewards of the plantation. They only receive an income from the land for just a few years out of a rotation length of several decades. It is a classic example of a top-down collaborative forestry system that effectively exploits rather than empowers the local community. The system evolved in a situation where there was a shortage of agricultural land and where the peasants had little option but to accept an arrangement with the plantation owner. But taungya did not promote responsible stewardship. If peasant farmers did a good job and promoted good growth of the plantation trees, they could be moved off the site earlier, thereby being effectively punished for good practice (Gajaseni, 1992). Farmers are more likely to care for the land if they own it. It is therefore not surprising that taungya cultivators will not always take care of the trees in order to try to prolong the cultivation period, or seek other opportunities as they arise. But gradually several innovations were introduced to increase the benefits for farmers, e.g. by stimulating better crop production through technical extension and financial assistance for using improved crop varieties and fertilizers, by allowing cultivation of perennial crops in addition to the annual crops, and by arrangements in benefit sharing from timber trees (Jordan *et al.*, 1992). These innovations in changing from temporary intercropping to longer-term multicropping aimed at making taungya more socially acceptable and equitable for the rural communities.

Alley cropping

In contrast to taungya, alley cropping is not focused on tree production but on food production. Alley cropping is also called hedgerow intercropping. This name reflects that hedges of woody perennials, usually legumes, are planted in rows, and agricultural crops are planted in the alleys between the rows. If the hedges are planted on the contours in sloping country, then they can act as a barrier to soil erosion. The legumes fix atmospheric nitrogen, which contributes to the nitrogen nutrition of the site. The hedges are regularly pruned, which provides additional radiation to the crop in the alley. The prunings contribute to surface litter, which acts as a mulch to conserve soil water and arrest soil erosion. When it decomposes, it contributes to soil organic matter and the provision of nutrients, particularly nitrogen, to the crops in the alley. The deeper rooting hedges also ensure a more closed nutrient-cycling system. The prunings can also be used for high-protein food and fodder, and as fuel. The hedges can rapidly regrow in the period between the annual crops.

The best tree species for alley cropping are nodulating legumes that grow fast and are amenable to frequent pruning. Historically, *Leucaena leucocephala* has been important, but its potential decreased because of defoliation by the psyllid *Heteropsylla cubana*. Other species of importance are *Calliandra calothyrsus*, *Inga edulis*, *Paraserianthes falcataria*, *Cajanus cajan*, *Flemingia macrophylla*, *Gliricidia sepium*, *Sesbania sesban*, *Sesbania rostrata* and *Sesbania grandiflora* (Bryan, 1999).

Alley cropping was considered to be a very promising technique for better utilization of poor and impoverished tropical soils. It was heavily promoted in the late 20th century as an innovative agroforestry technology (Kang, 1997), but it has seen mixed success. Its net value to the farmer depends on the balance between the negative effects of the hedges being a competitor with the crop for water, nutrients and light and the positive benefits associated with nitrogen fixation providing nitrogen to the crop and the additional food, fodder and fuel benefits of the trees. Alley cropping has been promoted as a means of increasing crop productivity and on this basis alone it often does not succeed and farmers have been reluctant to embrace it with enthusiasm. In some situations trees contributed to enhancing soil fertility, e.g. through nitrogen fixation, and improved crop yields, but in other situations (e.g. on shallow soils leading to heavy root competition) crop yields decreased. And removal of tree products for fodder, food and fuel means that these are no longer available as a green mulch to improve the crop. Alley cropping is of dubious merit for areas of low rainfall, highly acidic soils and high soil fertility, as well as with poorly adapted legumes and inadequate pruning (Bryan, 1999). It is promising, however, on steep slopes where soil erosion is a problem, but this process stabilizes rather than increases crop yields. Another farmer constraint to alley cropping is its increased labour requirements. For example, Swinkels *et al.* (2002) found, in western Kenya, that pruning hedgerows of *Leucaena leucocephala* and *Calliandra calothyrsus* considerably increased labour at the busiest time of the year and that the hedgerows had no effect on maize yield while decreasing soil erosion. They concluded that hedgerow intercropping was more likely to be useful in providing feed for an intensive dairy operation or in controlling soil erosion than in increasing the yield of the alley crop. Such experiences increased understanding how stimulation of new agroforestry practices does not only require proper understanding of their functioning and impacts on productivity, but also on their adoption processes (Mercer, 2004).

Homegardens

Homegardens are a traditional form of multistoreyed cropping systems that is widespread throughout the tropical world (Kumar and Nair, 2006). As indicated by its name, this agroforestry system is characterized by its location in an area around homes. This area is planted with a variety of trees, shrubs and vines of different sizes and configuration to provide a range of household products. Trees can provide shade, fodder, fuel, fruit, spices, vegetables, edible seeds, flowers, honey, medicines, timber for construction and materials for craft. They can protect the soil from erosion, maintain high soil fertility and soil organic matter, and improve the microclimate for the householders and grazing animals. They can provide a variety of food that is available at different times of the year. In near to closed canopy homegardens, few annual crops are present unless they are shade tolerant. In more open canopy homegardens there can be vegetable and other crops. Homegardens might also contain animals (pigs, goats) and fishponds.

The trees occupy different zones in space and time, which accords with the complementarity and diversity ideals of agroforestry systems. There are between two and four canopy layers, and these are patchy rather than even and organized. There is a range of tree sizes, meaning that regeneration of the different tree species is more or less even and continuous. In this respect the idealized homegarden resembles a multispecies uneven-aged forest managed under the single tree selection system (Kelty, 1999). However, in practice and as for single tree selection forestry, actual homegardens are not so exact. Homegardens have gaps and edges caused by the homestead and bordering roads; they often also include open areas used for family gatherings and household chores. These gaps and edges can enhance diversity and provide additional temporal and spatial growing zones compared with a continuous canopy. Homegardens are sustainable to the extent that they can conserve soil and hold their nutrients within a closed cycle. If the nutrients removed from the site by harvest and/or leaching are substantial, nutrients may need to be imported from off-site in the form of organic or inorganic fertilizers. Household waste can be an important contribution to the nutrient budget of homegardens. If possible, organic residues should not be removed from the site and burning should be avoided.

In several countries, such as Indonesia and Malaysia, the role of homegardens in rural livelihoods was already recognized in colonial times (Terra, 1958; Brownrigg, 1985). Originally, research and development programmes focused mostly on the role of homegardens in providing nutrient-rich food products supplementing the high-calorie staple food products, thus contributing to human nutrition and health. After the identification of the concept of agroforestry, homegardens became known an ideal-typical example of an indigenous agroforestry system that mimics nature by being rich in species and having a multi-storeyed structure. This ‘nature analogue’ system was also considered as demonstrating the indigenous knowledge and skills of rural communities to develop and maintain sustainable multi-storeyed cropping systems with high potentials to conserve biodiversity (Nair, 2006). Such systems were found to be present not only on homesteads, but also in forest areas. These forest gardens often involve commercial crops amendable to growing under tree canopies such as coffee or cocoa (Wiersum, 2004). Notwithstanding the increased reputation of homegardens, they still remain an enigma that eludes idealistic expectations of its nature (Nair, 2006). Recent research indicates that, rather than considering homegardens as a generic type of agroforestry, it is more appropriate to recognize a range from traditional to more modernized. The last are often less diverse in species and include increased rates of either commercial or ornamental plants. Some researchers lament the dynamics in homegarden structure and composition under the influence of rural transformations and propose measures to conserve and revitalize such traditional tree gardening systems. But others interpret it as indicating that farmer interests in forest resources are not static but dynamic, and that it reflects the dynamic nature of people–tree interactions, and that notwithstanding their dynamics homegardens still form a major asset in the livelihoods of rural people (Wiersum, 2006). Within such a dynamic scope, several options for further homegarden development have been identified, notably in the form of further inclusion and domestication of underexploited fruit and medicinal trees (Akinnifesi *et al.*, 2008).

Temperate Agroforestry Systems

Agroforestry has received most attention in the developing tropics in the context of poverty, underdeveloped or unsustainable agriculture, land degradation and deforestation. Agroforestry, however, is also practised in temperate regions and for much the same reasons as in the tropics. Farmers consider agroforestry options if they can increase and/or diversify their incomes and improve resource conservation. Some (a minority) of farmers are prepared to accept a direct or opportunity cost to establish trees on their farms for environmental conservation, but the majority are only likely to do so if there is some form of incentive to plant or disincentive to not plant. Government policy may be required to achieve this. Also resident full-time farmers are not the sole occupiers of the rural landscape and their numbers are falling in many temperate areas. Non-resident owners and part-time 'hobby' farmers are significant. Hobby farmers can be good custodians of the land. The profit component is not so essential to hobby farmers and they may embrace conservation measures due a desire to maintain the landscape legacy or to improve the land. Incorporating trees in the rural landscape ideally should be coordinated at the landscape level, rather than at the individual farm level because of off-site effects. For example, in southern Australia, tree removal over the last century has resulted in saline water tables rising and breaching the soil surface at lower parts of the catchment. This has taken large areas of agricultural land out of productivity. Replanting with trees is seen as one way (among others) of lowering water tables and rehabilitating the land, and planting trees on farms on middle slopes of catchments will benefit farmers on lower slopes. Farm forestry groups supported by government policy can assist in achieving broader landscape-level planning.

Historically, rural development was considered to rest on agricultural development, with forests being cleared for more productive crop lands. But availability of agricultural land is no longer an issue in much of the temperate world and farmers and rural planning authorities are increasingly seeing the benefits of incorporating forests and trees in the rural landscape. Trees can be part of the temperate rural landscape for a variety of reasons: provision of wood and non-wood products, providing shelterbelts and windbreaks to protect livestock and crops; establishing or repairing riparian strips to safeguard water quality; controlling soil erosion on slopes; ameliorating saline sites; enhancing biodiversity; providing hunting opportunities; rehabilitating degraded land; disposing of nutrient-rich sewage effluent and animal wastes; reducing the use of agrochemicals; retiring marginal land no longer required for crop production; and for beauty and recreation. Trees can increase rural property values considerably, but this represents a capital gain rather than a profit. Agroforestry can improve animal welfare, increase carbon sequestration and reduce fire risk. It may also be favoured for scenic purposes, as some people find agroforestry landscapes to be more attractive than either forest or open land because the scattered trees provide a shady and park-like landscape.

Examples of temperate agroforestry practices

Examples of agroforestry systems and practices exist in many parts of Europe and North America, and temperate parts of Australia, China and Latin America (Gordon and Newman, 1997; Hislop and Claridge, 2000). They include trees widely spaced over pasture or crops, as rows in alley cropping, in woodlots, in windbreaks, along property boundaries and road edges, in riparian strips, on contours, and scattered singly or in groups. For instance, in the USA five basic types are commonly recognized: alley cropping, windbreaks, riparian buffer strips, silvopastoral and forest farming. Some of these temperate agroforestry practices have a long tradition and were already common long before the term agroforestry came into use, and many show promise for further use. Etienne Saur discusses traditional agroforestry systems in Europe in Box 10.4

Box 10.4. Traditional agroforestry in Europe – by Etienne Saur

Europe has a large diversity of climates (from Boreal to Mediterranean), cultures and land-use practices. Traditional agroforestry systems are numerous and have evolved since the very early age of agriculture in response to environmental, technical and social constraints. The first agroforests were farming activities introduced into native forest after controlled thinning. One example is sylvopastoralism, which once was common where grazing capability was limited by poor soils or populated areas. Forest grazing is an ancient practice still used in many parts of Europe, especially in Mediterranean and mountain forests. Edible species like *Castanea sativa* and *Quercus* spp. were favoured when part of the local vegetation. The most successful and extended farming in native forests in Europe is an agrosylvopastoral system called 'Dehesa' in Western Spain and 'Montado' in Portugal. This covers an area of 4–5 million ha and was developed in a semi-arid climate under randomly scattered oaks (*Quercus ilex*, *Q. suber*, *Q. faginea*) with a typical density of 30–80 trees/ha. The undercrop is generally a cereal followed by 5–10 years of pasture management. Pigs, sheep and cattle benefit from the grass production, sweet acorns and microclimatic improvement. The whole system is considerably more productive than the separate cultures alone and in addition supports wood, cork and fruit production as well as hunting, but at the cost of intense manual labour and difficulty in using large machinery.

Later, farmers started breeding fruit trees and developed intercropped orchards to optimize available water and light. Many systems were developed before the Roman Empire and the Mediterranean climate favoured multi-strata associations like (a) cereal cultivation between olive trees (650,000 ha in Greece, 79,000 ha in Sicily and 3000 ha in France remaining today), (b) tree–grapevine–crop associations such as 'hautain' (where the tree acts as a stake for the grapevine – 2 million ha in Italy before 1950), 'joualle' (a mixed plantation of fruit trees and grapevines), (c) complex systems comparable to tropical home gardens (Coltura promiscua, grapevine–wheat–tomato–peas on terraces in Tuscany) and (d) '*Huerta*' (irrigated market-garden under peach, apricot, orange and cherry, e.g. in Valencia in Spain and Roussillon in France). Intercropped walnut orchards were very popular until the 19th century in the southern part of France (e.g. 'noyeraie du Dauphiné et de Dordogne') mostly based on rotational agroforestry practices. Grass orchards became very common in colder, more humid oceanic areas (Herefordshire in England, Normandy in France), and in mountain landscapes (France, Switzerland, Germany, Austria). Grass orchards cover 3 million ha of Europe, mainly with apple, pear, plum and cherry trees planted at 40–80 stems/ha. The income from the fruit, particularly when processed on the farm (juice, cider, alcohol), could be 3–4 times that of dairy. Grass orchards also conserve insects, bats and birds.

Forest trees on farmland developed later, after the Middle Ages, for fuelwood and to support agriculture under marginal conditions like steep slopes and excess rain or wind. During the 17th century agronomists developed 'bocage' from selected forest species planted in hedgerows around the fields. There were 4–5 million km of hedgerows in Europe at the beginning of the 19th century (United Kingdom, France, South Scandinavia, Switzerland, Austria, Slovenia, Romania). Modern hedgerows were developed during the 19th century as windbreaks (Southern France, Austria, Poland).

Traditional European agroforests confirmed the superiority of tree associations with farm production in most European conditions due to soil erosion control, improved soil fertility, microclimatic changes and biodiversity enhancement. The exception was fertile soils free of floods, high winds and drought, where open-field cultivation was more successful (eastern England, Central France, North Germany, Czech Republic, Hungary, Slovakia, Poland). The green revolution (since 1950) led to most trees on farms being cleared and replaced by monocultures with high inputs of fertilizer and chemicals. Most agroforestry systems have disappeared and the larger ones like Dehesa, bocage and grass orchards are fragile and endangered ecosystems. The green revolution increased food production, but Europe now faces challenges like flood risk, mineral pollution, droughts, biodiversity loss, increased pest risk and, ironically, over-production associated with decreased quality of food.

and the future of agroforestry in Europe in Box 10.5. Nick Ledgard discusses the development of agroforestry in New Zealand in Box 10.6 with specific attention to the development of novel systems for integration of commercial pine growing and animal grazing. These examples demonstrate the variety of agroforestry practices in temperate zones. There are two main motivations for stimulating agroforestry in temperate zones, i.e. economic motives and ecological concerns. As demonstrated by Rowan Reid (Box 10.7) in Australia, both motives are often equally important.

Box 10.5. The future of agroforestry in Europe – by Etienne Saur

Traditional agroforests have no chance of survival in Europe today because of the cost of labour, unless publicly subsidized and/or associated with high-value products. As an example, the future of the remaining Normandy grass orchards is to sell the image of cattle grazing under flowering apple trees as an extra-cost on the best quality cider or Camembert cheese in conjunction with agro-tourism development. In the same way, the pig industry in the Dehesa is healthy thanks to a very high-quality ham sold on the international market as the luxury product 'pata negra', with a gastronomic status close to caviar or foie gras. In this case, the appellation 'Real Ibérico de bellota' certifies the breed of pig and the feeding regime from acorns in the 'wild' environment of the Dehesa agroforest. South European countries give high priority to policies promoting quality food production, much of which goes to the agro-food industry. Specifically, France has long been characterized by the diversity of its local quality agricultural production, from Appellation d'Origine Contrôlée wines and cheeses to local meat, vegetable and fruit 'produits de terroir' that form a critical part of both the image and the economic strength of French farming. A raft of policy support mechanisms exists to develop and reinforce high added-value products that are often rooted in individual localities and local savoir-faire, dependent on relatively small and concentrated production chains, often accompanied by some form of specific labelling and usually including some on-farm product transformation.

Apart from these niche products rooted in history, the future of agroforestry is to invent new systems based on agronomical knowledge from the past and from ongoing scientific research but fully compatible with mechanized agriculture and most of all, with European economy and policy. Research, mainly from the SAFE UE programme (Silvoarable Agroforestry for Europe) indicates that modern agroforestry production systems can be efficient, innovative, environmentally friendly and profitable. The two main systems retained for European situations are high-quality timber trees in crop and pasture. Fodder trees have been widely explored but are not suited to the current market.

Tree configurations are determined by cultivation equipment with 10–14 metres between rows of trees (50–80 stems/hectare) and enlarged parcels. Wide spacing and lack of thinning necessitates the use of genetically improved trees with individual tree shelters and appropriate pruning in order to provide high-value timber. European broadleaved species are chosen for the demanding cabinetwork and marquetry wood chain (wild cherry – *Prunus avium*, service tree – *Sorbus domestica*, red oak – *Quercus rubra*, walnut – *Juglans* spp., sycamore – *Acer pseudoplatanus*, ash – *Fraxinus excelsior*). Generally, agroforestry is not eligible for either agricultural or forestry subsidies because it is not considered to be either, and this is an enormous competitive handicap. However, since very recently, French farmers and landowners can be subsidized for agroforestry: crops planted between the trees are eligible for Common Agricultural Policy (CAP) payments and tree rows are eligible for an annual payment to compensate for the loss of income due to afforestation of agricultural land. In some cases the agroforestry system is eligible for specific agri-environmental aid. At the European level, current regulations do not recognize agroforestry but the working group of the SAFE consortium is supporting new propositions to be added to the Common Agricultural Policy to be enforced in 2005 in the European Union.

In conclusion, growing high-quality trees in association with arable crops/pasture in European fields may improve the sustainability of farming systems (compulsory fallow use, better quality of the agricultural products), provide new temperate wood products competitive with tropical wood imports, create novel landscapes of high value, help to control fire, diversify farmers' incomes, sustain country employment, increase carbon sequestration and 're-educate' the farmer on tree management and environmental consciousness. New agroforestry systems are still embryonic in Europe, but are well positioned for a very quick start in the new CAP heading to innovative production methods that support environmentally friendly quality products that the public wants.

But in other cases economic motives play a major role. Notably, the intercropping in tree plantations may significantly increase early financial returns from otherwise long-duration investments in tree crops. Examples of such intercropping are diverse and range from intercropping of farmer plantations of *Paulownia elongata* timber trees in China to alley cropping with Black Walnut in North America. Agroforestry in temperate climates is very suitable for growing high-value tree crops such as walnut in North America and *Sorbus domestica* in Europe. Alley cropping in the temperate world is

Box 10.6. Farm forestry/agroforestry in New Zealand – by Nick Ledgard

Around half of New Zealand is farm land. The majority was converted from forest/shrubland to pasture during the last 150 years. Over that time the interest in planting more trees on farms has generally been low, despite there being excellent growing sites, and good commercial reasons for doing so.

In New Zealand the term 'agroforestry' used to create mental images of wide-spaced (80–100 stems/ha), pruned (to 6 m) radiata pine, underneath which contented sheep and cows are grazing. Such a two-tier 'silvopastoral' farming system was widely promoted. Today, good examples can only be found on a few farms. Why is this? As one keen farm forester stated, 'Trying to teach farmers to grow trees and graze animals on the same patch of ground is like trying to teach a child to ride a bicycle and juggle at the same time – only the most gifted will succeed.' Forestry problems quickly arise as wide-spaced pines on fertile land grow too fast, become unstable and sinuous, while growing large branches, which make pruning for a small diameter knotty core very difficult. In addition, a close watch has to be kept for browse damage to trees, and as they mature, animal problems manifest themselves in the form of poorer performance (declining pasture quality and quantity) and the likes of increasing tree debris in sheep wool. Forestry advisors quickly realized that if they wanted more trees on farms, they were much more likely to succeed if they recommended growing 300 trees on one fenced-off hectare, with animals grazing alone on another two, rather than to recommend 300 trees widely spaced over 3 hectares.

These days it is well recognized that farm forestry is much more than just woodlots and plantations on farm land. Trees have their traditional roles to play in providing shelter and shade, protecting soils from erosion, and making landscapes more attractive. Recently, new roles have arisen in the form of forage feed banks and treatment areas for the disposal of dairy-farm effluent. In addition, the consumers of New Zealand's high-value farm products are demanding that the goods they purchase come from sustainably managed and animal-friendly farm environments. Trees are an integral part of such production systems, and it is not surprising that virtually all the major winners of present-day sustainable farming awards feature trees in their farm management systems.

Ironically, despite the above benefits, and New Zealand having an active Farm Forestry Association with 3000 members in over 30 branches nationwide, widespread farmer indifference towards trees and forestry continues to persist. The reasons are various. The history of woody vegetation clearance continues to create suspicions about forestry. Long-term investments in timber growing are not encouraged by the facts that average farm tenure is only 11 years, and that there are no financial incentives (subsidies) to bridge the considerable gap between investment and return. Many farmers have had bad experiences with trees – falling on fences, providing good habitat for pests such as rabbits and possums, and creating localized shade that encourages concentration of grazing animals. Others complain about low commercial returns, although this is often due to poor siting and silviculture and/or weak marketing.

Such experiences are frequently the consequence of the major reason for low farmer appreciation of trees and forestry – a lack of basic silvicultural knowledge, due to few forestry learning opportunities in secondary and tertiary education and training institutes. For example, despite the country having world-leading agricultural centres at Lincoln and Massey universities, forestry courses are only recent introductions and are not widely promoted as an integral part of efficient land use. This reflects not only in most farmers being ill-informed about trees and forestry, but also in the fact that the majority of those employed in land-use policy making, advice and administration at local government and national level are equally naïve on the topic.

It is for these reasons that trees and forestry struggle for acceptance on most New Zealand farms, despite their having excellent environments for tree growth, and there being good commercial and environmental reasons supporting their increased use.

therefore more likely to be crops grown in the alley between rows of horticultural trees rather than leguminous hedges.

Urban Forestry

Towns and cities may have many trees. Indeed, many cities contain more trees than the surrounding rural landscape. The trees are found in the streets, municipal parks, gardens and reserves, golf courses, cemeteries, around streams, on private property, on catchments, in greenbelts, and indeed most everywhere. Together this forms the urban forest. There are several definitions of urban forestry, all similar in most respects to that of Nilsson *et al.* (2001a), who define urban forestry as 'the establishment,

Box 10.7. Australian agroforestry is about farmers growing trees for conservation and profit – by Rowan Reid

In Australia, rather than agroforestry, the term farm forestry is more widely used. The term emphasizes the role of the trees for farmers. Because most proponents are foresters, farm forestry has come to mean commercial timber production on farmland occupying part of a continuum between small-scale plantings on farms and large industrial plantations.

Adopting and promoting definitions based on predefined land-use practices or distinguishing systems on the basis of scale or intention is problematic. If someone rejects the model, such as pines on pasture, they also tend to reject the approach. This is critical in a field where locally appropriate practices are yet to be fully developed for most areas, let alone for individual farmers.

Growing trees on Australian farms is seen as a means of tackling land degradation, improving water quality, enhancing biodiversity and lifting rural incomes. The fact is that the vast majority of the land targeted for revegetation is controlled by farmers. So, it is the farmers who will decide if trees are planted and for what purpose. For this reason I argue that farm forestry and agroforestry definitions should relate to the process by which these forests are established and managed. My definition is simple: 'Agroforestry is the commitment of resources by farmers, alone or in partnerships, towards the establishment or management of forests on their land.'

If a farmer plants a forest, whatever the purpose or configuration, it is agroforestry. Having accepted this, the argument shifts from what the practice looks like to what the farmer wants and what type of tree growing might suit their situation. It also changes our focus from the paddock level to the farm level. It is at the farm level that decisions about land use are made and opportunity for forestry to contribute to the economic, social and environmental wellbeing of rural communities is best realized.

When looking at the whole farm enterprise, the problems of competition for land that plague conventional agroforestry options are often irrelevant. Trees can be grown on land unsuitable for agriculture, such as along water courses, or in arrangements that enhance agricultural production. Research shows that many Australian farmers do want to grow trees. Their primary interest is shelter (75%) and land protection (50%). Interestingly, around 30% of those who plant trees consider nature conservation and wildlife benefits to be an important driver and 10% even mention improved aesthetics. However, few farmers (about 1%) see commercial timber production as a primary purpose for growing trees.

Rather than trying to convince farmers to dedicate more of their productive land to elaborate timber-production options, the key is to link timber production to their other interests. Generating income from trees grown initially for conservation is seen as a bonus or 'icing on the cake'. This multipurpose approach is very different to conventional plantation forestry because it requires that each planting is carefully designed to suit the particular situation.

But how can this be a viable way to grow commercial tree products like timber? In fact, farmers may actually have a comparative advantage over industrial forest growers because of the multiple benefits. We're finding that farmers actually prefer to grow specialty timber species and are comfortable with long rotations because they receive real rewards while the trees are growing. This goes contrary to conventional economic wisdom that argues for uniform, large-scale, short-rotation, monocultural plantations.

The economics of multipurpose agroforestry is different. The need for trees justifies the cost of establishment. The environmental and agricultural services trees provide justify their presence on the farm. The only question is whether or not the timber is viable to harvest considering the going market price, harvesting costs and the possible loss of valued services. To keep this option alive, the farmers need to manage their trees with a focus on high log quality and reduced harvesting cost.

Research into agroforestry and farm forestry represents a different type for forestry because it involves farmers. It is critical that we acknowledge the varied interests and opportunities facing the millions of farmers who make the decisions that ultimately affect the way much of the world's land is managed. Agroforestry research in Australia is rightly focused on multipurpose design principles, silvicultural management, harvesting technology and processing. Extension initiatives, like our own Australian Master TreeGrower Program, help farmers and their supporters devise unique and elegant forestry options that they are proud of.

Australian agroforestry has moved on from the early days of wide-spaced pines on pasture. Fortunately, well-managed forests on farms, whatever the species or arrangement, generally also provide real environmental and social benefits to the wider community. That's why most of us are so passionate about trees, isn't it?

management, planning and design of trees and forest stands with amenity values, situated in or near urban areas'. The concept of urban forestry commenced at the University of Toronto in 1965 (Koch, 2000) and is probably most advanced in the USA and Europe (Kuser, 2000; Konijnendijk *et al.*, 2006). However, urban forestry is now a worldwide phenomenon. It can be considered an example of community forestry, in the sense that it is focused on forest benefits for local urban communities and that various sections of the community may be keen to be involved in the management of public forested land in the city.

Urban forestry is as much about trees as about forests. The urban forest is usually interpreted as including not only remnant forest patches and wooded areas, but also tree-dominated parks and trees planted along roads and in gardens. This urban forest resource is very large. The United States Department of Agriculture calculated that one third of all area in the USA under broad metropolitan control was covered in trees and that this equated to 8% of the entire country and one quarter of all US trees (Konijnendijk, 2004). Also the variety of trees and other plant species in the urban forest can be very large; they range from timber trees to ornamental trees, and from indigenous trees to domesticated and exotic trees. These urban trees have an important role for beautification, conservation of biodiversity, shade, recreation and amenity. Trees can trap air pollutants, conserve energy by reducing temperatures in and around buildings, screen unsightly structures and reduce noise. Trees in the urban environment can reduce storm runoff and improve water quality. Green areas in and around cities are known to contribute to the good health and general well-being of their citizens. Trees can also be an important source of wood energy and non-wood forest products that can be collected as a leisure activity (Konijnendijk, 2004). There is ample evidence to show that suburbs or streets with abundant trees have higher property values than suburbs and streets with sparse trees. The same follows for suburbs and streets that are close to parks and other wooded areas. The most elite suburbs are often those that have many large trees. But trees can also be a nuisance in the urban environment. They can blow down in the wind, causing damage to both person and property. They can interfere with power transmission lines. Leaf fall, particularly of deciduous species, can block drains, cripple rail networks and be a general nuisance. Tree roots can invade water pipes and disturb and break building foundations. Falling limbs can be a hazard. As a result of such nuisances, as well as undesirable shading effects, trees may be a cause of arguments between neighbours. Old, large and over-mature trees are one of the biggest problems. They are highly valued, but also the biggest nuisance and the most dangerous of the trees in the city. The cost of removing large trees in an urban environment can be substantial.

Urban forests need careful maintenance because urban environments can be very hostile to trees, particularly in some of the city canyons created by high buildings. Temperatures can be extreme, heavy traffic can cause considerable air pollution, trees may be shaded for most or all of the day, root space may be restricted by buildings and pavements, soils may be compacted, de-icing salts may be used in cold environments, trees may be damaged (accidentally and intentionally), city lighting may be continuous throughout the night and dogs can modify the nutrient balance. There are many hazards and the failure rate of new plantings in streets can be very high. Not all tree species are suited to streetscapes and parks. Successful species have not only to withstand the hazards of the urban environment, but they need (among other things) to be easy to raise and grow, require little maintenance, not cause damage to building foundations, not have roots that invade sewers and drains, not have suckers that break through pavements or invade private gardens, not have a propensity to weediness, and be attractive and of size and growth rate appropriate for the purpose. Practical considerations about establishing trees in the urban environment are given by Nilsson *et al.* (2001b). For this reason exotic species are sometimes preferred, although exotics also have often been preferred by colonizing immigrants to remind them of their homeland. Arguments about the appropriateness or otherwise of exotics in metropolitan streets and parks can be intense.

Many people visit metropolitan parks and gardens for recreation and for many this is their main experience of 'nature'. Most people choose to recreate close to their homes and consequently many more people visit urban forests than forests in the countryside. Most urbanites learn about 'nature' from green areas in the city rather than in the countryside. People often feel very attached to their green urban living environment and value urban forests as representations of the local identity of urban landscapes. The urban forests form the scene for a variety of leisure activities, ranging from sunbathing and barbecuing to hiking, cycling or horseback riding. Different people may prefer different activities, and consequently there are many stakeholders in urban forestry, not necessarily with compatible interests. The management of these green spaces should recognize the local importance of the forests and take the different forms of experiencing and using them seriously. To this extent urban forestry can be considered as a form of community forestry in the urban environment. It requires much attention to communication and extension, including participatory techniques for deciding on management practices such as tree cutting. Similar to collaborative forest management, the challenge is to mobilize and focus community participation and where appropriate to devolve management and power to community groups.

The management of urban forests is usually carried out by a range of different authorities, community organizations and private landowners. Urban forestry involves coordinated management across the city estate with sustainable objectives well into the future. Clearly this is more difficult to achieve than managing a forest in the countryside with a single owner. For instance, management of trees in the city is subject to many more rules and regulations than forestry practised in the rural environment. Managers of the urban forests need to be aware of interactions with buildings, utilities, pavements, drainage and sewers and of tree hazards to person and property. The great variety of trees and plants in the urban forests bring a different and more complex perspective to integrated pest management. The use of agrichemicals in the urban environment may be more restrictive than in the rural environment. Having said this, however, the most wasteful and irresponsible user of agrichemicals is probably the urban home gardener.

Urban forestry may be represented within municipal government by a city forestry department that works within an overall planning authority. Alternatively, there may be one city forester working alongside others in a parks and gardens group. There are many possible administrative structures. Most likely, urban foresters will be part of a municipal team where they need to sell the ideals of sustainable ecosystem management to a broader group who may well see trees in the city from a different perspective.

Regarding its management, several professional cultures meet in maintaining trees in the urban landscape. First there are arboriculturists who often have a horticultural background and are employed by municipal authorities to look after the tree components of parks and gardens. They also consult with and provide a service to private property holders about the care and maintenance of their trees. Next there are the landscape architects and designers who see trees and other plants as an integral part of the overall urban landscape. They are motivated by landscape planning and design. Finally, there are the foresters who see trees and other plants as part of a complex and interacting community, like a forest. Foresters bring an ecological and a sustainable management background. They see the potential of urban forests to provide sustained production of environmental, social and economic benefits. Urban foresters also have a culture of recycling, arising from their ecosystem management background, which can contribute to waste management in urban environments. They are skilled at managing trees as a community (a forest) for a range of uses for a range of stakeholders. On the other hand, arboriculturists are very skilled at the care and maintenance of trees, but see them as individuals rather than part of a community. The standard of tree care and maintenance in cities is very variable. Sometimes it is very obvious that street trees have been pruned under the guidance of city engineers who are more interested in the protection of structures and have no understanding of the growth habits of the trees. There is a pressing need for well-trained professional tree managers in the city environment that combine both cultures. Such urban foresters should manage the trees in a city as a renewable resource that can produce a range of benefits, which may include timber production. Clearly, timber production is not an overriding concern of the urban forester. Management for amenity is the major objective. Perhaps the greatest contribution that urban foresters can bring to a city is their skills in planning and in ecosystem management. The multiple-use sustained management of urban forests requires that urban forests are conceived as an socio-ecological system containing all of the trees, plants and associated animals in the urban environment, both in and around the city, as well as multiple users. The management of the urban forest requires attention to a complex of biological, social, political and environmental factors, and urban forestry thus requires a strongly multidisciplinary approach.

Conclusion

This chapter, and indeed the whole book, has highlighted the human dimensions of forest use and management. Much has happened in the last few decades. There has been a trend from institutionalized authoritarian forestry to collaborative community-based forestry. It is generally acknowledged that, in developing countries, sustainable forest management should go hand in hand with sustainable development and poverty alleviation. This requires new forms of multifunctional forestry adjusted to location-specific forest–people relations and rural dynamics. Instead of considering forestry and agriculture as competitors, the new approaches focus on the integration of forestry in rural landscapes and farming systems, and emphasizes synergetic relations between forests and trees and other rural activities. Also in the 'western' countries social issues require increased attention in forest management, and new forms of participation of urban-based people in managing forests for their amenity values have emerged. Because of the multifunctional nature of forests, forest management is often a controversial issue capable of arousing great passion and considerable conflict. The role of the modern forester has become that of a facilitator and a conflict manager. The forester should not only base her or his advice on the best evidence-based research and the best predictive models, but also on a thorough understanding of the normative dimensions of forestry and good insights into the values of forests for local people as well as the expressions of such values in a large variety of forest use and conservation practices.

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11 International Forest Policy

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Introduction

Forest policy has been defined as 'a definite course or method of action from amongst alternatives and in the light of given conditions to guide and usually determine future decisions (regarding the conservation, use and management of forests)' (Hummel, 1984, p. xvii). More recently it has been defined as

> a negotiated agreement between government and stakeholders (i.e. all those who depend on or benefit from forests or who decide on, control or regulate access to these resources) on the orientations and principles of actions they adopt, in harmony with national socioeconomic and environmental policies, to guide and determine decisions on the sustainable use and conservation of forest and tree resources for the benefit of society.
>
> (FAO, 2010)

As illustrated by these two definitions, the term is not tightly defined but is used in different ways on different occasions. The first definition refers to 'a course of action adopted and pursued' and suggests that it can rationally be designed based on deliberate aims and plans or as a consequence of political activity arising from a series of decisions. The second definition indicates that the process involves different actors, and that the process does not only involve policy design but also policy negotiation. Thus, forest policy concerns the formulation of a set of norms and principles for human interaction with forests, concrete aims and objectives for forest conservation and use, and an outline of a course of action to achieve them. The norms and principles on human interaction with forests do not only concern the actual use and management of forests, but also the organization and regulation of those practices, as well as processes of decision making on the required policy measures.

Historically, forest policies typically focused on governing the forestry sector. This forestry sector consisted of a clearly demarcated interacting network of governmental actors and non-governmental actors engaged in professional forestry activities. It was characterized by a closed corporatist structure consisting of a tightly defined group of professionals from the government, forestry organizations and the timber industry (Westoby, 1989). The government officials had the task to define the general situation of forests and their multiple functions, the measures necessary to meet the demands made on forests and the manifold legal, planning, organizing and other actions necessary in this context (Hummel, 1984). In order to do so, they maintained close working relations with representatives of private forestry organizations and interest groups. Within the setting of the clearly bounded forestry sector and clearly established working relations between the governmental policy makers and forestry organizations, the policy process focused strongly on policy outputs in the forms of laws and government regulations.

This conventional focus on national forest policies based on governmental rules and procedures has changed greatly in the last 30 years. The traditional focus on an ideal-type and well-institutionalized national forestry sector changed significantly as a result of forestry issues increasingly becoming related to other policy fields as well as a shift to forest governance. Three important developments took place. First, forestry became linked to broader concerns on sustainable development, which brought new challenges of pursuing forest policies that did not only consider the development and regulation of the forestry sector, but also wider issues of socio-economic development and environmental change, particularly biodiversity and climate change recently. Second, as a result of this widening of the policy focus, the number of actors involved in the policy process increased. This increase in actors reflected the growing societal interest in and involvement with forests as well as changing forest values and interests. As a result, stakeholders who did not adhere to the values and interests of the traditional forestry sector became involved in the policy process as well, and thus increased attention was needed to procedural aspects of forest policy. This latter aspect is related to the third development in forest policy, namely a shift to forest *governance*. This term refers to the multi-actor and multi-level nature of current forest policy. Due to trends of – and demands for – democratization, internationalization and decentralization, more citizens and more administrative levels have become involved in forest policy over the years. These trends and demands are generally referred to as 'governance' in the literature (Lemos and Agrawal, 2006; Arts and Visseren-Hamakers, 2012). Because of these three developments – broadening of forest values and interests, new stakeholders and governance shifts – current policy laws and regulations do not just depend on professional forestry knowledge and expertise anymore, but also on the governance quality of the policy process, including aspects such as involvement of all relevant actors and administrative levels and the ability to negotiate conflicting values and interests. Consequently, forest policy has become incorporated in newly emerging multi-actor and multi-level governance arrangements.

The first initiatives in international forest policy reflected the traditional professional approach to forestry. Within the Food and Agricultural Organization (FAO) of the United Nations, created after the Second World War, a forestry department was established to foster international forestry. The aim of this department was to serve as a neutral forum for policy dialogue and as a reliable source of information on forests and trees. It organized a Committee on Forestry (COFO), which brought together heads of national forestry services and other senior government officials every 2 years in order to identify emerging policy and technical issues, seek solutions and advise FAO and others on appropriate action. It also organized a World Forestry Congress every 5 years as a forum to discuss progress in forestry. The FAO Forestry Department aimed to provide expert technical assistance and advice to help countries develop and implement effective national forest programmes. Within the UN system, it was responsible for organizing the forestry development programmes in tropical countries that were financed through the United Nations Development Programme (UNDP). Consequently, much attention was focused on tropical forestry. When, in the second half of the 20th century, the traditional tenets of professional forestry as expressed in the tropical countries came under heavy criticism for contributing little to socioeconomic development, the FAO (as well as the World Bank, which also funded tropical forestry development programmes) undertook several initiatives to identify novel approaches to linking forestry and rural development. This involved advocacy for new forms of social forestry (see also Chapter 10). The World Forestry Congress of 1976 heralded this reorientation of tropical forest policies and provided new visions on forests contributing to rural development and local livelihoods rather than only concentrating on timber resources of strategic importance to states.

The international initiatives to stimulate effective forest policies intensified in the 1980s when the efforts in linking forestry and development became integrated in a more general discussion on linking environmental conservation and human development (Grayson, 1995; Humphreys, 1996). The need for an integrated approach towards conservation and development was first put forward in the World Conservation Strategy (IUCN, 1980). These ideas received further global recognition as a result of the report Our Common Future (WCED, 1987). This report introduced the concept of sustainable development as an overarching concept for approaching issues of natural resources, economic development and social promotion in an integrated manner. The UNCED Earth Summit in Rio de Janeiro in 1992 strongly endorsed this approach and elaborated on it not only in an International Convention on Biodiversity Conservation, but also in an Authoritative Statement on Forests. As demonstrated by this last document, forest concerns played an important role in the deliberations on major issues for stimulating sustainable development. On the one hand, deforestation and forest degradation were identified as major environmental problems, and much attention was given to formulate global principles to halt deforestation. On the other hand, the concerns about the need to develop new socially responsive conservation approaches mirrored the concerns that had resulted in the initiation of social forestry strategies.

The novel approaches in tropical forestry resonated well with new forest values and concerns in the more advanced countries. Also in these countries changes in social values on forests and newly emerging environmental concerns required new approaches to forest policy and management (Poore, 1995; Kennedy *et al*., 1998). Consequently, these new policy notions became extended to forestry in the more economically advanced countries in the 'West', where forestry had already been institutionalized much more strongly. New notions of how forests should be managed to provide a mix of social values for current and future generations (Koch and Kennedy, 1991) resulted in an opening-up of the traditional forestry sector. Hence, it became realized that the international forestry policies should not just focus on tropical countries, but rather on global forestry issues.

The incorporation of forestry in an enlarged policy field and the need to adjust forest policies to new social values, norms and demands had important repercussions on the nature of forest policies. Traditional forest policy was challenged to overcome the limitations of the traditional sectorial approach of authoritative policy making and to create more open systems of interest, representation and policy formulation. Consequently, it was no longer possible to relate forest policy to an ideal-type forestry sector or to a predefined set of practitioners. Rather, forest policy makers had to deal with a variety of institutions and multiple practitioners.

The Quest for an International Forest Regime

As a result of the growing concerns on the fate of the world's forests, since the Rio conference much attention has been given to the development of a new global forest regime. Such a regime should consist of a set of convergent principles, norms, rules, procedures and programmes for governing the interaction between people and forest resources (Humphreys, 1996; Rayner *et al*., 2010). It should not only focus on regulating the traditional forestry sector, but also stimulating environmental conservation and sustainability. Originally, much attention focused on the need to formulate an international forest convention. Such a convention should form a legally binding core of internationally agreed main principles, norms and rules for conserving and using forests. Starting with the UNCED Earth Summit, the international community has undertaken several attempts to adopt such a legally binding instrument for forests. During this conference serious consideration was given to the need to formulate an International Convention on Forests. No agreement on such a convention was reached, but instead a (legally) Non-binding Statement of Forest Principles was formulated and adopted by the UN General Assembly in 2007. Furthermore, two conventions (the UN Convention on Biological Diversity and the UN Framework Convention on Climate Change) were signed at the UNCED; both of these conventions include elements on forest conservation and management. After the UNCED, many international meetings have been held to further elaborate the UNCED agreements and to review their implementation, e.g. by the Intergovernmental Panel on Forests (IPF) and the World Commission on Forests and Sustainable Development (WCFSD).

All these efforts did not result in a legal forest convention, but only in a set of non-legally binding principles, norms and instruments. And despite these, tropical deforestation and forest degradation still continues in many countries (Chapter 6). Considering the failure to agree on a global forest convention and to stop deforestation, it is often suggested that international forest policy has failed (Dimitrov, 2005; Humphreys, 2006). However, there are several arguments against such a point of view (McDermott *et al*., 2007; Rayner *et al*., 2010; Arts and Babili, 2012). Rather than judging the success of international forest policies only in relation to its *outputs*, such as a legally binding forest convention, or to its final *impacts*, such as halted deforestation, it can better be judged in relation to its outcomes. According to this view, the international forest policy process has resulted in the development of many new programmes to better conserve and manage forests. As discussed in Chapters 6 and 10, several of these new programmes have resulted in new human interaction with forests and collective action; these have in many places resulted in increased areas of forest protection and forest certification. Thus, even though the international forest policy has not resulted in an international forest regime characterized by a legal document stating binding commitments for human dealings with forests, it has instead resulted in the emergence of an international forest regime *complex*. This complex consists of a set of specific governance arrangements that are more or less loosely linked together.

Forest Governance: Key Concepts

The notion that international forest policy should not be considered as concerning the formulation of a legally binding forest regime, but rather as concerning the development of a regime complex, is related to two major changes in thinking about the main norms and principles guiding forest governance: (i) a change from a governmental approach to a multi-actor and multi-level governance approach and (ii) a related change from hard forest law to a more soft forest law approach.

From governmental forest policy to forest governance

As indicated above, traditionally national governments were considered as the main actors in forest policy; they had main responsibility in both formulating and implementing these policies. Since the 1980s the dominant position of national governments (i.e. the state) in policy making has been seriously challenged, and new approaches for governance were advocated. This resulted in the development of new arrangements for forest governance. The concept of governance denotes a new mode of decision making and implementation of norms and regulations on policy issues. In its broadest interpretation, forest governance can be defined as 'the many ways in which public and private actors from the state, market and/or civil society govern forest-related issues at multiple scales, autonomously or in mutual interaction' (Arts and Visseren-Hamakers, 2012, p. 242). It implies a partial relocation of decision-making power from the nation state to international organizations and sub-national authorities, as well as an increasing role of non-governmental actors (Pierre and Peters, 2000). The multi-actor and multi-level forest governance arrangements that started to emerge in the 1980s involved three parallel processes of globalization, decentralization and participation, and marketization respectively (Humphreys, 1996; Lemos and Agrawal, 2006; Agrawal *et al.*, 2008). The process of globalization was already referred to above, in response to the global concerns on the need for sustainable development forest policy. As discussed in Chapter 10, because of concerns about democratization and participation, the policies also became increasingly localized with new arrangements for decentralization and devolution in programmes for participatory forestry. This approach reflected the growing recognition that the traditional notion of the state being primarily responsible for regulating ownership and access to forests did not have the expected outcomes with respect to sustaining forest resources. Consequently, the traditional professional approach to forest policy came under criticism, and several initiatives to develop new approaches towards stimulating and regulating forest conservation and management at local community level emerged. Such new policy initiatives were not only undertaken by national and international government organizations, but also by various environmental and development and/or market organizations (Cashore, 2002; Arts and Buizer, 2009). This reflected that the growing and diversifying concerns on the fate of the world's forests resulted in new actors entering the forest policy arena. Increasingly, non-profit, civil society organizations, ranging from social and grass-roots movements advocating local forest rights to environmental organizations addressing new forms of forest conservation, became involved in forest policy making.

The growth in actors involved in forest policy not only involved civil society and environmental organizations, but also commercial enterprises. In addition to the traditional role of timber enterprises in forest policy, other commercial enterprises became involved. For instance, enterprises that depend on forest resources for water supply or providing opportunities for (eco)tourism. This has resulted in the formation of new forest policy partnerships between commercial organizations, civil society organizations and forestry organizations (Visseren-Hamakers and Glasbergen, 2007). An important example of such marketization in forest policy is forest certification (Cashore *et al.*, 2004). It entails a market-based mechanism of independent labelling and monitoring that aims to guarantee both manufacturers and consumers that timber products originate from sustainably managed forests. As will be elaborated below, global debates on forest certification started back in the 1980s in the ITTO (International Tropical Timber Organization), but for years countries could not agree on a system (Humphreys, 2006). Frustrated about this government failure, non-state actors took the lead themselves. A group of environmental conservation (including the World-wide Fund for Nature, WNF) and development organizations and a limited number of commercial timber organizations formed an international membership organization for forest certification in 1993: the Forest Stewardship Council (FSC). This initiative was later followed by new business initiatives, for instance through the Programme for the Endorsement of Forest Certification (PEFC). Some countries such as Indonesia and Malaysia also set up their own national certification systems, which were subsequently endorsed by some of the international organizations, including PEFC. Together, the FSC and PEFC now operate in 80 and 30 countries respectively; these programmes cover nearly 400 million hectares of forests worldwide (about 10% of the world's forests) and thousands of companies and products.

Hard versus Soft Law?

The increased participation of non-governmental civil society and commercial organizations in the international forest policy arena has resulted in a gradual change of thinking about the best approach towards regulating forest conservation and use. There exist three basic types of instruments for implementing forest policy, i.e. legal instruments, market instruments and communication instruments. The first instruments take the form of laws and regulations that stipulate how forestry should be organized. The second instruments basically rely on the market forces of supply and demand. And the third are based on moral persuasion. The increased participation of civil society and commercial organizations in forest policy has resulted in a gradual increase in the importance of market and communication instruments compared with legal instruments. This is reflected in a change in the regulation practices. Three main approaches towards regulating forest practices may be distinguished, i.e. hard law, soft law and smart regulation (Table 11.1). Traditionally, government forest policies were based on hard law arrangements. They relied on authority and power of the state in the formulation and implementation of policy instruments having legally binding obligations. The notion that the lack of an international forest convention indicates a failure in developing an international forest regime reflects such hard-law thinking. In contrast, a soft law approach emphasizes codes and rules of conduct rather than legally binding obligations. This approach relies on the participation of non-governmental actors in formulating and implementing non-legally binding rules that represent moral convictions or market forces rather than governmental regulation. It is based on de-regulation of state legislation coupled with voluntary obligations of non-state actors. Such arrangements are of growing importance in international forest policies. Examples range from the non-binding Forest Principles formulated within the UN arena to the standards of timber certification programmes mentioned earlier. However, self-regulation also has its limits. Consequently, an intermediate approach of smart regulation has been recognized that aims at formulating a combination of both governmental and binding and non-governmental and voluntary policy instruments for addressing complex policy problems (Arts *et al*., 2010). Such a smart regulation approach positions itself between traditional top-down regulation and the more recent self-regulation.

A good example of smart regulation is the recent international programmes for controlling trade in

Table 11.1. Three approaches to regulating forestry practices. (After Rayner *et al*., 2010.)

Basic approach to regulating forestry	Characteristics
Hard law through state regulation	Command-and-control approach based on state authority. National states formulate and implement legal regulations on forest ownership, management and production, and on controlling access to forest lands, products and markets
Soft law through de-regulation of state regulations and self-regulation of forestry sector	Reliance on moral rather than legislative rules of conduct based on corporate social responsibility of forestry sector and effective means for direct civil-society participation in forest governance. Voluntary self-regulation goes hand-in-hand with deregulation of state regulations
Smart regulation through mixes of regulatory instruments	Smart mixes of governmental and binding and non-governmental and voluntary regulations with policy instruments that transcend the dichotomy between top-down regulation and self-regulation of the forestry sector

illegal timber. This programme is based on the recognition that timber certification proved to be a suitable instrument for improving forest management of environmentally and socially conscious timber enterprises, but that it was unsuccessful in curbing illegal timber exploitation by unscrupulous and fraudulent firms. Consequently, in the early 21st century several international agencies and national governments decided to develop new programmes on timber legality. For instance, the European Union (EU) initiated the Forest Law Enforcement, Governance and Trade (FLEGT) Action Programme in order to limit the import of illegally produced tropical timber into the European market. This programme is based on the notion that considering local forestry conditions and policy legacies it would not be very efficient for the EU to define general overarching legal standards for timber production in the different timber exporting countries. Moreover, such legislation would not be in agreement with World Trade Organization (WTO) rules on free trade. Instead, tropical timber exporting countries are encouraged to enter into a Voluntary Partnership Agreement (VPA) with the EU to only export legally produced timber to Europe. As part of this VPA, they formulate, in a participatory forest governance process, country-specific standards on timber legality. In this manner, the politically legitimated demands of European consumers on 'good' timber are met, good forest governance in timber exporting countries is stimulated, and the international legislation on free trade is taken care of (Brack, 2005; Cashore and Stone, 2012).

Main Policy Issues

The international forest policy process is not only characterized by changing norms on how best to govern forests and what systems of law to apply, but also by several basic principles on international development and cooperation as well as by key themes on forestry needing attention (Wiersum, 2000; Arts *et al*., 2010; Glück *et al*., 2010).

Basic principles in international relations

The international forest policies are embedded in three basic principles regarding international development and cooperation (Table 11.2). In addition, the principle of sovereignty states that national states are free to formulate their own policies as long as these do not negatively affect other countries or global common goods. The relative importance of these principles has changed over time. As discussed above, up to the mid 20th century, forestry was basically considered to be the concern of a specialized forestry sector subject to regulation and control by national governments. The first initiatives for stimulating international forestry cooperation and development started within the framework of international development cooperation as a tool for improving socio-economic development in tropical countries. Initially, this still concerned a sectorial activity among sovereign states with the forestry department of the FAO playing a coordinating role. For instance, they coordinated the Tropical Forests

Table 11.2. Basic principles in international forest policies.

Main international principle	Related norms and principles in international forest policies
Ethical principles regarding human rights, fulfilment of basic human needs and good governance	Forest management should maintain or enhance the flow of benefits from forest resources, with access generally perceived as just by all stakeholders, and with attention to forest-related basic needs and of forest ownership and use rights of local people. The voice of all stakeholders must inform forest management, with all stakeholders having an acknowledged right and means to participate in equitable forest management.
Principles on the need to address global environmental problems and stimulate environmental and biodiversity conservation	Conservation and sustainable use of forests and forest biodiversity. Maintenance of forest environmental services.
Principles regarding just international economic relations and international trade	Free international trade of legally produced timber and other forest products.

Action Programme that was launched in 1985 to stimulate improved forest conservation and management in tropical countries. They also organized World Forestry Congresses every 5 years to discuss the global state of forestry. As mentioned above, the first initiatives to adjust the traditional forest policies to more socially conscious approaches were introduced at the 1976 World Forestry Congress. As elaborated in Chapter 10, these new policy initiatives were related to ethical concerns on human rights and basic needs. Because of similar concerns in forest-related policy domains, these ethical concerns have gradually become stronger. For instance, the ground-breaking Brundtland Report of the World Commission on Environment and Development stated:

> The pursuit of sustainable development requires a political system that secures effective participation in decision-making.... This is best secured by decentralising the management of resources upon which local communities depend, and giving these communities an effective say over the use of these resources. It will also require promoting citizen's initiatives, empowering peoples' organisations, and strengthening local democracy.
>
> (WCED, 1987, p. 65)

These ideas echoed in the Convention on Biodiversity Conservation that was adopted at the UNCED Earth Summit in Rio de Janeiro in 1992. This convention explicitly acknowledges the need to recognize knowledge and practices of indigenous people and local communities. More recently, the UN Millennium Development Goals (MDGs) from 2000 formulated the goal of reducing extreme poverty and hunger by one half. It also indicated the aim of ensuring environmental sustainability by 2015. These two MDGs resulted in focused attention on policy options for combining forest conservation and poverty alleviation of forest-dependent people (see Chapter 10). Thus, the international forest policies have gradually extended beyond the traditional forestry sector to include both ethical concerns on human needs and global environmental concerns. In the early 21st century, the environmental concerns became even further extended to include concerns on climate change (see Chapter 8).

Still another important development affecting international forest policies was the trend towards globalization of markets and formulation of international principles for regularizing international trade. Within the framework of the WTO, international agreement was reached on trade liberalization and on organization of international trade agreements for balancing supply and demand of specific commodities, such as coffee and cocoa. These trade agreements reflect how the basic principles on international trade do not only concern free trade between sovereign states, but also concern the balance in supply and demand and prevention of bust-and-boom trading cycles that are disadvantageous to producers and consumers. When in the 1980s tropical timber production became under increasing attack for causing serious deforestation, it was internationally agreed that these principles for international trade should also be specified for tropical timber. This resulted in 1983 in the formulation of the International Tropical Timber Agreement (ITTA). Similar to other trade agreements on agricultural products such as coffee and cocoa, this agreement aims 'to promote the expansion and diversification of international trade in tropical timber'. This agreement was innovative by not only considering the principles on international trade, but also taking into account environmental concerns. During the formulation of the second ITTA in 1994, the norm was included that timber should be produced in sustainably managed forests. In order to administer the ITTA, the International Tropical Timber Organization (ITTO) was established. The ITTO has 57 members divided into two caucus groups: producer countries (31 members) and consumer countries (25 members, including European Community States). The ITTO membership represents 95% of world trade in tropical timber and covers 75% of the world's tropical forests. The ITTO administration identified the need to establish a system for timber certification as a means to verify the provenance of internationally traded timber. However, because of political disagreements on issues of national sovereignty, the ITTO country members did not agree on how to implement such a certification system. As mentioned above, such a certification system was only established when an international NGO–firm partnership formed the Forest Stewardship Council as an independent organization to accredit timber certification programmes.

Key Themes in Forest Policy

In addition to the basic principles concerning international relations, the international forest policies also concern several key themes related to forests (Arts and Buizer, 2009; McDermott *et al*., 2010). As already discussed above, one major theme concerns the notion of the need to change the institutional structure of forest policy and to develop new arrangements for forest governance. Other major themes concern either environmental issues or socio-economic issues.

Deforestation and land-use change

Much concern has been voiced about tropical deforestation and many international policies focus on redressing this process and its impacts. In the aftermath of the 1992 UNCED conference, several policies focused on the need to stimulate forest conservation and sustainable forest management, including afforestation, reforestation and forest restoration, and to limit deforestation and forest degradation. These issues are further detailed in Chapter 6. With the advent of new political concerns on climate change, and the understanding that forests form an important sink and reservoir for greenhouse gases, concerns on deforestation and forest degradation became (again) intensified and much attention was given towards reducing emissions from these forest dynamics and promoting reforestation as a means for carbon sequestration (currently referred to as REDD+). These climate issues are further discussed in Chapter 8.

Ecosystem services

In addition to the extent of forests, also the impacts of forest loss are a major theme in international policies. Rather than focusing only on the extent of forests, these policies are based on the understanding that forests provide important provisioning, regulating, carrier and cultural services. To optimize these services requires not only forest conservation, but also sustainable use and management. The maintenance and enhancement of the different forest ecosystem services requires both a system of strictly protected areas that safeguard natural ecosystem processes and services and of forests with enhanced production (=provisioning) services; several international policies focus on either one or both issues. Another important issue concerns the need to sustainably exploit forests; this requires attention not only to ecological issues, but also to social and economic issues (Chapter 7).

Biodiversity

Forests are not only important because of their structural characteristics and ecological services, but also for their biodiversity (see Chapter 3). The conservation of biological diversity in the sense of variability among living organisms, including diversity within species and of ecosystems, forms a third major theme in the international forest policies. It obtained a special significance from the fact that many tree species are endangered and that the rate of loss is steadily increasing. Species may not only be threatened by the loss of their habitat, such as through deforestation, but also by disturbance from human activities, such as hunting or overharvesting of plants. The 1975 Convention on the International Trade of Endangered Species of Wild Fauna and Flora (CITES) was the first multilateral agreement that specifically focused on this theme. Other policy instruments were developed within the Convention of Biological Diversity that was approved at the 1992 UNCED conference.

Economic development and poverty alleviation

Through their provisioning of services, forests can contribute to both poverty alleviation of disadvantaged groups and economic development (Chapter 10). The contribution of forests to poverty alleviation is endorsed by the UN Millennium Development Goals of 2000, which stated the aim of eradicating extreme poverty and hunger by one half by 2015. This aim is often related to the additional goal to ensure environmental sustainability; this relation forms an important consideration in several international forest policies. But forests may also contribute towards economic development through trade in forest products and services. Such trade forms an important stimulus to both global and international development; according to WTO rules, such trade should be based on the principle of non-discrimination and hence free trade. However, the trade in several agricultural commodities, such as soybean, palm oil and beef, is playing an important role in forest loss and degradation. Moreover, increased commercialization of forest products may limit the accessibility and availability of forest products for poor people. Because of these multifaceted dimensions of forest product trade, many international forest policies focus on the interplay between the basic principle of free world trade on the one hand and the need to address the unequal distribution of environmental and social costs and benefits on the other. For instance, the ITTA promotes trade in tropical timber and the UNFF advocates the increase in the proportion of forest products from sustainably managed forests. The FLEGT Action Plan stipulates that timber exports should be derived from legal sources. And the Convention of Biodiversity Conservation acknowledges the need to respect, preserve and maintain the knowledge, innovations and practices of indigenous and local communities in respect of traditional forms of forest use (such as medicinal plants) that show promise for international marketing.

Human rights and social welfare

As illustrated by the Convention on Biological Diversity (CBD) that endorses the intellectual property rights of traditional people when newly marketed forest products are based on their knowledge and practices, much attention is given to the issues of access and benefit-sharing and rights of indigenous people in international forest policy. These issues are further discussed in Chapter 10. Such human rights do not only concern indigenous and tribal groups and forest-dependent people, but also employees of commercial forest enterprises and manufacturing companies. For instance, the labour conventions of the International Labour Organization stipulate that the workers in forest industries should have freedom of association and collective bargaining and should not be subject to forced labour or discrimination.

Development of an International Forest Regime Complex

When in the mid 20th century new concerns about tropical forestry development emerged, at first they were approached as mainly concerning an issue requiring further professionalization. Consequently, initially international global forestry developments were mainly discussed within the FAO Forestry Department. In the mid 1980s international concerns about the fate of tropical forests resulted in the organization of a new Tropical Forest Action Programme; this programme was coordinated by the FAO. But at the end of the 20th century the professional forestry concerns approach was gradually augmented by more general environmental concerns. These concerns often involved political controversies about whether national states are primarily responsible for managing natural resources, or whether global action is needed. Consequently, the various basic principles and main themes that received attention in international forest policy debate were often not easy to reconcile. Countries sometimes had different priorities in respect to the basic principles and themes, and the process towards multi-actor and multi-level governance increased the variety of opinions on what issues needed consideration and what governance arrangements were most suitable to effectively address them. In the aftermath of the 1992 UNCED conference that heralded the incorporation of forestry issues in more general environmental debates, the traditional professional approach to international forest policy became increasingly politicized. In the follow-up of this meeting, within the United Nations system, forest policy was no longer only a concern of the FAO, but became a matter of general UN concern. Within the framework of the UN Commission on Sustainable Development an International Panel on Forests (IPF) was organized in 1992, which was followed up by an International Forum on Forests (IFF) and the UN Forum on Forests (UNFF). These served to stimulate international action on sustainable forest use and conservation. The IFF proposed to develop a legal framework on all types of forests. In order to accomplish this ambition, a formal organization with legal authority had to be established. Therefore a United Nations Forum on Forests was established as a subsidiary body of the Economic and Social Council (ECOSOC) of the UN. The objective of this arrangement was to promote the management, conservation and sustainable development of all types of forests and to strengthen long-term political commitment to this end. This should be accomplished through the promotion of the implementation of internationally agreed actions on forests at the national, regional and global levels and the provision of a coherent, transparent and participatory global framework for policy implementation, coordination and development (Box 11.1).

Notwithstanding the long process of policy negotiation at the various post UNCED meetings, it was not possible to formulate a legally binding international forest convention. Only a Non-Legally Binding Instruments on All Types of Forests was formulated in 2007. Most observers attribute

Box 11.1. Principle functions of the United Nations Forum on Forests

The formal ECOSOC resolution to establish a United Nations Forum on Forests identified six main functions for this international arrangement on forests:

- Facilitate and promote the implementation of the IPF/IFF proposals for action as well as other actions that may be agreed on; catalyse, mobilize and generate financial resources; and mobilize and channel technical and scientific resources;
- Provide a forum for continued policy development and dialogue to foster a common understanding of sustainable forest management and to address forest issues and emerging areas of priority concern in a holistic, comprehensive and integrated manner;
- Enhance cooperation as well as policy and programme coordination on forest-related issues among relevant international and regional organizations, institutions and instruments;
- Foster international cooperation, including North–South and public–private partnerships, as well as cross-sectorial cooperation at the national, regional and global levels;
- Monitor and assess progress at the national, regional and global levels through reporting by governments, and regional and international organizations, institutions and instruments, and on this basis consider future actions needed; and
- Strengthen political commitment to the management, conservation and sustainable development of all types of forests through: ministerial engagement; liaising with the governing bodies of international and regional organizations, institutions and instruments; and promoting action-oriented dialogue and policy formulation related to forests.

this failure to the diverse forest values and interests of the various countries around the world: some countries have much forest, others do not; some produce timber, others mainly import it; some countries prioritize the economic value of forests, others the environmental value; some consider forests as a global common good, others as a natural resource to be governed nationally, and so on (Hoogeveen and Verkooijen, 2010).

The task of the UNFF was not just to formulate an international forest convention, but also to stimulate continued policy development and dialogue and foster international cooperation in forest conservation and management. For this purpose they created a Collaborative Partnership on Forests (CPF) and invited relevant international and UN organizations as well as non-governmental organizations to participate in this programme. This approach reflects that during the last decades many new policy initiatives have been undertaken, also outside the UN system. Rather than a universally agreed international forest treaty, an international forest regime complex gradually emerged. This complex consists of both legally binding and non-legally binding treaties at either multilateral or bilateral level, voluntary statements on norms and principles of various international organizations, and the programmes and procedures for stimulating forest conservation and development of various international organizations, both governmental and non-governmental (Table 11.3). In addition to these global policy initiatives, in Africa, Latin America, Europe and the Asia-Pacific region, several regional forest policy programmes exist that translate and adapt the global commitments to regional contexts or that formulate new policy principles in cases where no global consensus has yet been reached (Glück *et al*., 2010). For instance, within Europe a discussion has been started on the scope of formulating a legally binding agreement on European forests.

The Fragmented International Forest Regime Complex: Regime Failure or Successful Diversification

The emergence of the international forest regime complex is considered by several observers as quite an achievement. They argue that from a procedural and outcome point of view the emergence of this complex demonstrates the incremental success of international forest policy rather than its failure (McDermott *et al*., 2007; Rayner *et al*., 2010; Arts and Babili, 2012). Rather than lament the lack of a global forest regime based on an internationally agreed convention, they refer to the intensive policy process and emergence of new policy initiatives and arrangements. The international regime complex reflects that the international forest policy is influenced by a variety of governance arrangements that

Table 11.3. Main elements of the international forest regime complex. (Adapted from Glück *et al.*, 2010; Arts and Babili, 2012.)

Main elements	Examples
Non-legally binding instruments aiming to promote ideas and norms related to conservation and sustainable use of forests worldwide	Documents UNCED Rio Conference 1992 (Authoritative Statement on Forests, Chapter 11 of Agenda 21). 2000 UN Millennium Development Goals (MDGs) including MDG 7 on ensuring environmental sustainability by 2015. Documents United Nations Forum on Forests 2007 (Non-Legally Binding Instruments on All Types of Forests).
Legally binding treaties on specific forest-related issues	ITTA (International Tropical Timber Agreement) stimulating expansion and diversification of trade in tropical timber. CITES (Convention on Illegal Trade in Endangered Species) regulating trade of endangered tree and animal species. CBD (Convention on Biodiversity Conservation) stimulating conservation and sustainable use of forest biodiversity.
Legally binding bilateral agreements	FLEGT (Forest Law Enforcement, Governance and Trade) between EU and several tropical timber-exporting countries to ban illegally produced timber on European markets.
Voluntary instruments of international organizations such as FAO, UNFF and ITTO for stimulating conservation and sustainable use of forests	National Forest Programmes. Criteria and Indicators for sustainable forest management.
Programmes and procedures of international organizations and bodies for stimulating conservation and sustainable use of forests	FAO (FAO Forestry Commission, World Forest Congress). UNFF (forest dialogue within the UN). ITTO (regulation tropical timber trade). UN Commission for Sustainable Development (role of forests in sustainable development). World Bank (design and funding of forest programmes and projects).
Programmes and procedures of public–private partnerships	Collaborative Partnership on Forests.
Private instruments focused on specific issues such as sustainable forest management and timber production	FSC and PEFC (certification of sustainably produced timber).

transcend the traditional policy process steered by national governments and international organizations. Even though several hard, legally binding policies exist that reflect the traditional governmental approach in policy making, there have also been developed a variety of voluntary policy agreements based on soft law approaches. Still others reflect an approach of smart regulation. The regime complex not only reflects the diversity in values and interests of different actor groups, but also the existence of different types of forested landscapes ranging from natural forest reserves, often situated in remote areas, to mosaic landscapes with a combination of often modified forests and agricultural lands (see Chapter 6). These different forest landscapes often require different policies for optimizing their ecological and socio-economic features (Chomitz, 2007); the mix of policies and programmes make it possible to effectively link specific forest conditions to specific international policies.

The multi-level forest governance arrangements make it possible to link the basic principles underlying the international forest policies to specific conditions by formulating regional or group-specific policies. Moreover, they allow that a new policy is introduced at a sub-global level in case no global consensus on that specific policy is reached. However, different regimes may also reflect different principles. The different elements of the regime mix are sometimes mutually reinforcing, but at other times they may be overlapping and conflicting. In order to better link the various regimes, interaction management is gaining importance in international forest policy. Such interaction involves conscious efforts by actor groups in specific policy programmes to improve the interaction with related programmes and to create effective synergy between different regimes (Oberthür and Stokke, 2011). This process is stimulated by the formation of various new partnerships for forest governance (Visseren-Hamakers *et al*., 2011). The policy dynamics in relation to timber certification provides a good example of how regime interaction may change over time. As discussed earlier, timber certification was taken up by the non-governmental organization FSC after ITTO as a multilateral organization failed to translate the general principle of certification into concrete policy instruments. Within FSC, decision making was based on equal representation of three chambers representing conservation interests, development interests and commercial interests respectively. After the initial success of FSC, a new organization with a different constellation of more traditional timber sector representatives was established: the Programme for the Endorsement of Forest Certification, or PEFC. At first, the interaction between FSC and PEFC was characterized by competition. But gradually a more positive interaction occurred, with both programmes learning from each other's strong and weak points. Another example of gradual adaptation of the certification programme because of experiences of other policy initiatives is the impact of the newly emerging FLEGT programme on timber legality. In reaction to the experiences of the FLEGT programme to systematically identify legality standards, the certification programmes are reconsidering their standards on legal timber production. Another example of synergy between regimes is the development by the FSC certification programme of new standards for certification of timber from small-scale (community) forest enterprises (Wiersum *et al*., 2013). This initiative was undertaken in response to the various international initiatives to stimulate new socially conscious forest management systems (Chapter 10).

Conclusion: International Forest Policy as a Process

Since the 1980s, the simultaneous processes of globalization, localization and marketization have resulted in a growing number of international forest policy programmes. Rather than a global forest regime, an often fragmented forest regime complex has been developed, characterized by a hybrid of principles for regulating and controlling forest conservation and use (Humphreys, 2006; Rayner *et al*., 2010). These core elements consist of either international or multilateral treaties, non-legally binding and voluntary instruments and multilateral programmes. As illustrated by the various examples discussed earlier, they are characterized by a diversity of multi-actor partnerships. They illustrate how, prompted by global concerns about the high rates of deforestation and lack of sustainable forest management in tropical countries since the 1980s, much attention has been given to the formulation of new principles, norms, rules, procedures and programmes for governing the interaction between people and forest resources. The first international forest policies still had the nature of upscaling of the traditional government policies for regulating the forest sector to international level. But the policy process was gradually transferred towards a more inclusive approach of good forest governance. This multi-actor and multi-level governing approach is based on the consideration that forest conservation and sustainable management involves the reconciliation of different ecologically, economically and socially oriented forest values held by various stakeholder groups. This requires multi-actor processes for decision making on and implementation of forest use and management, with specific attention to the equitable access of different stakeholders to these processes. It also requires attention to the multiple levels of decision making on forest use and management with due consideration for trends towards globalization, localization and marketization. As demonstrated by the evolution of the international forest policy, these basic policy principles can better be realized through a process of policy learning characterized by multi-trajectory pathways and a reiterative process of policy negotiation, formulation and gradual adaptation in view of experiences with implementation and relation to other policies rather than through a simple single-loop policy cycle of policy identification, formulation and implementation. International forest policies do not just concern the formulation of a legal convention as a global instrument identifying basic principles and norms, but also the further specification of norms and principles for operational policies. It also requires focused attention to procedural issues with regard to multi-actor involvement. At the interface between content and procedure, many initiatives have been developed; these demonstrate the great concern among many multiple actor groups of the need to stimulate better forest conservation and well-regulated sustainable use. Consequently, the international forest policy process does not take the form of a linear process of first formulating global principles in a legally binding policy document and next elaborating specific issues in further specialized documents, but rather a much more diversified process that involves better opportunities for multi-level and multi-actor initiatives and the development of innovative approaches towards forest governance. The basic norms and principles for forest policy emerge out of the different policy experiences rather than being centrally formulated. The vibrant process of forest governance has resulted in an interlocking and dynamic network of international forest policies and programmes rather than a systematically designed international forest policy.

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