

Course Name: Crop Modeling

Course Credit Hours & Code: AGR-712 & 3(3-0)

Course Incharge/Instructor: Dr. Wajid Nasim Jatoi (Agronomy Dept., UCA&ES), IUB.

Week No.	Contents/Description
1 st Week	Crop modeling, concept and types of models
2 nd Week	Philosophy and terminology of system science, scope of system analysis
3 rd Week	Statistical parameters in modeling; Parameterization and evaluation of crop models;
4 th Week	Model application in crops, soil, water and agrometeorology
5 th Week	Modeling for crop improvement and risk assessment
6 th Week	Assignments and Presentations/Class Discussion
7 th Week	Crop models application in research, education and extension
8th Week	Midterm Examination
9 th Week	Integration of crop models with GIS and remote sensing
10 th Week	Working with different models like DSSAT, APSIM, AQUACROP Models
11 th Week	Setting of appropriate coefficients for cultivars, calibration, evaluation and validation
12 th Week	Preparation of different input files; crop management, & experimental data files
13 th Week	Assignments and Presentations/Class Discussion
14 th Week	Preparation of weather and soil files; Working with sequence, seasonal, economic analysis, easy grapher, etc
15 th Week	Working with sequence, seasonal, economic analysis, easy grapher, etc
16th Week	Final Term Examinations

Recommended Books

1. Cao, W., J.W. White and E. Wang. 2009. Crop Modeling and Decision Support. Springer, Heidelberg, Germany.
2. Floor M. B. and M. van Ittersum. 2010. Environmental and Agricultural Modeling: Integrated Approaches for Policy Impact Assessment, Springer, Heidelberg, Germany.
3. Singh, P. 2008. Modeling crop production systems: Principles and applications. Science publishers. Enfield, New Hampshire 03784.USA.
4. Vohnout, K. D. 2003. Mathematical modeling for system analysis in agricultural research. Elsevier Sci., Amsterdam, The Netherlands.
5. Wallach, D., D. Makowski, J.W. Jones. 2006. Working with Dynamic Crop Models Evaluation, Analysis, Parameterization, and Applications. Elsevier Sci., Amsterdam, The Netherlands.

Crop Modeling: From Infancy to Maturity

Thomas R. Sinclair* and No'am G. Seligman

ABSTRACT

Crop modeling, the computerized simulation of dynamic crop systems, was born about 30 years ago, when systems analysis and modern computers presented a new technique to crop scientists. Since then, crop modeling has gone through a number of developmental stages, similar to those of living organisms. From its infancy, crop modeling seemed to promise a well-behaved, elegant surrogate for ambiguous and cumbersome field experimentation. Indeed, some of the earliest models proved to be among the most notable achievements to date. During the juvenile stage that followed, there was an impressive increase in complexity and computer sophistication, accompanied by some of the growing pains of childhood. Greater expectations led to more and more detailed descriptions of the functioning of the biotic and abiotic components of cropping systems. The results were often trivial, and the big payoff tended to recede into the future, but the need for predicting future crop performance for management and hypothesis testing, together with progress in crop science and computer technology, spurred crop modeling. The next phase, adolescence, a period marked by intense activity, confusion, and excessive confidence—sometimes challenged by doubt—appears to be extending into the present. Not only is the original promise turning out to be elusive, but widely accepted guidelines for scientific modeling, such as greater reductionism, universality, and validation, are being questioned. Maturity may be emerging as expectations become pragmatically adjusted to reality. Crop modeling, like advanced ecological modeling, is proving to be more a heuristic tool than a surrogate for reality. In academic, research, and applied roles, such models can be of great value when used as aids to reasoning about the functioning and response of crop systems under many relevant, nontrivial scenarios.

CROP MODELING, defined here as the dynamic simulation of crop growth by numerical integration of constituent processes with the aid of computers, is a technology used to construct a relatively transparent surrogate (or substitute) for a real crop, one that can be analyzed and manipulated with far greater ease than the complex and cumbersome original. The development of crop modeling, analogous to biological life cycles, can be described as a series of stages from infancy to maturity. Crop modeling was born more than 30 years ago, and its infancy was nurtured by the dawn of the computer age and the developing concepts of systems analysis. Expectations were high and, indeed, some of the proudest achievements of crop modeling were accomplished during this period. With the popularization of computer technology, there followed an intense and exciting juvenile phase, marked by an impressive increase in model complexity. Soon after came an adolescent stage fraught with confusion, and much expense of effort, coupled with emerging disillusion with the naïveté of earlier

expectations—and, today, a developing maturity based on accumulation of experience and a more realistic perspective of the uses and limitations of crop models. While crop models are used for crop predictions, we propose that crop models have a more assured role as heuristic aids to reasoning about interactions and feedbacks in crop systems. As such, they should be constructed at a level of aggregation that does not cloud the transparency necessary for meaningful analysis and greater insight. Because crops are complex heterogeneous systems, usually cumbersome to manipulate experimentally, user-friendly models can fulfill a vital heuristic function in teaching, research, and management planning.

INFANCY

In the period following World War II, systems analysis and computer science, stimulated by the Cold War and space exploration, developed to the stage where they provided convenient and relatively friendly techniques to emulate the interaction of components in complex systems. Crop modeling was born in this exciting era of new technologies when, literally, the sky was no longer the limit. The first steps for crop modeling were models developed to estimate light interception and photosynthesis in crop canopies (Loomis and Williams, 1963; de Wit, 1965; Duncan et al., 1967). These models calculated the light profile in a canopy and made it possible to assess the sensitivity of crop photosynthetic rates to sun angles, leaf angle distribution, and the latitudinal position of the crop. These were relatively simple models, but they opened the way to quantitative, mechanistic estimates of maximum attainable growth rates. Crop growth and potential yield became quantitatively and demonstrably linked via biochemical and biophysical mechanisms to the amount of solar energy available for the accumulation of chemical energy and biomass by plants.

The quantitative determination of potential yield and the realization that it was within reach using existing cropping technologies marked the end of an era in agricultural science, and a shift in emphasis from the objective of growing "two blades of grass where only one grew before" to an emphasis on deeper understanding of assimilate partitioning, ontogeny, product quality, and genetic control of crop characteristics. This advance in perspective on crop production also marked the end of the infancy stage of crop modeling. After the early successes in modeling photosynthesis of leaf canopies, it seemed only a matter of time before a full description of crop growth and development would be incorporated into models.

JUVENILITY

Like the widening horizons of childhood, the new technologies opened new vistas for many scientists. It seemed straightforward to proceed with modeling the

T.R. Sinclair, USDA-ARS, Agronomy Physiology Lab., Univ. of Florida, P.O. Box 110840, Gainesville, FL 32611-0840; N.G. Seligman, The Volcani Ctr., Inst. of Field and Garden Crops, POB 6, Bet Dagan 50250, Israel. Presented at a symposium, Use and Abuse of Crop Simulation Models (jointly sponsored by Div. A-3, the Computer Software Applications Committee, Div. C-2, and Div. S-1), at the ASA-CSSA-SSSA annual meetings in Seattle, WA, 14 Nov. 1994. Received 26 June 1995. *Corresponding author.

many factors that influence crop yield: weather, soils, crop genetics, plant physiology, and pest damage. The promise was that age-old questions about the linkages among these factors could be resolved so that crop yields could be readily predicted and management manipulations could be optimized. Models offered the promise of abbreviating experimentation in the evaluation of improved genetic material and new management techniques in the context of a wide range of cropping environments (e.g., Bowen et al., 1973).

As a further stimulus to crop modeling, tremendous advances in equipment for field experimentation provided entirely new sets of data to use in models. Spin-offs from the space program included photocells to measure canopy light levels, improved anemometers to monitor wind speed in and above the crop, and data loggers with magnetic data storage. The new experimental data encouraged a physicochemical view of crop growth based on a detailed description of the crop microclimate and the response of the plants to this environment (e.g., Lemon et al., 1971).

The complexity of crop models increased as the various details of crop mass accumulation and an accounting of the factors that alter plant growth were incorporated into the models. Important advances in describing various subcomponents of carbon assimilation in particular were made during this period. The significance of stomatal conductance in regulating leaf gas exchange was quantitatively described (e.g., Cowan, 1977). The fate of photo-assimilates in respiratory pathways was carefully analyzed (Penning de Vries, 1975).

Developmental processes of plants became an important consideration as the time frame of models was lengthened to include the entire growing season. Expressions for the partitioning of assimilate among various tissues, particularly to the grain, were important. Ultimately, the addition of these various components led to a number of models of daunting complexity, such as GOSSYM (Whisler et al., 1986), CERES (Ritchie et al., 1985), and SOYGRO (Wilkerson et al., 1985).

The development of these complex models was accompanied by some of the stresses and strains frequently associated with juvenility. As models became more complex, the number of parameters required to describe the system in all its specific detail increased greatly. Many of the biological coefficients needed to describe critical cultivar characteristics required complex experimentation. Inevitable experimental error in these coefficients propagated and usually compounded through the model. Some variables that could not be measured directly in experiments had to be estimated, often guesstimated. These variables were often *calibrated* with the model, thereby turning the modeling process into a curve-fitting process. All these complications inhibited implementation of the model and created murky interconnections that hindered understanding of model behavior. Soil and climatic input data were (and remain) particularly vexing because uniformity in environmental conditions is the exception rather than the rule.

In addition, there was a realization that the role and function of models in solving engineering problems does

not apply to biological systems (de Wit, 1970). An engineering model is a point of departure that leads to the construction of a structure or a device. All the components are defined and have clear specifications. The complexity of the model and the complexity of the final product are almost identical within the limits of narrow tolerances. This is so even when some of the components are represented as black boxes, because their inputs and outputs are clearly and accurately specified. In the case of crop models, as well as ecological and economic models, the point of departure is a very complex system. The model is therefore of necessity a highly simplified surrogate system, even when defined in great detail. Consequently, the tolerance between the model and the actual system is inevitably wide and attainment of one-to-one representation is unattainable, except in trivial cases. The biological reality is composed of a vast number of components and processes interacting over such a wide range of organizational levels that it is impossible to identify all possible factors for all situations that may influence crop performance (Mayr, 1982; Pease and Bull, 1992). Understanding and summarizing the hundreds of thousands of molecular processes that are occurring simultaneously in the plant make it futile to attempt a complete description of its physiological performance. In addition, each growing season, each region, each field, each site offers a new environment where the interplay of many factors determine crop performance. In the colorful words of Thomas Mann (1944, p. 157-158):

In the long run it is impossible to narrate life as it flows. . . . It would be quite beyond human powers. Whoever got such an idea into his head would not only never finish, he would be suffocated at the outset. Entangled in a web of delusory exactitude, a madness of detail.

Consequently, the dilemma presented by the attempt to model the complexity of the crop system while avoiding the danger of sinking into a "madness of detail" became increasingly acute.

ADOLESCENCE

Adolescence is commonly associated with considerable confusion and turmoil. In this stage of transition from juvenility to adulthood, basic assumptions are questioned and perspectives are changed. The unbounded possibilities of earlier developmental stages shrink as the realities of limited resources and possibilities encroach on original expectations. So too with crop modeling the original tenets need to be reevaluated in the light of accumulated experience.

Extensive Reductionism

An assumption that was implicit in many crop modeling efforts was that scientific rigor could be ensured by expressing processes only in basic physical, chemical, and physiological terms. Consequently, there was a tendency to adopt an extensive reductionist approach while maintaining an integrated, holistic framework so as to extrapolate the laboratory to the field. As a result, com-

plex systems came to imply complex models. To make the complexity more tractable, various hierarchical approaches to organizing the system were proposed (e.g., Goodall, 1976; van Keulen and de Wit, 1982).

In many cases, however, increasing reductionism forced the use of expressions that were often no more than weakly supported assumptions of the model builder. For example, the processes that determine how materials are partitioned within the plant are not well understood. In order to describe these process within the plant, model builders have defined hypothetical pools of compounds that responded to supply and demand. Such reductionism when inappropriately applied can be misleading. When a high level of plant organization is being modeled, its use may well give a more distorted representation of organ growth than the use of conservative allometric relationships.

There are a number of examples where detailed, reductionist models are less reliable than simpler models for simulating observations or predicting yields. A simple water balance model was found superior to COTTAM and GOSSYM in approximating crop water stress and field water balance (Asare et al., 1992). An empirical equation was found superior to CERES in predicting annual potential wheat (*Triticum aestivum* L.) yields in Mexico (Bell and Fischer, 1994). SOYGRO was found to be inferior to a simple average of a sample in predicting soybean yield in unsampled populations (Colson et al., 1995). In simulating the water runoff from various agricultural watersheds, Loague and Freeze (1985) found that a regression model was superior to a quasi-physically based model.

Most recently, a comparison was done of the simulation results among 14 mechanistically based wheat models (Goudriaan, 1995). The models represented a full range of complexity from very simple models involving only a few lines of code, to a model of such great complexity that a CRAY supercomputer was required for simulations. The models were given the same input data for two locations to simulate wheat growth and yield. There was poor agreement among the models in the simulated results. For the two test locations, simulated grain yields ranged from 2.5 to 8.0 t ha⁻¹ and 5.4 to 10.3 t ha⁻¹. No particular trend in yield predictions or improved agreement among models was associated with model complexity. Certainly, increasing reductionism in models did not result in less variability in predictions among the complex models.

Universal Models

As a rule, crops have been modeled as deterministic, continuous systems. In fact, plants are comprised of discrete organs, and organs are composed of discrete cells. The development of each of these discrete units may be drastically altered by only a slight internal or external contextual variation, especially during transitional stages, when small effects amplify with further development. Consequently, the development of each unit is in reality a combination of deterministic and stochastic processes. While the development of a commu-

nity of elements in any biological system must follow a general pattern set by genetic blueprints and controlled by negative and positive feedbacks, it is impossible to predict the precise developmental path of the suite of elements that comprise the organism. Even the full multi-dimensional development of a single element can rarely, if ever, be predicted precisely. This is not unlike the uncertainty recognized by physicists in predicting the future path of individual atoms. This unpredictability is conserved at all hierarchical levels, so the problem does not disappear with greater aggregation. A corollary to the above dilemma is that, within the physical bounds set by system integrity, the crop system is open and there are unlimited paths for individual plant development. This noise or random component in experimental observations sparked the development of statistical theory for analysis of variance.

The practical consequence is that it is impossible to create universal crop models (Spitters, 1990). Not surprisingly, it has been found that each new season or new location brings new challenges that were not foreseen in the original model, and the expectation of universality fails. For example, attempts to use existing crop models developed for higher latitudes failed when an attempt was made to simulate crops in the semiarid tropics of Australia (Carberry and Abrecht, 1991). Important deficiencies were found in each of three complex wheat models even after they had been calibrated for a new set of conditions in New Zealand (Porter et al., 1993). Slafer and Rawson (1994) found large variation among wheat genotypes in the response of their ontogenetic development to the environment, and the variation could not be described in a single generic model. Considerable effort and model modification are required to make models account for discrepancies that derive from changes in cultivars, cropping conditions and peculiarities of the application environment. Some models incurred a very heavy investment in time and resources only to produce very meager if not trivial results (Seligman, 1990).

The failure of many complex crop models has, understandably, been ascribed to insufficient knowledge about the details and intricacies of the underlying physiological processes. Monteith (1981) even suggested a moratorium on crop modeling until the necessary understanding was acquired. Others, undaunted, went ahead and filled in the details, making complex models ever more complex. This approach leads to the addition of new equations or new switches to deal with the failed circumstance. The addition of all these special functions, and especially the commonly used calibration parameters, prompted de Wit (already as early as 1970) to label such efforts as the "most cumbersome method of curve fitting" to have been devised.

Validation

Finally, there is the tenet that crop models must be verified—or in the common vernacular, *validated*.¹ The fundamental difficulty is that all models are basically

¹ Although technically model validation denotes only establishment of legitimacy rather than verification, *validation* and *verification* are commonly used synonymously (Konikow and Bredehoeft, 1992).

a collection of hypotheses and not a single falsifiable hypothesis, so they inherently cannot be validated (Pease and Bull, 1992; Oreskes et al., 1994). Not only can other collections of hypotheses approximate the experimental results equally well, but the validation data themselves are flawed by substantial experimental and observational error.

Despite all these shortcomings, however, crop models can be used effectively to study the possible implications of various assumptions about a crop or an environment. This viewpoint has been explicitly adopted by the American Society of Agronomy in the editorial policy for publication of agronomic models in the *Agronomy Journal*. Modeling papers are desired that "deal with both concepts and integration of agronomic information into models," and model "validation" is not to be considered as a major factor in the acceptance of a paper (Hatfield, 1993).

Attempts to validate models can show only how well (or badly) a model performs in a particular circumstance. They cannot guarantee the performance of the model under any other environmental condition especially when the model has been calibrated to fit a specific circumstance or set of circumstances (Oreskes et al., 1994). Validation exercises are probably useful only when a model is to be moved to an applications role. The users of the model need to be given some notion of situations in which the model has proven useful, with a disclaimer for reliability in any other situation. In addition, precision levels attained in the tested situations should be indicated as maximum attainable precision. It should not be forgotten that in reality the cropping system is always changing and the error limits originally established when calibrating the model are likely to increase as new situations develop.

Overall, three of the original, basic tenets of crop models have been discredited: models are not necessarily improved by extensive reductionism, universal crop models cannot be constructed, and models cannot be validated. A new perspective on the construction and benefits of crop models is necessary.

MATURITY

Maturity brings a developing awareness not only of the limits to system behavior but also of the nature of the essential limiting factors. The ability to identify critical relationships and to separate them from the often very loud background noise can develop from the accrued life experiences of an organism and from the finite resources it has been able to sequester. Such an analogy seems appropriate to characterize the current stage of crop modeling.

We propose that the limits of crop models as surrogates for reality should be recognized and accepted as inevitable consequences of simplification. Further, because crop models can be used effectively to discover (or uncover) faulty reasoning or interesting implications about a crop, they should be viewed essentially as *heuristic tools* to aid our interpretation of reality (Wulschleger et al., 1994). That is, we envision crop models in teaching, research, and applied modes as powerful aids to reasoning about the performance of a crop or about the relative

benefits of alternative management strategies. Models allow us to set our knowledge and assumptions about the behavior of a crop in an organized, logical, and dynamic framework. After studying or using the models, it is often the case that faulty assumptions can be identified and a more structured insight to the importance of specific feedback effects can be acquired.

New insights derived from modeling exercises can be useful guides to future action, even when the model results have not yet been confirmed in reality. The heuristic value of such aid, especially in a gaming mode, is apparent when decisions in research and management must be taken in the present under conditions of limited knowledge, future uncertainty, and in the multidimensional context of biological systems in general and of crop systems in particular.

The conclusion that biological models are most useful in a heuristic role was anticipated many years ago by Imanuel Noy-Meir (unpublished technical report, 1972). In a retrospective on a workshop to develop biome models as part of the International Biological Program, Noy-Meir concluded "that the construction of the model was an exercise of great intellectual and education value for every one of the participants." This conclusion was reached in spite of the fact that no working model was produced by the workshop. In fact, Noy-Meir goes on to argue that the additional benefits to be gained by making a model operational may not even be worth the effort: "The ratio of 'total utility' to 'total effort' for models of this type is likely to be high at the construction stage, rapidly decreasing at the beginning of the operation stage" (Noy-Meir, as quoted in Innis et al., 1980). The value of the model was to force logical, quantitative thinking about the variables and processes that influence the performance of the organisms of interest.

The heuristic benefit of crop models in teaching is clear. Crop models were introduced into the classroom more than 15 years ago, and upgraded teaching models continue to be developed (e.g., Waldren, 1984; Hart and Hanson, 1990; Wulschleger et al., 1992). Crop modeling exercises are perceived by students as an effective tool for teaching factors that influence crop production (Meisner et al., 1991). Relatively simple, transparent models allow students to explore the major factors that influence crop production under various circumstances. Learning is likely to be facilitated by using a model that is simple and transparent enough in structure to allow students to dissect it and to understand the logic underlying its behavior.

Research on crop systems or subsystems can use models to organize concepts and information that reflect current understanding of the system and to determine their adequacy in explaining relevant phenomena. Shortcomings of the model can highlight important but poorly understood aspects of the crop. The model needs to be structured so that variables are physically or physiologically meaningful and can be investigated experimentally or by observation of system behavior. Crop models can then be quite useful for analyzing experimental results by virtue of their ability to substantiate possible causes of differences in the results, and so provide a level of interpretation beyond the bounds of statistical signifi-

cance that currently guide the analysis of crop experiments.

Even the use of crop models in farm management has succeeded more in an heuristic role than as an on-line decision aid. Two examples are the SIRATAC model for cotton (*Gossypium* spp.) pest management in Australia (Ives and Hearn, 1987) and the EIPRE model for wheat pest management in the Netherlands (Rabbinge and Rijsdijk, 1983). Each model required growers to pay for membership and to supply field observations to a central processing center. At the central processing center, model simulations were done to provide growers with updated pest management recommendations. In each case, there was an initial steady increase in grower membership which resulted in a general improvement in pest management. However, both systems suffered a loss of membership after the initial successes. The decline in participation has been ascribed not to dissatisfaction with the model results but to the fact that the growers felt they had learned the lessons of the models and could now manage on their own (Weiss, 1994). The models were a success in that they taught the growers improved pest management by helping them interpret their own field observations more effectively.

ATTRIBUTES OF HEURISTIC MODELING

Recognizing the role of crop models as heuristic tools in teaching, research, and applied activities makes it easier to formulate guidelines for better returns on the investment in crop modeling.

1. A clear statement of specific objectives is essential to defining the need and nature of a crop model, as indeed of any system model (Spedding, 1979). It is more likely that success will be achieved when the objectives are modest, tractable, and have a clear *raison d'être* for a modeling approach. What specific situation is to be investigated, and what problem is to be studied with the model? In an applications mode, there is little need to investigate a wide range of grower options that are not managerially or economically realistic.
2. Criteria for judging the acceptability of a model should be defined in relation to the model's objectives. In an applications mode, statistical criteria concerning model predictions relative to a sample of observations are appropriate. In a research mode, the criteria for acceptability are more ambiguous. High predictive capability may be less important than the need to identify weaknesses in conceptualization of hypotheses about particular processes. A research model is more likely to be concerned with behavioral patterns than with precise quantitative predictions.
3. The heuristic benefit will probably be greater when the modeling approach is not prejudiced by automatically using existing models. While efficiency demands that successful approaches used previously not be ignored, as new problems arise new models may need to be developed or an old model may need to be extensively modified for each new objective. This mode of operation is facilitated

when research and extension personnel are able to construct their own models, customized to specific problems and not overloaded with the considerable redundancy necessary to construct a supposedly universal or generalized crop model. These ad hoc models need not be very complex and should be as simple as the nature of the objective allows. Today, software is available for such user friendly model construction, including, for example, Wageningen software (van Kraalingen, 1995) for more complex models, or Stella (Richmond et al., 1987) for simpler problems.

4. The organizational level of the problem (tissue, organ, plant, canopy, or crop) should determine model structure. It is rare that a model objective at one level of organization cannot be achieved by modeling processes at only one subordinate level of description (the *explainable* and the *explanatory* levels of de Wit, 1970). For example, model studies of crop performance are likely to require submodels only at the subordinate plant or canopy level of detail. Increasing crop model complexity by adding lower-level and peripheral processes or by involving cellular and molecular submodels is not likely to improve model performance or relevance. Rather the contrary: Excessive complexity will obscure and even distort whatever heuristic benefit may be gained about crop performance at the desired level of interest.
5. Summary models of *emergent properties* or *conservative relationships* (Penning de Vries, 1982; Monteith, 1990) should be incorporated into models whenever appropriate. There are several summary relationships that are sufficiently robust to efficiently express underlying empirical patterns or complex theories. Examples of such summary relationships include exponential radiation interception (Monsi and Saeki, 1953), radiation use efficiency (Sinclair and Horie, 1989), transpiration-photosynthesis relationships (de Wit, 1958; Tanner and Sinclair, 1982; Monteith, 1990), and maintenance and growth respiration (Penning de Vries, 1975).

Even though such summary relationships can be reduced to greater detail, in many cases this does not lead to greater insight or improved predictability at higher levels in the model hierarchy. Summary relationships are useful because they override spurious variability at low organizational levels or short time intervals—variability that commonly is damped out and disappears at the higher organizational levels or at the longer time intervals relevant to the question of interest. Further, the more detailed expressions involve a heavy cost deriving from the need to marshal a large number of empirical coefficients that, in turn, are dependent on extensive experimental observations. Certainly, understanding interactions between the processes that determine model behavior is more accessible if the model itself is transparent (Spitters, 1990). At one extreme, Wallach et al. (1990), in a study of modeling N uptake by trees, found that the overall predictive ability of the model was maximized by using only three parameters.

Simplification, in contrast to an exaggerated reduction-

ist approach, can be useful even if the simplification is not completely correct (Weiss, 1990; Maddox, 1990). Probably the best example is that of Newtonian physics. Although fundamentally incorrect in view of modern understanding of relativity and quantum physics, the 300-year-old equations of Isaac Newton are still valuable and crucial tools in science and engineering. Simplifying assumptions that are appropriate to specific circumstances, such as Newton's equations, may result in extremely useful relationships even though they are flawed beyond a certain scale or situation.

CONCLUSION

While crop models cannot produce all the answers to crop production problems, when reasonably constructed they can be important heuristic tools in teaching, research, and in management and administrative applications. They can be used to harness hypotheses and knowledge, thereby allowing the user to reason more consistently and transparently about factors or conditions that deserve thought by students, additional experimental study by researchers, or more attention from growers. Intelligent, consistent, transparent reasoning—as well as observation, experimentation, and experience—cannot be replaced by crop models, but they can be well supported by them. Because of the large number of situations where the heuristic function of crop models can be a crucial if not an indispensable tool, we believe crop modeling can be expected to have a long and productive maturity.

REFERENCES

- Asare, D.K., T.W. Sammis, H. Assadian, and J.F. Fowler. 1992. Evaluating three cotton simulation models under different irrigation regimes. *Agric. Water Manage.* 22:391-407.
- Bell, M.A., and R.A. Fischer. 1994. Using yield prediction models to assess yield gains: A case study for wheat. *Field Crops Res.* 36:161-166.
- Bowen, H.D., R.F. Colwick, and D.G. Batchelder. 1973. Computer simulation of crop production: Potential and hazards. *Agric. Eng.* 54(10):42-45.
- Carberry, P.S., and D.G. Abrecht. 1991. Tailoring crop models to the semiarid tropics. p. 157-182. *In* R.C. Muchow and J.A. Bellamy (ed.) *Climatic risk in crop production: Models and management for the semiarid tropics and subtropics*. CAB Int., Wallingford, UK.
- Colson, J., D. Wallach, A. Bouniols, J.B. Denis, and J.W. Jones. 1995. Mean squared error of yield prediction by SOYGRO. *Agron. J.* 87:397-402.
- Cowan, I.R. 1977. Stomatal behaviour and environment. *Adv. Bot. Res.* 4:117-228.
- de Wit, C.T. 1958. Transpiration and crop yields. *Agric. Res. Rep.* 64.6. Pudoc, Wageningen, Netherlands.
- de Wit, C.T. 1965. Photosynthesis of leaf canopies. *Inst. Biol. Chem. Res. Field Crops Herb. Agric. Res. Rep.* 663. Wageningen, Netherlands.
- de Wit, C.T. 1970. Dynamic concepts in biology. p. 17-23. *In* I. Setlik (ed.) *Prediction and measurement of photosynthetic activity*. Pudoc, Wageningen, Netherlands.
- Duncan W.G., R.S. Loomis, W.A. Williams, and R. Hanau. 1967. A model for simulating photosynthesis in plant communities. *Hilgardia* 38:181-205.
- Goodall, D.W. 1976. The hierarchical approach to model building. p. 10-21. *In* G.W. Arnold and C.T. de Wit (ed.) *Critical evaluation of systems analysis in ecosystems research and management*. Pudoc, Wageningen, Netherlands.
- Goudriaan, J. 1996. Predicting crop yields under global change. *In* B.H. Walker and W. Steffen (ed.) *Global change and terrestrial ecosystems*. Cambridge Univ. Press, Cambridge.
- Hart, R.H., and J.D. Hanson. 1990. PASTORAL grazing simulator. *J. Agron. Educ.* 19:55-58.
- Hatfield, J.L. 1993. Agronomic models. *Agron. J.* 85:713.
- Innis, G.S., I. Noy-Meir, M. Godron, and G.M. Van Dyne. 1980. Total-system simulation models. p. 759-797. *In* A.I. Breymer and G.M. Van Dyne (ed.) *Grasslands, systems analysis and man*. Cambridge Univ. Press, Cambridge.
- Ives, P.M., and A.B. Hearn. 1987. The SIRATAC system for cotton pest management in Australia. p. 251-268. *In* P.S. Teng (ed.) *Crop loss assessment and pest management*. APS Press, St. Paul, MN.
- Konikow, L.F., and J.D. Bredehoeft. 1992. Ground-water models cannot be validated. *Adv. Water Res.* 15:75-83.
- Lemon, E.R., D.W. Stewart, and R.W. Shawcroft. 1971. The sun's work in a corn field. *Science (Washington, DC)* 174:371-378.
- Loague, K.M., and R.A. Freeze. 1985. A comparison of rainfall-runoff modeling techniques on small upland catchments. *Water Resour. Res.* 21:229-248.
- Loomis, R.S., and W.A. Williams. 1963. Maximum crop productivity: An estimate. *Crop Sci.* 3:67-72.
- Maddox, J. 1990. Virtue in imperfect models. *Nature (London)* 347:13.
- Mann, T. 1944. *Joseph the provider*. Translated from the German by H.T. Lowe-Porter. Alfred A. Knopf, New York.
- Mayr, E. 1982. *The growth of biological thought*. Harvard Univ. Press, Cambridge, MA.
- Meisner, C.A., K.J. Karnok, and J.N. McCrimmon. 1991. Using crop models in a beginning crop science laboratory. *J. Agron. Educ.* 20:157-158.
- Monsi, M., and T. Saeki. 1953. Über den Lichtfaktor in den Pflanzengesellschaften und seine Bedeutung für die Stoff Produktion. *Jpn. J. Bot.* 14:22-52.
- Monteith, J.L. 1981. Epilogue: Themes and variation. *Plant Soil* 58:305-309.
- Monteith, J.L. 1990. Conservative behaviour in the response of crops to water and light. p. 3-16. *In* R. Rabbinge et al. (ed.) *Theoretical production ecology: Reflections and prospects*. Pudoc, Wageningen.
- Oreskes, N., K. Shrader-Frechette, and K. Belitz. 1994. Verification, validation, and confirmation of numerical models in the earth sciences. *Science (Washington, DC)* 263:641-646.
- Pease, C.M., and J.J. Bull. 1992. Is science logical? *BioScience* 42:293-298.
- Penning de Vries, F.W.T. 1975. Use of assimilates in higher plants. p. 459-480. *In* J.P. Cooper (ed.) *Photosynthesis and productivity in different environments*. Cambridge Univ. Press, Cambridge.
- Penning de Vries, F.W.T. 1982. Phases of development of models. p. 20-25. *In* F.W.T. Penning de Vries and H.H. Van Laar (ed.) *Simulation of plant growth and crop production*. Pudoc, Wageningen, Netherlands.
- Porter, J.R., P.D. Jamieson, and D.R. Wilson. 1993. Comparison of the wheat simulation models AFRCWHEAT2, CERES-Wheat, and SWHEAT for non-limiting conditions of crop growth. *Field Crops Res.* 33:131-157.
- Rabbinge, R., and F.H. Rijdsdijk. 1983. EPIPRE: A disease and pest management system for winter wheat, taking account of micrometeorological factors. *EPPO Bull.* 13:297-305.
- Richmond, B., S. Peterson, and P. Vescuso. 1987. An academic user's guide to "Stella." High Performance Systems, Lyme, NH.
- Ritchie, J.T., D.C. Godwin, and S. Otter-Nacke. 1985. CERES-Wheat. A simulation model of wheat growth and development. Texas AM Univ. Press, College Station.
- Seligman, N.G. 1990. The crop model record: Promise or poor show? p. 249-263. *In* R. Rabbinge et al. (ed.) *Theoretical production ecology, reflections and prospects*. Pudoc, Wageningen, Netherlands.
- Sinclair, T.R., and T. Horie. 1989. Leaf nitrogen, photosynthesis, and crop radiation use efficiency: A review. *Crop Sci.* 29:90-98.
- Slafer, G.A., and H.M. Rawson. 1994. Sensitivity of wheat phasic development to major environmental factors: A re-examination of some assumptions made by physiologists and modellers. *Aust. J. Plant Physiol.* 21:393-426.
- Spedding, C.R.W. 1979. *An introduction to agricultural systems*. Applied Science Publ., London.

- Spitters, C.J.T. 1990. Crop growth models: Their usefulness and limitations. *Acta Hortic.* 267:349-362.
- Tanner, C.B., and T.R. Sinclair. 1982. Efficient water use in crop production: Research or re-search? p. 1-27. *In* H.M. Taylor et al. (ed.) *Limitations of water use in crop production*. ASA, CSSA, and SSSA, Madison, WI.
- van Keulen, H., and C.T. de Wit. 1982. A hierarchical approach to agricultural production modeling. p. 139-143. *In* G. Gobulev and I. Shvytov (ed.) *Modeling agricultural-environmental processes in crop production*. Proc. IIASA Symp., Laxenburg, Austria. IIASA, Laxenburg.
- van Kraalingen, D.W.G. 1995. The FSE system for crop simulation, version 2.1. Quantitative Approaches in System Analysis 1. DLO Res. Inst. for Agrobiological and Soil Fertility, The C.T. de Wit Graduate School for Production Ecology, Wageningen Agric. Univ., Wageningen, Netherlands.
- Waldren, R.P. 1984. CROPROD: A crop management computer model for undergraduate agronomy courses. *J. Agron. Educ.* 13: 53-56.
- Wallach, D., P. Loisel, B. Goffinet, and R. Habib. 1990. Modeling the time dependence of nitrogen uptake in young trees. *Agron. J.* 82:1135-1140.
- Weiss, A. 1990. The role of climate-related information in pest management. *Theor. Appl. Climatol.* 41:87-92.
- Weiss, A. 1994. From crop modelling to information systems for decision making. p. 285-290. *In* J.F. Griffiths (ed.) *Handbook of agricultural meteorology*. Oxford Univ. Press, New York.
- Whisler, F.D., B. Acock, D.N. Baker, R.F. Fye, H.F. Hodges, J.R. Lambert et al. 1986. Crop simulation models in agronomic systems. *Adv. Agron.* 40:141-208.
- Wilkerson, G.G., J.W. Jones, K.J. Boote, and J.W. Mishoe. 1985. SOYGRO V5.0. Soybean crop growth and yield model. Technical documentation. Agric. Eng. Dep., Univ. of Florida, Gainesville.
- Wullschlegel, S.D., P.J. Hanson, and R.F. Sage. 1992. PHOTOBIO: Modeling the stomatal and biochemical control of plant gas exchange. *J. Nat. Resour. Life Sci. Educ.* 21:141-145.
- Wullschlegel, S.D., J.P. Lynch, and G.M. Berntson. 1994. Modeling the belowground response of plants and soil biota to edaphic and climate change: What can we expect to gain? *Plant Soil* 165:149-160.

Contribution of agrometeorology to the simulation of crop production and its applications

Gerrit Hoogenboom*

Department of Biological and Agricultural Engineering, the University of Georgia, Griffin, GA, USA

Abstract

Weather has a significant impact on crop growth and development. This paper presents an overview of crop modeling and applications of crop models, and the significance of weather related to these applications. To account for the impact of weather and climate variability on crop production, agrometeorological variables are one of the key inputs required for the operation of crop simulation models. These include maximum and minimum air temperature, total solar radiation, and total rainfall. Most models use daily data as input, because variables at a smaller time scale are usually unavailable for most locations. It is important to define standard file formats for weather and other input data; this will expand the applicability of weather data by different models. Issues related to missing variables and data, as well as locations for which no data are available, need to be addressed for model applications, as it can affect the accuracy of the simulations. Weather generators can be used to stochastically generate daily data when data are missing or long-term historical data are unavailable. However, the use of observed weather data for model input will provide more precise crop yield simulations, especially for tropical regions. Many of the crop models have been applied towards strategic and tactical management decision making as well as yield forecasting. The predicted variability of crop yield and related variables as well as natural resource use is mainly due to the short- and long-term variation of weather and climate conditions. The results produced by the models can be used to make appropriate management decisions and to provide farmers and others with alternative options for their farming system. The crop models have been used extensively to study the impact of climate change on agricultural production and food security. Recently, they have also been applied towards the impact of climate variability and the effect of El Niño/Southern Oscillation (ENSO) on agricultural production and food security. It is expected that, with the increased availability of computers, the use of crop models by farmers and consultants as well as policy and decision makers will increase. Weather data in the form of historical data or observations made during the current growing season, and short-, medium-, and long-term weather forecasts will play a critical role in these applications. © 2000 Elsevier Science B.V. All rights reserved.

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1. Weather and agriculture

Weather is one of the key components that controls agricultural production. In some cases, it has been stated that as much as 80% of the variability

of agricultural production is due to the variability in weather conditions, especially for rainfed production systems (Petr, 1991; Fageria, 1992). Weather has a major impact on plants as well as pests and diseases. Before discussing the contribution of agrometeorology to the simulation of crop production, it is important to summarize the potential effect of the different weather variables on crop growth and development.

* Tel.: +1-770-229-3438; fax: +1-770-228-7218.

E-mail address: gerrit@griffin.peachnet.edu (G. Hoogenboom)

The critical agrometeorological variables associated with agricultural production are precipitation, air temperature, and solar radiation. Air temperature is the main weather variable that regulates the rate of vegetative and reproductive development (Hodges, 1991). In most cases, an increase in temperature causes an increase in the developmental rates. At extremely high temperatures, the inverse occurs, and developmental rates slow down as the temperature further increases. Solar radiation provides the energy for the processes that drive photosynthesis, affecting carbohydrate partitioning and biomass growth of the individual plant components (Boote and Loomis, 1991). Photosynthesis is normally represented through an asymptotic response function, with a linear response at low light levels.

Precipitation does not directly control any of the plant processes. It is considered to be a modifier, that indirectly affects many of the plant growth and developmental processes. Drought occurs during periods of insufficient rainfall, while water logging occurs during periods of extensive rainfall. Drought stress in plants is a result of a combination of factors, such as potential evapotranspiration, extractable soil moisture in the rooting zone, root distribution, canopy size, and other plant and environmental factors. Drought can cause an increase or decrease in developmental rates, depending on the stage of development. In many cases, the response to drought stress is also a function of species or cultivar, as some species or cultivars are more drought-tolerant than others. Drought can also reduce gross carbon assimilation through stomatal closure, causing a modification of biomass partitioning to the different plant components. Water logging stress is caused by flooding or intense rainfall events. It can cause a lack of oxygen in the rooting zone, which is required for root growth and respiration. A decrease in oxygen content in the soil can result in a decrease in root activities, causing increase in root senescence and root death rates. The overall effect of water logging is a reduction in water uptake; the ultimate impact is similar to the drought stress effects discussed earlier.

Other weather factors that can affect crop production include soil temperature, wind, and relative humidity or dew point temperature. In many regions, soil temperature is important during the early part of the growing season, as it affects planting and germination. For winter crops, such as winter wheat, the soil tem-

perature can also affect vernalization. Relative humidity, dew point temperature or vapor pressure deficit are similar agrometeorological factors, that express the amount of water present in the air. They affect transpiration and the amount of water lost by the canopy, causing drought stress under water-limited conditions as discussed previously. They can also influence biotic stresses, such as the presence as well as the activity of pests and diseases. At harvest maturity, both air and dewpoint temperature affect the dry down time of the harvestable product. In some cases, extreme rainfall can make a crop unharvestable, when farmers are unable to enter the field due to saturation of the top soil. Wind can also have a multiple impact on crop production. First of all, it can affect the rate of transpirational water loss by the leaves. In addition, it can affect the transport and the distribution of insects and diseases in the atmosphere, and subsequent presence in the plant canopy. Extreme wind can also affect the potential for lodging, especially for tall crops. Potential evapotranspiration is a very important agrometeorological variable. However, it is a derived value based on other weather variables, such as solar radiation, air temperature, wind speed, and vapor pressure deficit (Penman, 1948; Priestley and Taylor, 1972; Linacre, 1977). It is critical that most or all of the processes discussed here are included in a model, so that they can simulate the potential impact of weather conditions on plant growth and development and resource use.

2. Crop simulation models and weather

Computer models, in general, are a mathematical representation of a real-world system (Mize and Cox, 1968). In reality, it is impossible to include all the interactions between the environment and the modeled system in a computer model. In most cases, a computer model, therefore, is a simplification of a real-world system. A model might include many assumptions, especially when information that describes the interactions of the system is inadequate or does not exist. Depending on the scientific discipline, there are different types of models, ranging from very simple models that are based on one equation to extremely advanced models, that include thousands of equations. For instance, in the aerospace industry, computer models are used to design the entire structure of an

airplane and simulate its operation prior to even being built. As airplanes and their interactions with the areal environment mainly deal with the laws of physics, engineering principles can be applied. However, agriculture involves biological factors for which, in many cases, the interactions with the environment are unknown. The science of plants and crops represents an integration of the disciplines of biology, physics, and chemistry. Plant and crop simulation models are a mathematical representation of this system.

One of the main goals of crop simulation models is to estimate agricultural production as a function of weather and soil conditions as well as crop management. The weather variables discussed previously, such as air temperature, precipitation, and solar radiation, are, therefore, key input variables for the simulation models. We would like to define these as primary weather input variables and to define the other input variables, including wind speed, relative humidity or dewpoint temperature, open pan evaporation, and soil temperature, as secondary weather input variables. Some scientists consider relative humidity also as a primary variable, because of its impact on plants as well as on pests, especially diseases. A critical issue is the availability of weather data to be able to run crop simulation models for a certain location or for a particular application. Especially, the secondary weather variables are measured at only a few sites. Although the primary variables are measured at most locations, solar radiation is sometimes missing. A good substitute for solar radiation is sunshine hours, which can be used to estimate solar radiation if the Angström coefficients are known. Many agricultural sites where weather stations have been installed record maximum and minimum temperature as well as precipitation at least once a day.

3. Weather data for modeling

3.1. Data sources

The national meteorological organizations, such as the National Weather Service (NWS) in the US, are the most common source of weather data for modeling applications. Unfortunately, most of these weather stations are located at airports, as their primary duty

is to serve the aviation industry. In general, airports are located around large cities and the conditions at airports are not very representative for the main agricultural production regions, due to buildings, runways and other developmental structures normally found around airports. The weather stations at airports are first-order stations; both primary and secondary weather input variables are collected either manually or through automated procedures. The national meteorological organizations also operate other types of weather stations that measure weather variables. In some cases, these weather station networks are mainly located in more remote locations. For instance, in the US, the NWS maintains a Cooperative Climate Network. A volunteer observer reads the maximum and minimum thermometers and rain gauge once or twice a day, either in the morning or late in the afternoon. This provides a combined summary of yesterday's and today's weather data, although all data are reported with yesterday's date. For many of these sites, long-term records exist, going back at least 50–100 years (EarthInfo, 1998). For many European networks, weather records exist for several centuries.

The emphasis of the national meteorological organizations on serving the aviation industry and the lack of weather data for agricultural environments, has led to the development of automated weather station networks (Tanner, 1990). These networks are mainly operated by national agricultural institutes, universities, private industry and farmers (Meyer and Hubbard, 1992). The weather data collected by the weather stations of these networks have been one of the main sources for primary and secondary weather input data for crop simulation models. Unfortunately, most automated weather networks were developed during the last 10–15 years, so no long-term weather records exist. The networks, in general, are also not compatible, due to differences in instrumentation, sensor height and data logging. This makes it more difficult to use the data collected by automated weather station networks for modeling applications (Ley et al., 1994).

3.2. Time scale of data

The time scale of weather data used for modeling applications is also important. Many long-term weather records are based on daily observations. As a result, most crop simulation models are restricted

with respect to their weather inputs, due to the lack of detailed weather data recorded at hourly or shorter intervals. They, therefore, use daily weather data as input, although they might operate internally at smaller time steps (Hunt et al., 1994). The use of weather input data reported at time intervals longer than 1 day has shown to be unacceptable for modeling applications. The use of monthly weather data for model input resulted in large under- and overestimations of yield (Nonhebel, 1994a). Several models have been developed to calculate hourly temperature values through the interpolation of the daily maximum and minimum temperature extremes, using either half-sine curves or other curve fitting techniques (Floyd and Braddock, 1984; Fernández, 1992; Ephraïm et al., 1996). These hourly temperatures can then be used as input for a model, or the interpolation functions can be included in the model. For instance, the grain legume simulation model CROPGRO calculates vegetative and reproductive development at hourly time steps based on hourly temperature values, although the model uses daily maximum and minimum temperature data as input (Boote et al., 1997).

Several soil physical models that simulate a detailed soil water balance, especially runoff, drainage, and water flow, use time intervals as small as 1 s, depending on the dynamics of changes in moisture and water flow in the soil profile (De Jong and Bootsma, 1996). These models sometimes require that rainfall is presented as breakpoint data in a special precipitation file. For each rainfall or storm occurrence, both the intensity and the duration of this event are needed (Singh and Kanwar, 1995; Agnese and Bagarello, 1997; Hanson et al., 1998). Although it is beyond the scope of this paper, the accuracy of the input data has an impact on the accuracy of the simulated results (Nonhebel, 1994b, c). Also, differences in observations between different sensors that measure the same variable (Bruton et al., 1998; Llasat and Snyder, 1998) can affect the accuracy of the simulated results.

3.3. Data standards for crop modeling

The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) Project initiated an effort to define a minimum data standard for crop model applications (ICRISAT, 1984; IBSNAT, 1990a, b). This standard includes a minimum set for weather

data, consisting of maximum and minimum air temperature, solar radiation, and precipitation. It also defines specific formats for the structure and the naming convention of files, including the weather files (Jones et al., 1994; Hunt and Boote, 1998). Various other modeling groups, such as the Global Change and Terrestrial Ecosystems (GCTE, 1994) Committee and the Commission on Global Change Data (CODATA) (Hunt et al., 1994; Uhler and Carter, 1994), have adapted this file format. GCTE is especially interested in developing experimental data sets that can be used for the evaluation of various crop models for climate change applications. For these types of comparisons, it is critical that uniform file formats and data standards are defined. GCTE's effort has already led to an easy exchange of model input data between different models and has provided opportunities for collaboration between modeling groups (Semenov et al., 1996; Wolf et al., 1996; Jamieson et al., 1998). The recently established International Consortium for Agricultural Systems Applications (ICASA) (Ritchie, 1995), a collaboration between the 'De Wit School' of modelers and the IBSNAT modeling group, has led to the development of an improved set of input file standards and data formats that can be used as input data for all models, developed by both groups. Similar recommendations for data standards as well as software that use weather and other environmental data as inputs were made by Maracchi and Sivakumar (1995). Unfortunately, they were not very successful in their implementation.

3.4. Weather generators

It is important to use observed historical weather data for all modeling applications, except for those related to prognostic applications. However, in many cases, the availability of these weather data might be limited. Sometimes, the period of record is too short to conduct a modeling application, long periods of records are missing, or only monthly averages and totals are available. In other cases, only a few variables are recorded, such as rainfall and maximum and minimum temperatures, or in the worst case, only daily rainfall. In all these situations, weather generators can be used to generate daily rainfall, maximum and minimum temperatures, and solar radiation. A significant amount of research has, therefore, been spent

on the development and evaluation of weather generators (Meinke et al., 1995).

All weather generators require some type of local climate data as input to define the monthly mean values and associated variability over time for each weather variable. The most common weather generators that have been used include WGEN (Richardson, 1981, 1985), Simmeteo (Geng et al., 1986), CLIGEN (Johnson et al., 1996) as well as various other weather simulation models (Peiris and McNicol, 1996; Duvrosky, 1997; Friend, 1998; Semenov et al., 1998). The accurate generation of precipitation, both the occurrence of an event as well as the amount, is the most difficult task, especially for tropical and sub-tropical regions (Arnold and Elliot, 1996; Schmidt et al., 1996; Jimoh and Webster, 1997). Several improvements of existing simulators that include a higher order Markov model to account for the high variability of tropical precipitation have been developed (Jones and Thornton, 1997; Schmidt et al., 1997). Several weather generators have been integrated in weather utility programs that analyze and prepare weather data for model applications, such as WeatherMan (Pickering et al., 1994). They have also been incorporated in several simulation models such as the CROPGRO and CERES models (Hoogenboom et al., 1994) or are an integral part of a modeling or decision support system (Tsuji et al., 1994; Baffaut et al., 1996).

4. Modeling approaches

Crop models, in general, integrate current knowledge from various disciplines, including agrometeorology, soil physics, soil chemistry, crop physiology, plant breeding, and agronomy, into a set of mathematical equations to predict growth, development and yield. Baier (1979) provided some interesting background and terminology for what he called 'crop-weather models'. The paper is based on a review for a World Meteorological Organization (WMO) expert meeting on crop-weather models, held in Ottawa, Canada in 1977. Baier (1979) distinguished between crop growth simulation models, crop-weather analysis models, and empirical-statistical models.

Crop growth models are physiologically based, in that they calculate the causal relationships between the various plant functions and the environment. The

opposite would be a statistical approach, using correlative relations between all processes. Crop models can also be identified as being deterministic, in that they make an exact calculation or prediction. In this case, the opposite would be stochastic or probabilistic models, which provide a different answer for each calculation. Crop models are simulation models, in that they use one or more sets of differential equations, and calculate both rate and state variables over time, normally from planting until harvest maturity or final harvest. Some of the earliest crop simulation models simulated only photosynthesis and a simple carbon balance over time. Other processes, such as vegetative and reproductive development and the plant water balance, were added at a later date (Duncan et al., 1967; Curry, 1971; Curry and Chen, 1971; Splinter, 1974).

Ritchie (1994) identified three types of deterministic models. The first type are statistical models, which have been used to make large-area yield predictions. To develop these models, final yield data are correlated with the regional mean weather variables (Thompson, 1969a, b, 1970). On account of its many limitations, this statistical approach has slowly been replaced with the use of simple or more complex simulation models (Abbaspour et al., 1992). Mechanistic models include mathematical descriptions of most of the plant growth and development processes as they are currently known in the field of plant sciences. These models have mainly been used in research applications, and are not very practical for agricultural applications at a farm level. Ritchie's (1994) third category consists of the functional models. These models include simplified equations or empirical relationships to represent the various complex plant processes and their interactions with the environments.

The 'School of De Wit' (de Wit and Goudriaan, 1974; Bouman et al., 1996) defines four different levels or facets with respect to the evolution of plant growth models (Penning de Vries and van Laar, 1982; Penning de Vries et al., 1989). In Phase 1, temperature and solar radiation are used as inputs to simulate growth and development and to calculate potential production. Growth in this case only includes the simulation of the plant carbon balance. In Phase 2, precipitation and irrigation are added as an input, and the soil and plant water balances are simulated. In Phase 3, soil nitrogen is added as an input to simulate growth and development, the soil and plant water

balance, and the soil and plant nitrogen balance. In Phase 4, other soil minerals are added as inputs as well as pests, diseases, and weeds. In this phase, the complete soil–plant–atmosphere system is simulated, including interactions with most of the biotic and abiotic components.

There are hardly any crop simulation models that currently operate at Phase 4. This is mainly due to the complexity of the soil–plant–atmosphere system. Most of the widely used crop simulation models, such as those included in the Agricultural Production System Simulator (APSIM) (McCown et al., 1996), the Decision Support System for Agrotechnology Transfer (DSSAT) version 3 (Tsuji et al., 1994; Jones et al., 1998), the Simulation and Systems Analysis for Rice Production (SARP) models (Kropff et al., 1994; Riethoven et al., 1995), and the ‘School of de Wit’ crop models (van Keulen and Seligman, 1987; Bouman et al., 1996), have only reached Level 3. The models in these systems simulate crop growth and development as well as the soil and plant water and nitrogen balances (van Keulen, 1982; Godwin and Singh, 1998; Probert et al., 1998; Ritchie, 1998). A few models include one or more processes at Level 4, such as the model Ecosys (Grant and Heaney, 1997) and a preliminary version of CERES (Gerakis et al., 1998); both models present a simulation of the phosphorus balance. Several models also include the option to simulate the impact of pest and disease damage (Teng et al., 1998), such as CROPGRO (Batchelor et al., 1993; Sridhar et al., 1998) CERES-Rice (Pinnschmidt et al., 1995) and ORYZA (Ehlings and Rubia, 1994). When pest and disease simulations are added to a model, additional weather variables might be needed as inputs, such as relative humidity or dew point temperature. Modeling of the interaction between crops and weeds has only been addressed at a limited scale (Kropff and Lotz, 1992; Kropff and van Laar, 1993; Oryokot et al., 1997).

It is expected that progress towards including the simulation of additional processes in the current simulation models will be slow. As models become more complex by including the simulation of more processes, the requirement to define input data for these new processes also increases (Hunt, 1994). Although model users would like to be able to simulate the complete soil–plant–atmosphere continuum, they normally have a very difficult time in obtaining the input param-

eters required to simulate these processes (Hunt and Boote, 1998). Computer modelers have a tendency to request input information for their simulation models that, in many cases, is not available. The lack of adequate input data requires that some of these model inputs have to be scaled back to the level at which input data are available. One of the examples is the request for hourly weather data for some models, but the existence of only daily weather data for real-world applications. Maintaining an even balance between the level and the amount of user-supplied input data (Hoogenboom, 1998) and the complexity and details of the modelled processes, will remain a delicate issue. It is also important to keep a balance between all the processes that are simulated by a model, so that they contain the same amount of details (Monteith, 1996). One needs to keep in mind that this approach might require different types of models for different applications, depending on the complexity of the problem that is being investigated (Boote et al., 1996).

One recent advancement in model development has been the change towards modularity. Although this concept has originated through object-oriented modeling (Hodges et al., 1992; Waldman and Rickman, 1996; Acock and Reddy, 1997), the trend now seems to have changed towards developing modules that can be exchanged between different modeling systems (Timlin et al., 1996; Acock and Reynolds, 1997). The APSIM system is built on the premise that the user can build a model, based on a selected set of modules that simulate the various plant and soil processes (McCown et al., 1996; Keating et al., 1997). A similar approach is also being implemented in the CROPGRO model for grain legumes (Boote et al., 1997).

5. Applications and weather

Crop simulation models can play an important role at different levels of applications, ranging from decision support for crop management at a farm level to advancing understanding of sciences at a research level. Weather data are the most important input data for all these applications of the simulation models. The main goal of most applications is to predict final yield in the form of either grain yield, fruit yield, root or tuber yield, biomass yield for fodder, or any other harvestable product. In some cases, associated vari-

ables, such as resource use or the impact of pollution on the environment, might also be of interest. Certain applications link the price of the harvestable product with the cost of inputs and production to determine economic returns. One application is the use of crop simulation models for policy management. As most of the applications discussed in this paper include some type of policy issue, we will not address policy applications separately. Some specific applications of models related to policy issues can be found in de Wit et al. (1987) and Rabbinge and van Laatesteijn (1992). The discussion of research applications of crop models is also beyond the scope of this paper. Readers are referred to Loomis et al. (1979) and Boote et al. (1996), and others for further discussions on this topic.

In general, the management applications of crop simulation models can be defined as strategic applications, tactical applications, and forecasting applications. In strategic applications, the crop models are run prior to planting of a crop to evaluate alternative management strategies. In tactical applications, the crop models are run before planting or during the actual growing season. Both strategic and tactical applications provide information for decision making by either a farmer, consultant, policy maker, or other person involved directly with agricultural management and production. Forecasting applications can be conducted either prior to planting of a crop or during the growing season. The main objective is to predict yield; this information can be used at a farm-level for marketing decisions or at a government level for policy issues and food security decisions.

5.1. Strategic applications

In strategic applications of crop simulation models and decision support systems, the models are mainly run to compare alternative crop management scenarios. This allows for the evaluation of various options that are available with respect to one or more management decisions (Tsuiji et al., 1998). To account for the interaction of these management scenarios with weather conditions and the risk associated with unpredictable weather, simulations are conducted for at least 20–30 different weather seasons or weather years (Jame and Cutforth, 1996). In most cases, daily historical weather data are used as input and the assumption is made that these historical weather data will repre-

sent the variability of the weather conditions in the future. When no long-term daily historical weather data are available, a weather generator can be used to generate daily weather variables. With the use of multiple weather years, the model will calculate one set of outcomes for each weather year. As a result, various statistical values can be calculated for each simulated variable, such as the mean and the standard deviation as well as the distribution in the form of percentiles or cumulative probability distributions. In addition, the biological outputs and management inputs can be combined with economic factors to determine the risk associated with the various management practices that are being evaluated (Gold et al., 1990; Jones, 1993; van Noordwijk et al., 1994; Lansigan et al., 1997; Selvarajan et al., 1997; Thornton and Wilkens, 1998).

5.1.1. Seasonal analysis

In the seasonal analysis applications, a management decision is evaluated for a single season (Aubrey et al., 1998). This can include both crop and cultivar selection; plant density and spacing; planting date (Egli and Bruening, 1992); timing and amount of irrigation applications; timing, amount and type of fertilizer applications (Hodges, 1998); and other options that a particular model might have. Applications can also include investment decisions, such as those related to the purchase of irrigation systems (Boggess and Amerling, 1983). Thornton and Hoogenboom (1994) describe a special software program that was developed for seasonal analysis applications of the DSSAT crop simulation models (Tsuiji et al., 1994), but can also be applied to outputs produced by other models.

5.1.2. Sequence analysis

In the sequence or crop rotation analysis, one or more crop rotations can be analyzed. In this mode, different cropping sequences are simulated across multiple years (Plentinger and Penning de Vries, 1997). It is critical that, in a crop rotation analysis, the water, nitrogen, carbon and other soil balances are simulated as a continuum. The main goal of a cropping sequence application is to determine the long-term change of soil variables as a function of different crop rotation strategies (Bowen et al., 1993, 1998; Probert et al., 1995). Several models have been specifically developed to study the long-term dynamics of nitrogen and organic matter in the soil, such as the CENTURY model (Cole

et al., 1993; Gijssman et al., 1996; Yiridoe et al., 1997). One of the disadvantages of these models is that they do not predict crop yield or predict yield using very simplistic methods. Other modeling systems, such as CropSyst (Stockle et al., 1994; Donatelli et al., 1997), Ecosys (Grant, 1997), and the Erosion Prediction Impact Calculator (EPIC) (Jones et al., 1991) were specially developed to study the long-term sustainability of cropping systems. Thornton et al. (1995) present a general sequence analysis tool for crop simulation models. It has been implemented in the DSSAT suite of models (Hoogenboom et al., 1994), but can also be applied to other modeling systems.

Weather again plays a key role as input for these long-term crop rotation and crop sequencing simulations. One can use a sequence of observed historical weather data to simulate a particular long-term crop rotation. This would be applicable for evaluating the performance of a modeling system with data from long-term crop rotation trials (McVoy et al., 1995). In this case, the weather conditions observed during these long-term crop rotation trials as well as the crop management scenario would be used as inputs for the crop rotation modeling study. However, this will allow for the simulation of only one weather sequence. To account for the interaction of weather with crop rotations and to evaluate different crop rotation management scenarios, it is not possible to use historical weather data as input. Instead, a weather generator has to be used and different weather sequences have to be generated, using a different 'seed' or random number to initiate the weather generator at the start of each sequence of weather years.

5.1.3. Spatial analysis

One of the limitations of the current crop simulation models is that they can only simulate crop yield for a particular site for which both weather and soil data as well as crop management information is available. One recent advancement is the linkage of crop models with a Geographic Information System (GIS). A GIS is a spatial data base, in which the value of each attribute and its associated *x*- and *y*-coordinates are stored. It is not within the scope of this paper to discuss the various GIS and modeling approaches. The latest state-of-the-art of linkages between agricultural models and GIS can be found in Hartkamp et al. (1999). This approach has opened a whole new field of crop

modeling applications at a spatial scale, from the field level for site-specific management (Han et al., 1995; Thornton et al., 1997a) to the regional level for productivity analysis and food security (Lal et al., 1993; Stoorvogel, 1995; Engel et al., 1997; Georgiev et al., 1998).

Weather and climate play an integral part in the spatial application of crop models. As weather is measured at a weather station, it represents 'point' information. One can assume that the weather data collected at this site are representative for either a small area, such as a field, or a larger area, such as a district or a province. However, the latter might not be a valid assumption. If weather data are observed at more than one weather station in the region, one can interpolate the weather data between the weather stations prior to the application (Carbone, 1993). The other option is to run the crop models for the various unique areas and interpolate the results after the simulation. An important concern is the simulation for areas for which no weather or long-term climate records exist (Hutchinson, 1991). The handling of 'spatial' weather data for modeling applications is an important issue that has not been resolved yet. Most of the studies that have been conducted so far have dealt with handling climate variability at a spatial scale and determining spatially-based input parameters for weather generators (Hutchinson, 1995; Guenni et al., 1996; Mackey et al., 1996; Guenni, 1997; Wilks, 1998).

5.2. Tactical applications

In tactical applications, the crop models are actually run prior to or during the growing season to help farmers, producers, and consultants make management decisions. One of the main objectives is to integrate the growth of a crop with the current observed weather conditions, and to decide on a daily basis as to which management decisions should be made. Although we know the weather conditions for the previous days, we do not really know what the future weather conditions will be like, except for predictions provided by the weather forecasts. We have to deal with this uncertainty of weather conditions in our modeling application as well. Therefore, for any crop model run, only the weather data up to the previous day will be available. If the weather forecasts are provided in some type of quantitative format, they can also be included

with the simulation. There are various methods for handling the uncertainty of future weather conditions. The first one is to use historical weather data and to run the system for multiple years. Instead of historical weather data, generated data can also be used. If multiple years of historical or generated weather data are used as input, a mean and associated error variable can be determined for predicted yield as well as for other predicted variables. Over time, the error will become smaller, as the uncertain weather forecast data are being replaced with observed weather variables. If two or more management alternatives are being compared, one can evaluate the risk associated with each management decision, using both mean and error values of each predicted variable.

Most of the tactical decisions during the growing season are related to irrigation management and nitrogen fertilizer management, because of the limitations of the crop models discussed previously (Boggess and Ritchie, 1988; Scheierling et al., 1997; Smith, 1997). Boggess et al. (1983), Swaney et al. (1983) and Fortson et al. (1989) describe various applications related to irrigation scheduling during the growing season, using the soybean crop growth simulation model SOYGRO (Wilkerson et al., 1983; Hoogenboom et al., 1992). An irrigation example of the maize crop growth model CERES-Maize (Jones and Kiniry, 1986; Ritchie et al., 1998) is presented by Epperson et al. (1993). Unfortunately, these irrigation decisions were never applied by farmers. Abrecht and Robinson (1996) present an application for tactical decision making in wheat, using the wheat crop growth model CERES-Wheat (Ritchie et al., 1998).

5.2.1. *On-farm management*

One of the most successful applications of a crop simulation model for on-farm management, especially related to in-season and tactical decisions, is the GOSSYM–COMAX system (Boone et al., 1993; Reddy et al., 1997). GOSSYM is a dynamic crop simulation model for cotton, and COMAX is an expert shell that handles the interactions with the user. The GOSSYM–COMAX system was developed to aid cotton farmers with their irrigation and nitrogen management decisions (Usrey et al., 1994; Staggenborg et al., 1996; Stevens et al., 1996). Other options have since been added, such as the application of growth regulators (Reddy et al., 1995b). GLYCIM, a sister

model of GOSSYM that simulates soybean growth and development, was also released for on-farm applications (Reddy et al., 1995a).

Cotton is a high cash crop that requires many inputs during the growing season. Therefore, optimizing the crop inputs, using either crop simulation models, expert systems, or other decision support systems, can significantly benefit a farmer. Many other crops, especially those grown under rainfed conditions, require hardly any inputs during the growing season. Therefore, the application of crop simulation models as a tactical management tool does not provide much benefit for farmers, except for possibly the management of pests and diseases. Unfortunately, the transfer of the GOSSYM–COMAX technology to the private sector was not successful, although most of the farmers who ran the system seemed to have learned from their use and application on their farm. In general, farmers do not want to pay for weather-related services, including the access and use of crop simulation models.

In the area of pest and disease management, especially integrated pest management (IPM), the application of models has been shown to be very profitable. Most IPM models do not include a crop model component that predicts yield and they are, therefore, not considered crop simulation models. However, in many cases, they include degree day calculators to determine the actual stage of a crop (Pusey, 1997). As the application of pesticides is rather expensive, farmers are interested in minimizing the application of pesticides, both from an economic viewpoint as well as from an environmental viewpoint. In the early 1980s, a system to spray for pests and diseases in winter wheat was developed in The Netherlands (Rabbinge and Carter, 1984; Zadoks et al., 1984). This system, called EIPRE, was extended to other countries in Europe, although there was a significant difference in climatic conditions between these countries (Zadoks, 1989). Unfortunately, the discussion of successful IPM models for on-farm management is beyond the scope of this paper (Coulson, 1992; Berry, 1995; Ende et al., 1996; Rabbinge and van Oijen, 1997).

The United Soybean Board (USB), an American farmers' organization responsible for managing soybean checkoff funds, recently sponsored a project for the development of a soybean decision support system for on-farm applications, based on

the CROPGRO-Soybean model (Boote et al., 1997). PCYield is a tactical management decision tool that allows a farmer to make irrigation decisions and provides an expected yield (Jacobson et al., 1997). It requires current weather data from either a soybean field or farm as input and uses 10 years of historical weather data from a local weather station for the remainder of the growing season. A private company has shown interest in PCYield. During the 1997 and 1998 growing season, it conducted preliminary evaluations with various soybean producers. Based on the interest shown by farmers, a PCYield for maize based on the CERES-Maize model (Ritchie et al., 1998) has been developed and extension of PCYield for other crops is currently being discussed. One of the main advantages of this company is that it can provide local weather data via one of its subsidiaries, Weather Services International (WSI). WSI is one of the main commercial weather data suppliers in the US. It has developed a technology that allows it to provide daily weather data at a 2 km grid level for the entire US. Both the weather data as well as the simulations are delivered via the Internet. It is expected that delivery of weather data via the world wide web as well as the operation of simulation models via the world wide web will be new agrotechnologies for the near future (Georgiev and Hoogenboom, 1998, 1999).

5.3. Forecasting applications

The application of crop simulation for forecasting and yield prediction is very similar to the tactical applications discussed previously. However, in the tactical decision application, a farmer or consultant is mainly concerned about the management decisions that are made during the growing season. In the forecasting application of the crop models, the main interest is in the final yield and other variables predicted at the end of the season. Most of the national agricultural statistics services provide regular updates during the growing season of total acreage planted for each crop as well as the expected yield levels. Based on the expected yield, the price of grain can vary significantly. It is important for companies to have a clear understanding of the market price so that they can minimize the cost of their inputs. Traditionally, many of the yield forecasts were based on a combination of scouting reports as well as statistical techniques. However, it seems that

crop simulation models can play a critical role in crop yield forecasting applications if accurate weather information is available, both with respect to observed conditions as well as weather forecasts (Nichols, 1991; Abawi et al., 1995).

The weather data for yield forecasting applications is handled in a manner very similar to the one for the weather data for tactical decision making applications. During the actual growing season, the current weather data up to the previous day are used as input. For the remainder of the season, either historical weather data or generated weather data are used (Duchon, 1986). In some cases, some type of short-term or long-term weather forecast might be available, which can be used to modify the weather data inputs to represent future conditions. Most weather forecasts are available in a qualitative format, and the crop models actually require weather inputs in a quantitative format. More work will be needed to transform the weather forecasts, both short-term and long-term forecasts, into a format that can be used by crop simulation models.

One of the most recent applications of models for yield prediction is for the Famine Early Warning System (FEWS). FEWS is currently being implemented for Africa, especially the drought prone areas in the Sudan-Sahelian countries. Thornton et al. (1997b) describe a prototype application to predict yield for millet production in Burkina Faso, using the CERES-Millet model. Due to the lack of current weather data, especially precipitation, decadal data had to be transformed into daily rainfall data. Most of the research related to the prediction of food security has concentrated on improving the local weather forecasts (LeComte, 1994). However, it will be important to link the crop simulation models to the local short- and long-term weather forecasts. This will improve the yield predictions and provide policy makers with advanced yield information to help manage expected famines and other associated problems.

The Department of Science and Technology (1990) in India has developed a very strong program in medium-range weather forecasting and agrometeorological services. It currently is in the process of linking the medium-range weather forecasts with crop simulation models. It is expected that the Center for Medium-Range Weather Forecasting will be able to provide crop model-based yield forecasts and

recommendations that can be used by local extension personnel and farmers (Gadgil et al., 1995).

5.3.1. Remote sensing

Accurate application of crop simulation models requires, in many cases, some type of evaluation of the model with locally collected data. Especially for yield forecasting, it is critical that yields are predicted accurately, as policy decisions related to the purchase of food could be based on the outcome of these predictions. One option is to use remotely sensed data, that are being used to estimate yield, based on a greenness index (Smith et al., 1995). A more advanced application would be to link physical remote-sensing models with crop simulation models (Bouman, 1992). With this approach, the simulated biomass can be adjusted during the growing season, based on remotely sensed or satellite data, and yield predictions can be improved based on these adjusted biomass values (Bouman, 1992, 1995; Maas, 1993; Baumgardner, 1994). One of the limitations of this linkage is that simulations are point-based applications, while remotely-sensed data are spatially based (Guerif and Duke, 1998). This problem is similar to the spatial applications of the crop models discussed earlier. There still seems to be a gap in collaboration between crop modelers and scientists with expertise in remote sensing (Moran et al., 1995; Carbone et al., 1996). For future applications in yield forecasting, it will be critical that the weather forecasts, remotely sensed information, and the crop simulation models are closely integrated in effective forecasting tools for yield prediction, famine early warning and other potential food disasters.

6. Climate change and climate variability

The variability of our climate and especially the associated weather extremes is currently one of the concerns of the scientific as well as the general community (Climate Research Committee, 1995). The application of crop models to study the potential impact of climate change and climate variability provides a direct link between models, agrometeorology and the concerns of society. Early reports related to the impact of climate change used surveys of climatologists and

agricultural scientists (National Defense University, 1978). As climate change deals with future issues, the use of general circulation models (GCMs) and crop simulation models provides a more scientific approach to study the impact of climate change on agricultural production and world food security compared to surveys (Curry et al., 1990a; Kaiser and Drennen, 1993; Matthews et al., 1995; Rosenzweig et al., 1995; Downing, 1996; Goudriaan, 1996). Similarly, the issue of climate variability, especially related to the variation in sea surface temperature (SST) of the Pacific Ocean or El Niño/Southern Oscillation (ENSO), has opened an area where crop simulation models also can play an important role. They can potentially be used to help determine the impact on agricultural production due to ENSO and recommend alternative management scenarios for farmers that might be affected, thereby mitigating the expected impact of ENSO.

6.1. Climate change applications

The early generation of crop simulation models were not intended for use in climate change applications. One of the main reasons is that most models did not respond to changes in the carbon dioxide concentration of the atmosphere. The models were also developed to only simulate the effect of weather conditions similar to the local environments where they were originally evaluated. As a result, many of the relationships incorporated in the models could not handle any temperature extremes, either high or low temperatures, which were being predicted by the climate change scenarios. Modifications, therefore, were made in various models, such as EPIC (Stockle et al., 1992b) and the CERES-Maize and SOYGRO models (Peart et al., 1988). A special DSSAT was developed to handle issues related to climate change (Hoogenboom et al., 1995). More research is still needed to evaluate the performance of the models for these types of conditions. Very limited information is available with respect to modeling the impact of climate change on pests, diseases and weeds (Goudriaan and Zadoks, 1995).

In most climate change applications, long-term historical weather data are used as input for the crop models. In general, at least 30 years of historical weather data are preferred to represent annual weather variability; different climate change scenarios can then be

applied to these data records. The simplest approach is to assume a fixed climate change and to modify the data with a constant number, such as an increase or decrease of 1, 2, 3°C etc. for temperature. Similarly, rainfall and solar radiation can be changed with a certain percentage, such as an increase or decrease of 10, 20, 30% etc. These changes are then applied to the daily weather data and the crop simulation models are run with these modified inputs. A more realistic approach is to use the outputs from the GCMs to modify the historical weather data (Robock et al., 1993). The predictions of the GCMs in general can represent both current and future climate conditions as well as the expected climate change. The GCM predictions normally only provide monthly changes, which are in absolute terms for temperature and in relative terms for solar radiation and precipitation. These GCM predictions are again applied to the historical weather data and the modified historical weather data are used as input for the crop simulation models (Curry et al., 1990b; Mearns et al., 1992). The models can then be run, using various climate change scenarios. These include the standard historical weather data, the standard historical weather data and a doubling of the CO₂ concentration, GCM-modified historical weather data, and the GCM-modified historical weather data and a doubling of the CO₂ concentration. In addition, different GCM scenarios can be created with different GCMs (ANL, 1994). Some recent applications include the use of weather generators, rather than using historical weather data, to generate climate change scenarios (Riha et al., 1996; Mearns et al., 1997). In this case, one can account for both the mean change as well as the change in variability. The latter might especially be critical with respect to precipitation.

There are various issues related to the climate change scenarios, predicted by the GCMs, and the actual implementation in crop simulation models. There are several GCMs, developed by different climate groups in various countries, and some models have different versions, based on when they were released. Unfortunately, each climate model predicts a different climate change scenario. Several GCM models do not predict the local climate very well, so some type of GCM model evaluation is needed with local climate data (Mearns et al., 1995b; Alexandrov et al., 1999). Another concern is that the spatial scale of most GCMs is rather large. In some cases, the scale

of one climate or grid cell might cover more than one political or climatic district or region. As a result, the same climate change scenario has to be applied to weather data, collected at weather stations that are located at different sites (Bardossy, 1997). This makes it especially difficult to predict the impact of climate change at a regional level, unless some major assumptions are made. Another problem is that the GCMs provide a monthly climate change prediction. As the crop models operate with daily weather data inputs, the monthly change needs to be interpolated over time to be able to apply the climate change scenario from the GCM towards the daily weather data required for the crop models. One final issue relates to the change in rainfall patterns and rainfall frequency that could occur because of climate change (Mearns et al., 1995a). This can especially be important in the arid and semi-arid tropics, where most production is water-limited (Sivakumar, 1992). The current GCMs only predict a change in rainfall amount and not in rainfall distribution, such as the start of the rainy season, the end of the rainy season, and the distribution of wet and dry spells.

One of the first projects to study climate change and its potential impact in the US was sponsored by the United States Environmental Protection Agency (Smith and Tirpak, 1989; Adams et al., 1990). This project was later expanded to study the impact of climate change at a global level (Rosenzweig and Parry, 1994; Rosenzweig et al., 1995). Both projects used the DSSAT suite of crop models. They were also used in the PAN-EARTH project, which studied the impact of climate change in developing countries (Harwell, 1993). The EPIC model was used extensively to study the impact of climate change on agricultural production in the Missouri–Iowa–Nebraska–Kansas (MINK) region (Stockle et al., 1992a; Easterling III et al., 1993; Rosenberg, 1993). One of the most recent studies is the United States Country Studies Program, which includes assessments of vulnerability to climate change and options for adaptation, especially for those countries that are the most vulnerable to the potential impact of climate change (Sathaye et al., 1997).

It is impossible to provide a comprehensive review of all studies associated with climate change and the potential impact on agricultural production and food security. Unfortunately, most of the results of these studies are not conclusive. On account of the interac-

tion of temperature, precipitation and CO₂ on plant growth and development, yield predictions differ depending on the GCM climate change prediction, local climate at a site, and the management scenario applied. It is expected that developing countries will be impacted the most, mainly due to the lack of adequate financial resources needed to adapt the management scenarios of local farmers.

6.2. Climate variability and El Niño applications

The connection of the Southern Oscillation episodes with El Niño was not identified until the late 1960s (Rasmusson and Wallace, 1983). Most of the applications of crop simulation models towards the impact of ENSO on agricultural production have been conducted in Australia (Rimington and Nicholls, 1993; Hammer et al., 1996; Meinke and Hammer, 1997) and Zimbabwe (Cane et al., 1994; Philips et al., 1998). It is expected that the potential impact of El Niño in other regions will be studied in the near future, especially for the most vulnerable countries. There are many opportunities for potentially successful application of the crop models, because a possible occurrence of an ENSO event can be predicted at least 6 months in advance. The crop models can be run, using historical weather years that are representative for ENSO events. Alternative management scenarios can be evaluated with the models to identify those scenarios that can reduce the potential impact (Frenken et al., 1993; Iglesias et al., 1996). The optimum scenarios can then be presented to farmers to provide them with various options to adapt their crop management regime for the current growing season.

System for Analysis, Research and Training (START) has been very active in studying the impact of climate variability on agricultural productivity and food security in the tropics. Most countries in the tropics are very vulnerable, due to the strong correlation between weather conditions and agricultural production. Manton et al. (1997) and Sivakumar (1997) recommended various applications of crop simulation models to study the impact of climate variability on crop productivity in the Asian Monsoon region and tropical Sub-Saharan Africa. Gadgil et al. (1999a, b) presented an example for India, using the peanut model PNUTGRO. It will be important to develop forecasting systems for these regions that link climate

models and crop simulation models and to provide products that can be used by both farmers and policy makers to help reduce the expected impact. This concept of linking crop simulation models and weather forecast products is very similar to the system discussed previously for famine early warning.

7. Future issues

The application of crop simulation models has become more acceptable in the agricultural community during the last few years. For any application of a crop model, weather data is one of the key inputs. It will be critical that weather data continue to be collected for all regions where agricultural production is an economic source of income. To account for spatial weather and climate variability, denser weather station networks might be needed. It will also be important that data are collected at daily intervals, but preferably more frequently, and that at least the primary set of variables needed for crop modeling are included. As automated weather stations are becoming more common in both developed and developing countries, it will be crucial that standards are developed for weather station equipment and sensors, installation, and maintenance. It will also be important that a uniform file format is defined for storage and distribution of weather data, so that they can easily be exchanged between agrometeorologists, crop modelers, and others using the crop simulation models. Easy access to weather data, preferably through the Internet and the world wide web, will be critical for the application of crop models for yield forecasting and tactical decision making. For large area and regional yield predictions, the issues of weather data interpolation and data gaps need to be addressed.

It seems that there have been no significant advances in the development of new crop simulation models during the last decade. Instead, crop models have been evaluated and applied for a wide range of environmental conditions and management scenarios, including issues related to climate change and variability. Existing crop models are being improved, but at a slow pace. More efforts are needed to improve the current crop models and add the simulation of processes that are important for agricultural practices in both developed and developing countries. Although most models have

been developed for only one or two specific applications, it will be critical for modeling groups to collaborate, given the limited amount of resources available for model improvement. An open source code policy and easy exchange of crop models and modules will aid in the overall improvement of the models.

There still seems to be a large gap between the products, generated by crop simulation models and decision support systems, and the application of these products by potential users. These users can range from farmers, consultants, extensionists to local, regional or national policy and decision makers. Although some models might continue to operate for research purposes only, it is important that models become a more effective decision support tool. Therefore, a concerted effort is needed to narrow the gap between the researchers and those who work directly with farmers, consultants and others associated with agribusiness. Private industry can possibly play a partial role in this venture. At the same time, it is of crucial importance that the models maintain their credibility. One or two bad examples or case studies will negatively impact any potential for future applications of the crop models.

The distribution and maintenance of crop modeling products for on-farm applications should be handled by the private sector in order for it to be economically sustainable. However, it is critical that researchers are involved in the development of modeling concepts as well as the evaluation of their models and decision support systems for on-farm applications. The most successful applications might be those in which the actual models reside with researchers, and the application shell or product resides with the private sector.

Crop simulation models will never be a substitute for experimental data collection. Field data continue to be needed for model evaluation as well as for improvement of the models. However, as our society becomes more computerized, there will be more scope for the application of crop simulation models to help provide guidance in solving real-world problems related to agricultural sustainability, food security, the use of natural resources and protection of the environment. Agrometeorology will be a critical component of all these applications to help understand the impact of weather variability and the uncertainty of future weather conditions.

References

- Abawi, G.Y., Smith, R.J., Brady, D.K., 1995. Assessment of the value of long range weather forecasts in wheat harvest management. *J. Agric. Eng. Res.* 62, 39–48.
- Abbaspour, K.C., Hall, J.W., Moon, D.E., 1992. A yield model for use in determining crop insurance premiums. *Agric. For. Meteorol.* 60, 33–51.
- Abrecht, D., Robinson, S., 1996. TACT: a tactical decision aid using a CERES based wheat simulation model. *Ecol. Modelling* 86, 241–244.
- Acock, B., Reddy, V.R., 1997. Designing an object-oriented structure for crop models. *Ecol. Modelling* 94, 33–44.
- Acock, B., Reynolds, J.F., 1997. Introduction: modularity in plant models. *Ecol. Modelling* 94, 1–6.
- Adams, R.M., Rosenzweig, C., Peart, R.M., Ritchie, J.T., McCarl, B.A., Glycer, J.D., Curry, R.B., Jones, J.W., Boote, K.J., Allen Jr., L.H., 1990. Global climate change and US agriculture. *Nature* 345, 219–224.
- Agnese, C., Bagarello, V., 1997. Describing rate variability of storm events for infiltration prediction. *Trans. ASAE* 40 (1), 61–70.
- Alexandrov, V.A., Hoogenboom, G., Georgiev, G., 1999. Vulnerability and adaptation of important agricultural crops in southeastern USA. In: Preprints 11th Conf. on Applied Climatology. American Meteorological Society, Boston, MA, pp. 89–96.
- Argonne National Laboratory (ANL), 1994. Guidance for Vulnerability and Adaptation Assessments. US Country Studies Program. Argonne National Laboratory, 205 pp.
- Arnold, C.D., Elliot, W.J., 1996. CLIGEN Weather generator predictions of seasonal wet and dry spells in Uganda. *Trans. ASAE* 39 (3), 969–972.
- Aubrey, C., Papy, F., Capillon, A., 1998. Modeling decision making process for annual crop management. *Agric. Systems* 56 (1), 45–65.
- Baffaut, C., Nearing, M.A., Nicks, A.D., 1996. Impact of CLIGEN parameters on WEPP-predicted average annual soil loss. *Trans. ASAE* 39 (2), 447–457.
- Baier, W., 1979. Note on the terminology of crop-weather models. *Agric. Meteorol.* 20, 137–145.
- Bardossy, A., 1997. Downscaling from GCMs to local climate through stochastic linkages. *J. Environ. Manage.* 49, 7–17.
- Batchelor, W.D., Jones, J.W., Boote, K.J., Pinnschmidt, H.O., 1993. Extending the use of crop models to study pest damage. *Trans. ASAE* 36, 551–558.
- Baumgardner, M.F., 1994. The role of remote sensing in crop modeling. In: Uhler, P.F., Carter, G.C. (Eds.), *Crop Modeling and Related Environmental Data. A Focus on Applications for Arid and Semiarid Regions in Developing Countries*. CODATA, Paris, France, pp. 205–214.
- Berry, J.S., 1995. The role of computer models in the grasshopper integrated pest management project. *Comput. Electron. Agric.* 13, 13–26.
- Boggess, W.G., Amerling, C.B., 1983. A bioeconomic simulation analysis of irrigation investments. *S. J. Agric. Econ.* 15, 85–91.

- Boggess, W.G., Ritchie, J.T., 1988. Economic and risk analysis of irrigation decisions in humid regions. *J. Prod. Agric.* 1 (2), 116–122.
- Boggess, W.G., G.D., Jones, J.W., Swaney, D.P., 1983. Risk-return assessment of irrigation decisions in humid regions. *S. J. Agric. Econ.* 15, 135–143.
- Boone, M.Y.L., Porter, D.O., McKinion, J.M., 1993. Calibration of GOSSYM: theory and practice. *Comput. Electron. Agric.* 9, 193–203.
- Boote, K.J., Jones, J.W., Hoogenboom, G., 1997. Simulation of crop growth: CROPGRO model. In: Peart, R.M., Curry, R.B. (Eds.), *Agricultural Systems Modeling*. Marcel Dekker, New York, pp. 651–692.
- Boote, K.J., Jones, J.W., Pickering, N.B., 1996. Potential uses and limitations of crop models. *Agron. J.* 88, 704–716.
- Boote, K.J., Loomis, R.S. (Eds.), 1991. Modeling crop photosynthesis — from biochemistry to canopy. *CSSA Special Publication Number 19*. Crop Science Society of America, Madison, WI.
- Bouman, B.A.M., 1992. Linking physical remote-sensing models with crop growth simulation models applied for sugar beet. *Int. J. Remote Sensing* 13 (14), 2565–2581.
- Bouman, B.A.M., 1995. Crop modelling and remote sensing for yield prediction. *Neth. J. Agric. Sci.* 43, 143–161.
- Bouman, B.A.M., van Keulen, H., van Laar, H.H., Rabbinge, R., 1996. The School-of-de-Wit crop growth simulation models: a pedigree and historical overview. *Agric. Systems* 52 (2–3), 171–198.
- Bowen, W.T., Jones, J.W., Carsky, R.J., Quintana, J.O., 1993. Evaluation of nitrogen submodel of CERES — maize following legume green manure incorporation. *Agron. J.* 85, 153–159.
- Bowen, W.T., Thornton, P.K., Hoogenboom, G., 1998. The simulation of cropping sequences using DSSAT. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 313–327.
- Bruton, J.M., Hoogenboom, G., McClendon, R.W., 1998. Comparison of automatically and manually collected weather data. *ASAE Paper 98–2188*, American Society of Agricultural Engineers, St. Joseph, MI.
- Cane, M.A., Eshel, G., Buckland, R.W., 1994. Forecasting Zimbabwean maize yield using eastern equatorial Pacific sea surface temperature. *Nature* 370, 204–205.
- Carbone, G.J., 1993. Considerations of meteorological time-series in estimating regional-scale crop yield. *J. Climate* 6 (8), 1607–1615.
- Carbone, G.J., Narumalani, S., King, M., 1996. Application of remote sensing and GIS technologies with physiological crop models. *Am. Soc. Photogrammetry Remote Sensing* 62 (2), 171–179.
- Climate Research Committee, 1995. *Natural Climate Variability on Decade-to-Century Time Scales*. National Research Council. National Academic Press, Washington, DC.
- Cole, C.V., Paustian, K., Elliott, E.T., Metherell, A.K., Ojima, D.S., Parton, W.J., 1993. Analysis of agroecosystem carbon pools. *Water Air Soil Pollut.* 70, 357–371.
- Coulson, R.N., 1992. Intelligent geographic information systems and integrated pest management. *Crop Protection* 11, 507–516.
- Curry, R.B., 1971. Dynamic simulation of plant growth I. Development of a model. *Trans. ASAE* 14 (5), 946–959.
- Curry, R.B., Chen, L.H., 1971. Dynamic simulation of plant growth II. Incorporation of actual daily weather and partitioning of net photosynthesis. *Trans. ASAE* 14 (6), 1170–1175.
- Curry, R.B., Peart, R.M., Jones, J.W., Boote, K.J., Allen, L.H., 1990a. Simulation as a tool for analyzing crop response to climate change. *Trans. ASAE* 33 (3), 981–990.
- Curry, R.B., Peart, R.M., Jones, J.W., Boote, K.J., Allen, L.H., 1990b. Response of crop yield to predicted changes in climate and atmospheric CO₂ using simulation. *Trans. ASAE* 33 (4), 1383–1390.
- Department of Science and Technology, 1990. *Developments on agrometeorology in India*. National Center for Medium-Range Weather Forecasting, New Delhi, India.
- Donatelli, M., Stockle, C., Ceotto, E., Rinaldi, M., 1997. Evaluation of Crop Syst for cropping systems at two locations of northern and southern Italy. *Eur. J. Agron.* 6, 35–45.
- Downing, T.E. (Ed.), 1996. *Climate Change and World Food Security*. NATO ASI Series. Series 1: Global Environmental Change, Vol. 37. Springer, Berlin, Germany.
- Duchon, C.E., 1986. Corn yield prediction using climatology. *J. Climate Appl. Meteorol.* 25 (5), 581–590.
- Duncan, W.G., Loomis, R.S., Williams, W.A., Hanau, R., 1967. A model for simulating photosynthesis in plant communities. *Hilgardia* 38, 181–205.
- Duvrosky, M., 1997. Creating daily weather series with use of weather generator. *Environmetrics* 8 (5), 409–424.
- EarthInfo, 1998. Database guide for EarthInfo CD NCDC summary of the day. EarthInfo, Inc., Boulder, CO.
- Easterling III, W.E., Crosson, P.R., Rosenberg, N.J., McKenney, M.S., Datz, L.A., Lemon, K.M., 1993. Agricultural impacts of and responses to climate change in the Missouri–Iowa–Nebraska–Kansas (MINK) region. *Climatic Change* 24, 23–61.
- Egli, D.B., Bruening, W., 1992. Planting date and soybean yield — evaluation of environmental effects with a crop simulation model — SOYGRO. *Agric. For. Meteorol.* 62 (1–2), 19–29.
- Ehlings, A., Rubia, E.G. (Eds.), 1994. *Analysis of Damage Mechanisms by Pests and Diseases and their Effect on Rice Yield*. SARP Research Proceedings. DLO Research Institute for Agrobiology and Soil Fertility, Wageningen, Netherlands, 279 pp.
- Ende, V.D., E. L., Trapman, M., 1996. Gaby: a computer-based decision support system for integrated pest management in Dutch apple orchards. *Integr. Pest Manage. Rev.* 1, 147–162.
- Engel, T., Hoogenboom, G., Jones, J.W., Wilkens, P.W., 1997. AEGIS/WIN — a computer program for the application of crop simulation models across geographic areas. *Agron. J.* 89 (6), 919–928.
- Ephrath, J.E., Goudriaan, J., Marani, A., 1996. Modelling diurnal patterns of air temperature, radiation, wind speed and relative humidity by equations from daily characteristics. *Agric. Systems* 51 (4), 377–393.
- Epperson, J.E., Hook, J.E., Mustafa, Y.R., 1993. Dynamic programming for improving irrigation scheduling strategies of maize. *Agric. Systems* 42, 85–101.

- Fageria, N.K., 1992. Maximizing Crop Yields. Marcel Dekker, New York.
- Fernández, C.J., 1992. Simulation of normal annual and diurnal temperature oscillations in non-mountainous mainland United States. *Agron. J.* 84, 244–251.
- Floyd, R.B., Braddock, R.D., 1984. A simple method for fitting average diurnal temperature curves. *Agric. For. Meteorol.* 32, 107–119.
- Fortson, R.E., McClendon, R.W., Hook, J.E., 1989. Managing irrigation with the SOYGRO crop growth model in the coastal plain of Georgia. *Appl. Eng. Agric.* 5 (3), 441–446.
- Frenken, G., Hornetz, B., Jaetzold, R., Willems, W., 1993. Actual landuse advice in marginal areas of SE-Kenya by atmosphere-ocena-teleconnection. *Tropenlandwirt* 94, 3–12.
- Friend, A.D., 1998. Parameterisation of a global daily weather generator for terrestrial ecosystem modelling. *Ecol. Modelling* 109 (2), 121–140.
- Gadgil, S., Abrol, Y.P., Seshagiri Rao, P.R., 1999a. On growth and fluctuation of Indian foodgrain production. *Curr. Sci.* 76 (4), 548–556.
- Gadgil, S., Rao, P.R., Joshi, N.V., Sridhar, S., 1995. Forecasting rain for groundnut farmers — how good is good enough? *Curr. Sci.* 68 (3), 301–309.
- Gadgil, S., Seshagiri Rao, P.R., Sridhar, S., 1999b. Modeling impact of climate variability on rainfed groundnut. *Curr. Sci.* 76 (4), 557–569.
- Geng, S., Penning de Vries, F.W.T., Supit, I., 1986. A simple method for generating daily rainfall data. *Agric. For. Meteorol.* 36, 363–376.
- Georgiev, G.A., Hoogenboom, G., 1999. Near real-time agricultural simulations on the web. *Simulation*, 73(1), 22–28.
- Georgiev, G., Hoogenboom, G., 1998. Crop growth and yield estimation using current weather forecasts and weather observations. Preprints 23rd Conf. on Agricultural and Forest Meteorology. American Meteorological Society, Boston, MA, pp. 69–72.
- Georgiev, G.A., Hoogenboom, G., Raghupathy, K., 1998. Regional yield estimations using a linked Geographic Information System, crop growth models and a weather observation network. *Proc. Institute of Biological Engineering* 1:B135-B145, IBE Publications, Athens, Georgia.
- Gerakis, A., Daroub, S., Ritchie, J.T., Friesen, D.K., Chien, S.H., 1998. Phosphorus simulation in the CERES models, *Agronomy Abstracts* (1998) 14.
- Gijsman, A.J., Oberson, A., Tiessen, H., Friesen, D.K., 1996. Limited applicability of the CENTURY model to highly weathered tropical soils. *Agron. J.* 88, 894–903.
- Global Change and Terrestrial Ecosystems (GCTE), 1994. GCTE Focus 3 Wheat Network: 1993 model and experimental meta data. Report No. 2. GCTE, Canberra, Australia.
- Godwin, D.C., Singh, U., 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 55–77.
- Gold, H.J., Wilkerson, G.G., Yu, Y., Stinner, R.E., 1990. Decision analysis as a tool for integrating simulation with expert systems when risk and uncertainty are important. *Comput. Electron. Agric.* 4, 343–360.
- Goudriaan, J., 1996. Predicting crop yields under global change. In: Walker, B., Steffen, W. (Eds.), *Global Change and Terrestrial Ecosystems*. Cambridge University Press, Cambridge, pp. 260–274.
- Goudriaan, J., Zadoks, J.C., 1995. Global climate change: modelling the potential responses of agro-ecosystems with special reference to crop protection. *Environ. Pollut.* 87, 215–224.
- Grant, R.F., 1997. Changes in soil organic matter under different tillage and rotation: mathematical modeling in Ecosys. *Soil Sci. Soc. Am. J.* 61, 1159–1175.
- Grant, R.F., Heaney, D.J., 1997. Inorganic phosphorus transformation and transport in soils: mathematical modeling in Ecosys. *Soil Sci. Soc. Am. J.* 61, 752–764.
- Guenni, L., 1997. Spatial interpolation of stochastic weather model parameters. *J. Environ. Manage.* 49, 31–42.
- Guenni, L., Hutchinson, M.F., Hogarth, W., Rose, C.W., Braddock, R., 1996. A model for seasonal-variation of rainfall at Adelaide and Turen. *Ecol. Modelling* 85 (2-3), 203–217.
- Guerif, M., Duke, C., 1998. Calibration of the SUCROS emergence and early growth module for sugar beet using optical remote sensing data assimilation. *Eur. J. Agron.* 9 (2-3), 127–136.
- Hammer, G.L., Holzworth, D.P., Stone, R., 1996. The value of skill in seasonal climate forecasting to wheat crop management in a region with high climatic variability. *Aust. J. Agric. Res.* 47 (5), 717–737.
- Han, S., Evans, R.G., Hodges, T., Rawlins, S.L., 1995. Linking a geographic information system with a potato simulation model for site-specific crop management. *J. Environ. Quality* 24, 772–777.
- Hanson, J.D., Ahuja, L.R., Shaffer, M.J., Rojas, K.W., Decoursey, D.G., Farahani, H., Johnson, K., 1998. RZWQM: Simulating the effects of management on water quality and crop production. *Agric. Systems* 57 (2), 161–195.
- Hartkamp, A.D., White, J.W., Hoogenboom, G., 1999. Interfacing geographic information systems with agronomic modeling: a review. *Agron. J.* 91 (5), 762–772.
- Harwell, M.A., 1993. Assessing the effects of global climate change: the PAN-EARTH project series. *Climatic Change* 23, 287–292.
- Hodges, T. (Ed.), 1991. *Predicting Crop Phenology*. CRC Press, Boca Raton, FL.
- Hodges, T., 1998. Water and nitrogen applications for potato: commercial and experimental rates compared to a simulation model. *J. Sustainable Agric.* 13 (2), 79–90.
- Hodges, T., Johnson, S.L., Johnson, B.S., 1992. A modular structure for crop simulation models: implemented in the SIMPOTATO model. *Agron. J.* 84, 911–915.
- Hoogenboom, G., 1998. Plant growth model development and parameterization. In: Dalezios, N.R. (Ed.), *International Symposium on Applied Agrometeorology and Applied Climatology*. Proceedings, Volos, Greece, 24–26 April 1996. Office for Official Publications of the European Communities, Luxembourg, pp. 343–357.
- Hoogenboom, G., Jones, J.W., Boote, K.J., 1992. Modeling growth, development and yield of grain legumes using SOYGRO,

- PNUTGRO, and BEANGRO: a review. *Trans. ASAE* 35 (6), 2043–2056.
- Hoogenboom, G., Jones, J.W., Wilkens, P.W., Batchelor, W.D., Bowen, W.T., Hunt, L.A., Pickering, N.B., Singh, U., Godwin, D.C., Baer, B., Boote, K.J., Ritchie, J.T., White, J.W., 1994. Crop models. In: Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), *DSSAT version 3*, Vol. 2. University of Hawaii, Honolulu, Hawaii, pp. 95–244.
- Hoogenboom, G., Tsuji, G.Y., Jones, J.W., Singh, U., Godwin, D.C., Pickering, N.B., Curry, R.B., 1995. Decision support system to study climate change impacts on crop production. In: Rosenzweig, C., Allen Jr., L.H., Harper, L.A., Hollinger, S.E., Jones, J.W. (Eds.), *Climate Change and Agriculture: Analysis of Potential International Impacts*. ASA special publication no. 59. American Society of Agronomy, Madison, WI, pp. 51–75.
- Hunt, L.A., 1994. Data requirements for crop modeling. In: Uhler, P.F., Carter, G.C. (Eds.), *Crop Modeling and Related Environmental Data. A Focus on Applications for Arid and Semiarid Regions in Developing Countries*. CODATA, Paris, France, pp. 15–25.
- Hunt, L.A., Boote, K.J., 1998. Data for model operation, calibration, and evaluation. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 9–39.
- Hunt, L.A., Jones, J.W., Hoogenboom, G., Godwin, D.C., Singh, U., Pickering, N., Thornton, P.K., Boote, K.J., Ritchie, J.T., 1994. General input and output files structures for crop simulation models. In: Uhler, P.F., Carter, G.C. (Eds.), *Crop Modeling and Related Environmental Data. A Focus on Applications for Arid and Semiarid Regions in Developing Countries*. CODATA, Paris, France, pp. 35–73.
- Hutchinson, M.F., 1991. Climatic analyses in data sparse regions. In: Muchow, R.C., Bellamy, J.A. (Eds.), *Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics*. CAB International, Wallingford, pp. 55–71.
- Hutchinson, M.F., 1995. Stochastic space-time weather models from ground-based data. *Agric. For. Meteorol.* 73 (3–4), 237–264.
- Iglesias, A., Erda, L., Rosenzweig, C., 1996. Climate-change in Asia — a review of the vulnerability and adaptation of crop production. *Water Air Soil Pollut.* 92, 13–27.
- International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), 1984. *Proc. Int. Symposium on Minimum Data Sets for Agrotechnology Transfer*, 21–26 March 1983. ICRISAT Center, Patancheru, India.
- International Benchmark Sites Network for Agrotechnology Transfer Project, 1990a. Technical Report 2. Field & Laboratory Methods for the Collection of the IBSNAT Minimum Data Set for the Decision Support System for Agrotechnology Transfer (DSSAT V2.1). Department of Agronomy and Soil Sci., College of Trop. Agric. and Human Resources, University of Hawaii, Honolulu, Hawaii.
- International Benchmark Sites Network for Agrotechnology Transfer Project, 1990b. Technical Report 5. Documentation for IBSNAT Crop Model Input and Output Files, Version 1.1: for the Decision Support System for Agrotechnology Transfer (DSSAT V2.1). Department of Agronomy and Soil Sci., College of Trop. Agric. and Human Resources, University of Hawaii, Honolulu, Hawaii.
- Jacobson, B.M., Jones, J.W., Welch, S.M., 1997. PCYield: a decision support system with real-time soybean yield. *Agronomy Abstracts* (1997) 16.
- Jame, Y.W., Cutforth, H.W., 1996. Crop growth models for decision support systems. *Can. J. Plant Sci.* 76, 9–19.
- Jamieson, P.D., Porter, J.R., Goudrian, J., Ritchie, J.T., van Keulen, H., Stol, W., 1998. A comparison of the models AFRCWHEAT2, CERES-Wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought. *Field Crops Res.* 55, 23–44.
- Jimoh, O.D., Webster, P., 1997. The optimum order of a Markov chain model for daily rainfall in Nigeria. *J. Hydrol.* 185, 45–69.
- Johnson, G.L., Hanson, C.L., Hardegree, S.P., Ballard, E.B., 1996. Stochastic weather simulation — overview and analysis of two commonly used models. *J. Appl. Meteorol.* 35 (10), 1878–1896.
- Jones, C.A., Dyke, P.T., Williams, J.R., Kiniry, J.R., Benson, V.W., Griggs, R.H., 1991. EPIC: an operational model for evaluation of agricultural sustainability. *Agric. Systems* 37, 341–350.
- Jones, C.A., Kiniry, J.R., 1986. *CERES-Maize: A Simulation Model of Maize Growth and Development*. Texas A & M University Press, College Station, TX.
- Jones, J.W., 1993. Decision support systems for agricultural development. In: Penning de Vries, F.W.T., Teng, P., Metselaar, K. (Eds.), *Systems Approaches for Agricultural Development*. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 459–471.
- Jones, J.W., Hunt, L.A., Hoogenboom, G., Godwin, D.C., Singh, U., Tsuji, G.Y., Pickering, N., Thornton, P.K., Bowen, W.T., Boote, K.J., Ritchie, J.T., 1994. Input and output files. In: Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), *DSSAT version 3*, Vol. 2. University of Hawaii, Honolulu, Hawaii, pp. 1–93.
- Jones, J.W., Tsuji, G.Y., Hoogenboom, G., Hunt, L.A., Thornton, P.K., Wilkens, P.W., Imamura, D.T., Bowen, W.T., Singh, U., 1998. Decision support system for agrotechnology transfer DSSAT v3. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 157–177.
- Jones, P.G., Thornton, P.K., 1997. Spatial and temporal variability of rainfall related to a third-order Markov model. *Agric. For. Meteorol.* 86 (1–2), 127–138.
- De Jong, R., Bootsma, A., 1996. Review of recent developments in soil water simulation models. *Can. J. Soil Sci.* 76, 263–273.
- Kaiser, H.M., Drennen, T.E. (Eds.), 1993. *Agricultural Dimensions of Global Climate Change*. St. Lucie Press, Delray Beach, FL.
- Keating, B.A., Hammer, G.L., Carberry, P.S., Freebairn, D.M., Meinke, H.M., McCown, R.L., 1997. APSIM's contribution to the simulation of agricultural systems. *Agronomy Abstracts* (1997) 21.
- van Keulen, H., 1982. Crop production under semi-arid conditions, as determined by nitrogen and moisture availability. In: Penning de Vries, F.W.T., van Laar, H.H. (Eds.), *Simulation of Plant Growth and Crop Production*. Simulation Monographs. PUDOC, Wageningen, Netherlands, pp. 234–251.

- van Keulen, H., Seligman, N.G., 1987. Simulation of water use, nitrogen nutrition, and growth of a spring wheat crop. *Simulation Monographs*. PUDOC, Wageningen, Netherlands, 310 pp.
- Kropff, M.J., van Laar, H.H. (Eds.), 1993. *Modelling crop-weed interactions*. CAB International, Wallingford, 274 pp.
- Kropff, M.J., van Laar, H.H., Matthews R., 1994. ORYZA1, An Ecophysiological Model for Irrigation Rice Production. SARP Research Proceedings. DLO Research Institute for Agrobiology and Soil Fertility, Wageningen, Netherlands, 110 pp.
- Lal, H., Hoogenboom, G., Calixte, J.-P., Jones, J.W., Beinroth, F.H., 1993. Using crop simulation models and GIS for regional productivity analysis. *Trans. ASAE* 36 (1), 175–184.
- Lansigan, F.P., Pandey, S., Bouman, B.A., 1997. Combining crop modeling with economic-risk analysis for the evaluation of crop management strategies. *Field Crops Res.* 51 (1–2), 133–145.
- LeComte, D.M., 1994. The NOAA/NESDIS impact assessment project for drought early warning in the Sahel. In: Uhler, P.F., Carter, G.C. (Eds.), *Crop Modeling and Related Environmental Data. A Focus On Applications For Arid And Semiarid Regions In Developing Countries*. CODATA, Paris, France, pp. 171–181.
- Ley, T.W., Elliot, R.L., Bausch, W.C., Brown, P.W., Elwell, D.L., Tanner, B.D., 1994. Review of ASAE standards project X505: Measurement and reporting practices for automatic agricultural weather stations. ASAE Paper 94–2086. American Society for Agricultural Engineers, St. Joseph, MI.
- Linacre, E.T., 1977. A simple formula for estimating evaporation rates in various climates, using temperature data alone. *Agric. Meteorol.* 18, 409–424.
- Llasat, M.C., Snyder, R.L., 1998. Data error effects on net radiation and evapotranspiration estimation. *Agric. For. Meteorol.* 91, 209–221.
- Loomis, R.S., Rabbinge, Ng.E., 1979. Explanatory models in crop physiology. *Annu. Rev. Plant Physiol.* 30, 339–367.
- Maas, S.J., 1993. Within-season calibration of modeled wheat growth using remote sensing and field sampling. *Agron. J.* 85, 669–672.
- Mackey, B.G., Mckenney, D.W., Yang, Y.Q., McMahon, J.P., Hutchinson, M.F., 1996. Site regions revisited — a climatic analysis of hills site regions for the province of Ontario using a parametric method. *Can. J. For. Res.* 26 (3), 333–354.
- Manton, M., Phelan, A., Virji, H. (Eds.), 1997. *Workshop on Climate Variability, Agricultural Productivity and Food Security in the Asian Monsoon Region*. Report no. 2. START, Washington, DC.
- Maracchi, G., Sivakumar, M.V.K., 1995. Coordination and harmonization of databases and software for agroclimatic applications. *Coordination and harmonisation of databases and software for agroclimatic applications*. FAO Agrometeorology Series Number 13. FAO Rome, Italy, pp. 11–38.
- Matthews, R.B., Kropff, M.J., Bachelet, D., van Laar, H.H., 1995. *Modelling the impact of climate change on rice production in Asia*. CAB International, Wallingford, 304 pp.
- McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P., Freebairn, D.M., 1996. APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. *Agric. Systems* 50, 255–271.
- McVoy, C.W., Kersebaum, K.C., Arning, M., Kleeberg, P., Othmer, H., Schröder, U., 1995. A data set from north Germany for the validation of agroecosystem models: documentation and evaluation. *Ecol. Modelling* 81, 265–300.
- Mearns, L.O., Giorgi, F., McDaniel, L., Shields, C., 1995a. Analysis of variability and diurnal range of precipitation in a nested regional climate model — comparison with observations and doubled CO₂ results. *Climate Dynamics* 10, 55–78.
- Mearns, L.O., Giorgi, F., McDaniel, L., Shields, C., 1995b. Analysis of variability and diurnal range of daily temperature in a nested regional climate model — comparison with observations and doubled CO₂ results. *Climate Dynamics* 11, 193–209.
- Mearns, L.O., Rosenzweig, C., Goldberg, R., 1992. Effect of changes in interannual climatic variability on CERES-Wheat yields: sensitivity and 2×CO₂ general circulation model studies. *Agric. For. Meteorol.* 62, 159–189.
- Mearns, L.O., Rosenzweig, C., Goldberg, R., 1997. Mean and variance change in climate scenarios — methods, agricultural applications, and measures of uncertainty. *Climatic Change* 35 (4), 367–396.
- Meinke, H., Carberry, P.S., McCaskill, M.R., Hills, M.A., McLeod, I., 1995. Evaluation of radiation and temperature data generators in the Australian tropics and sub-tropics using crop simulation models. *Agric. For. Meteorol.* 72, 295–316.
- Meinke, H., Hammer, G.L., 1997. Forecasting regional crop production using SOI phases: an example for the Australian peanut industry. *Aust. J. Agric. Res.* 48, 789–793.
- Meyer, S.J., Hubbard, K.G., 1992. Nonfederal automated weather station and networks in the United States and Canada: a preliminary survey. *Bull. Am. Meteorol. Soc.* 73, 449–457.
- Mize, J.H., Cox, J.G., 1968. *Essentials of simulation*. Prentice Hall, Englewood Cliffs, NJ.
- Monteith, J.L., 1996. The quest for balance in crop modeling. *Agron. J.* 88, 695–697.
- Moran, M.S., Maas, S.J., Pinter Jr., P.J., 1995. Combining remote sensing and modeling for estimating surface evaporation and biomass production. *Remote Sensing Rev.* 12, 335–353.
- National Defense University, 1978. *Climate Change to the Year 2000. A Survey of Expert Opinion*. Fort Lesley J. McNair, Washington, DC.
- Nichols, N., 1991. Advances in long-term weather forecasting. In: Muchow, R.C., Bellamy, J.A. (Eds.), *Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics*. CAB International, Wallingford, pp. 427–444.
- Nonhebel, S., 1994a. The effects of use of average instead of daily weather data in crop growth simulation models. *Agric. Systems* 44, 377–396.
- Nonhebel, S., 1994b. Inaccuracies in weather data and their effects on crop growth simulation results I. Potential production. *Clim. Res.* 4, 47–60.
- Nonhebel, S., 1994c. Inaccuracies in weather data and their effects on crop growth simulation results II. Water-limited production. *Clim. Res.* 4, 61–74.
- van Noordwijk, M., Dijksterhuis, G.H., van Keulen, H., 1994. Risk management in crop production and fertilizer use with uncertain rainfall how many eggs in which baskets. *Neth. J. Agric. Sci.* 42 (4), 249–269.

- Oryokot, J.O., Hunt, L.A., Murphy, S., Swanton, C.J., 1997. Simulation of pigweed (*Amaranthus* spp.) seedling emergence in different tillage systems. *Weed Sci.* 45 (5), 684–690.
- Peart, R. M., Jones, J.W., Curry, R.B., Boote, K.J., Allen, L.H., 1988. Final Report. Impact of climate change on crop yield in the Southeastern USA: A simulation study. Institute of Food and Agricultural Sciences University of Florida Gainesville, FL.
- Peiris, D.R., McNicol, J.W., 1996. Modelling daily weather with multivariate time series. *Agric. For. Meteorol.* 79, 219–231.
- Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. *Proc. Royal Soc. London A* 193, 120–145.
- Penning de Vries, F.W.T., Jansen, D.M., ten Berge, H.F.M., Bakema, A., 1989. Simulation of ecophysiological processes of growth of several annual crops. *Simulation Monographs*. Centre for Agricultural Publishing and Documentation (Pudoc). Wageningen, Netherlands.
- Penning de Vries, F.W.T., van Laar, H.H. (Eds.), 1982. Simulation of plant growth and production. *Simulation Monographs*. Centre for Agricultural Publishing and Documentation (Pudoc). Wageningen, Netherlands.
- Petr, J., 1991. *Weather and Yield*. Elsevier, Amsterdam, Netherlands.
- Philips, J.G., Cane, M.A., Rosenzweig, C., 1998. ENSO, seasonal rainfall patterns and simulated maize yield variability in Zimbabwe. *Agric. For. Meteorol.* 90, 39–50.
- Pickering, N.B., Hansen, J.W., Jones, J.W., Wells, C.M., Chan, V.K., Godwin, D.C., 1994. Weatherman — a utility for managing and generating daily weather data. *Agron. J.* 86 (2), 332–337.
- Pinnschmidt, H.O., Batchelor, W.D., Teng, P.S., 1995. Simulation of multiple species pest damage on rice. *Agric. Systems* 48, 193–222.
- Plentinger, M.C., Penning de Vries, F.W.T., 1997. Rotation models for ecological farming. CAMASE/PE workshop report. Quantitative Approaches in Systems Analysis no. 10. DLO Research Institute for Agrobiological and Soil Fertility & C.T. de Wit Graduate School for Production Ecology, Wageningen, Netherlands.
- Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation on large-scale parameters. *Monthly Weather Rev.* 100, 81–92.
- Probert, M.E., Dimes, J.P., Keating, B.A., Dalal, R.C., Strong, W.M., 1998. APSIMs water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agric. Systems* 56 (1), 1–28.
- Probert, M.E., Keating, B.A., Thompson, J.P., Parton, W.J., 1995. Modelling water, nitrogen and crop yield for a long-term fallow management experiment. *Aust. J. Exp. Agric.* 35, 941–950.
- Pusey, P.L., 1997. Crab apple blossoms as model for research on biological control of fire blight. *Phytopathology* 87 (11), 1096–1102.
- Rabbinge, R., Carter, N., 1984. Monitoring and forecasting of cereal aphids in the Netherlands: A subsystem of EIPRE. In: Conway, G.R. (Ed.), *Pest and Pathogen Control: Strategic, Tactical and Policy Models*. Wiley, New York, pp. 242–251.
- Rabbinge, R., van Latesteijn, H.C., 1992. Long-term options for land use in the European community. *Agric. Systems* 40, 195–210.
- Rabbinge, R., van Oijen, M., 1997. Scenario studies for future agriculture and crop protection. *Eur. J. Plant Pathol.* 103, 197–201.
- Rasmusson, E.M., Wallace, J.M., 1983. Meteorological aspects of El Niño/Southern oscillation. *Science* 222, 1195–1202.
- Reddy, V.R., Acock, B., Whisler, F.D., 1995a. Crop management and input optimization with GLYCIM — different cultivars. *Comput. Electron. Agric.* 31 (1), 37–50.
- Reddy, K.R., Boone, M.Y.L., Reddy, A.R., Hodges, H.F., 1995b. Developing and validating a model for plant growth regulators. *Agron. J.* 87, 1100–1105.
- Reddy, K.R., Hodges, H.F., McKinion, J.M., 1997. Crop modeling and applications: a cotton example. *Adv. Agron.* 59, 225–290.
- Richardson, C.W., 1981. Stochastic simulation of daily precipitation, temperature, and solar radiation. *Water Resources Res.* 17 (1), 182–190.
- Richardson, C.W., 1985. Weather simulation for crop management models. *Trans. ASAE* 28 (5), 1602–1606.
- Riethoven, J.J.M., ten Berge, H.F.M., Drenth, H. (Eds.), 1995. Software development in the SARP project: a guide to applications and tools. *SARP Research Proceedings*. DLO Research Institute for Agrobiological and Soil Fertility, Wageningen, Netherlands, p. 301.
- Riha, S.H., Wilks, D.S., Simoons, P., 1996. Impact of temperature and precipitation variability on crop model predictions. *Climatic Change* 32, 293–311.
- Rimmington, G.M., Nicholls, N., 1993. Forecasting wheat yields in Australia with the southern oscillation index. *Aust. J. Agric. Res.* 44, 625–632.
- Ritchie, J.T., 1994. Classification of crop simulation models. In: Uhler, P.F., Carter, G.C. (Eds.), *Crop Modeling and Related Environmental Data. A Focus on Applications for Arid and Semiarid Regions in Developing Countries*. CODATA, Paris, France, pp. 3–25.
- Ritchie, J.T., 1995. International consortium for agricultural systems applications (ICASA): establishment and purpose. *Agric. Systems* 49, 329–335.
- Ritchie, J.T., 1998. Soil water balance and plant stress. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 41–54.
- Ritchie, J.T., Singh, U., Godwin, D.C., Bowen, W.T., 1998. Cereal growth, development and yield. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 79–98.
- Robock, A., Turco, R.P., Harwell, M.A., Ackerman, T.P., Andressen, R., Chang, H.-S., Sivakumar, M.V.K., 1993. Use of general circulation model output in the creation of climate change scenarios for impact analysis. *Climatic Change* 23, 293–335.
- Rosenberg, N.J., 1993. A methodology called ‘MINK’ for study of climate change impacts and responses on the regional scale. *Climatic Change* 24, 1–6.
- Rosenzweig, C., Allen, L.H., Harper, L.A., Hollinger, S.E., Jones, J.W. (Eds.), 1995. *Climate Change and Agriculture: Analysis of Potential International Impacts*. ASA special publication no. 59. American Society of Agronomy, Madison, WI.

- Rosenzweig, C., Parry, M.L., 1994. Potential impact of climate change on world food supply. *Nature* 367, 133–138.
- Sathaye, J.A., Dixon, R.K., Rosenzweig, C., 1997. Climate-change country studies. *Appl. Energy* 56 (3–4), 225–235.
- Scheierling, S.M., Cardon, G.E., Young, R.A., 1997. Impact of irrigation timing on simulated water–crop production functions. *Irrig. Sci.* 18, 23–31.
- Schmidt, G.M., Smajstrla, A.G., Zazueta, F.S., 1996. Parametric uncertainty in stochastic precipitation models — wet day amounts. *Trans. ASAE* 39 (6), 2093–2103.
- Schmidt, G.M., Smajstrla, A.G., Zazueta, F.S., 1997. Long-term variability of monthly total precipitation. *Trans. ASAE* 40 (4), 1029–1039.
- Selvarajan, S., Aggarwal, P.K., Pandey, S., Lansigan, F.P., Bandyopadhyay, S.K., 1997. Systems approach for analyzing tradeoffs between income, risk, and water-use in rice-wheat production in Northern India. *Field Crops Res.* 51 (1–2), 147–161.
- Semenov, M.A., Brooks, R.J., Barrow, E.M., Richardson, C.W., 1998. Comparison of WGEN and LARS-WG stochastic weather generators for diverse climate. *Clim. Res.* 10 (2), 95–107.
- Semenov, M.A., Wolf, J., Evans, L.G., Eckerstein, H., Iglesias, A., 1996. Comparison of wheat simulation models under climate change II. Application of climate change scenarios. *Clim. Res.* 7, 271–281.
- Singh, P., Kanwar, R.S., 1995. Modifications of RZWQM for simulating subsurface drainage by adding a tile flow component. *Trans. ASAE* 38 (2), 489–498.
- Sivakumar, M.V.K., 1992. Climate change and implications for agriculture in Niger. *Climatic Change* 20, 297–312.
- Sivakumar, M.V.K. (Ed.), 1997. *Climate Variability Prediction, Water Resources and Agricultural Productivity: Food Security Issues in Tropical Sub-Saharan Africa*. Report No. 3. START, Washington, DC.
- Smith, J.B., Tirpak, D.A. (Eds.), 1989. *The Potential Effects of Global Climate Change on the United States*. Appendix C — Agriculture. US Environmental Protection Agency, Washington, DC.
- Smith, J.U., 1997. Constructing a nitrogen fertilizer recommendation system using a dynamic model: what do farmers want? *Soil Use Manage.* 13, 225–228.
- Smith, R.C.G., Adams, J., Stephens, D.J., Hick, P.T., 1995. Forecasting wheat yield in a Mediterranean-type environment from the NOAA satellite. *Aust. J. Agric. Res.* 46, 113–125.
- Splinter, W.E., 1974. Modelling of plant growth for yield prediction. *Agric. Meteorol.* 14, 243–253.
- Sridhar, S., Hoogenboom, G., Georgiev, G., 1998. Linking a pest model for peanut leafminer with the peanut crop simulation CROPGRO. In: *Preprints 23rd Conf. Agricultural and Forest Meteorology*. American Meteorological Society, Boston, MA, pp. 73–76.
- Staggenborg, S.A., Lascano, R.J., Krieg, D.R., 1996. Determining cotton water use in a semiarid climate with the GOSSYM cotton simulation model. *Agron. J.* 88, 740–745.
- Stevens, W.E., Varco, J.J., Johnson, J.R., 1996. Evaluating cotton nitrogen dynamics in the GOSSYM simulation model. *Agron. J.* 88, 127–132.
- Stockle, C.O., Dyke, P.T., Williams, J.R., Jones, C.A., Rosenberg, N.J., 1992a. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part II. Sensitivity analysis at three sites in the Midwestern USA. *Agric. Systems* 38, 239–256.
- Stockle, C.O., Williams, J.R., Rosenberg, N.J., Jones, C.A., 1992b. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part I. Modification of the EPIC model for climate change analysis. *Agric. Systems* 38, 225–238.
- Stockle, C.O., Martin, S.A., Campbell, G.S., 1994. Crop Syst, a cropping systems simulation model: water/nitrogen budgets and crop yield. *Agric. Systems* 46, 335–359.
- Stoorvogel, J.J., 1995. Linking GIS and models: structures and operationalization for a Costa Rican case study. *Neth. J. Agric. Sci.* 43, 19–29.
- Swaney, D.P., Jones, J.W., Boggess, W.G., Wilkerson, G.G., Mishoe, J.W., 1983. A crop simulation method for evaluation of within season irrigation decisions. *Trans. ASAE* 26, 362–368.
- Tanner, B.D., 1990. Automated weather stations. *Remote Sensing Rev.* 5 (1), 73–98.
- Teng, P.S., Batchelor, W.D., Pinnschmidt, H.O., Wilkerson, G.G., 1998. Simulation of pest effects on crops using coupled pest-crop models. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 221–266.
- Thompson, L.M., 1969a. Weather and technology in the production of wheat in the United States. *J. Soil Water Conserv.* 24, 219–224.
- Thompson, L.M., 1969b. Weather and technology in the production of corn in the US corn belt. *Agron. J.* 61, 453–456.
- Thompson, L.M., 1970. Weather and technology in the production of soybeans in the Central United States. *Agron. J.* 62, 232–236.
- Thornton, P.K., Hoogenboom, G., 1994. A computer program to analyze single-season crop model outputs. *Agron. J.* 86 (5), 860–868.
- Thornton, P.K., Wilkens, P.W., 1998. Risk assessment and food security. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 329–345.
- Thornton, P.K., Hoogenboom, G., Wilkens, P.W., Bowen, W.T., 1995. A computer program to analyze multiple-season crop model outputs. *Agron. J.* 87 (1), 131–136.
- Thornton, P.K., Booltink, H.W.G., Stoorvogel, J.J., 1997a. A computer program for geostatistical and spatial analysis of crop model output. *Agron. J.* 89, 620–627.
- Thornton, P.K., Bowen, W.T., Ravelo, A.C., Wilkens, P.W., Farmer, G., Brock, J., Brink, J.E., 1997b. Estimating millet production for famine early warning: an application of crop simulation modelling using satellite and ground-based data in Burkina Faso. *Agric. For. Meteorol.* 83, 95–112.
- Timlin, D., Pachepsky, Y.A., Acock, B., 1996. Agronomic models: a design for a modular, generic soil simulator to interface with plant models. *Agron. J.* 88, 162–169.
- Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), 1998. *Understanding Options for Agricultural Production*. Systems

- Approaches for Sustainable Agricultural Development, Vol. 7. Kluwer Academic Publishers, Dordrecht, Netherlands, 400 pp.
- Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), 1994. DSSAT version 3. University of Hawaii, Honolulu, Hawaii.
- Uhlir, P.F., Carter, G.C. (Eds.), 1994. Crop Modeling and Related Environmental Data, a Focus on Applications for Arid and Semiarid Regions in Developing Countries. CODATA, Paris, France.
- Usrey, L.J., Camp, C.R., Bauer, P.J., Hunt, P.G., 1994. Evaluation of GOSSYM/COMAX for scheduling microirrigation in the southeastern coastal plain. ASAE Paper 94-2585, American Society of Agricultural Engineers, St. Joseph, MI.
- Waldman, S.E., Rickman, R.W., 1996. MODCROP: a crop simulation framework. *Agron. J.* 88, 170–175.
- Wilkerson, G.G., Jones, J.W., Boote, K.J., Ingram, K.T., Mishoe, J.W., 1983. Modeling soybean growth for management. *Trans. ASAE* 26, 63–73.
- Wilks, D.S., 1998. Multisite generalization of a daily stochastic precipitation generation model. *J. Hydrol.* 210 (1–4), 178–191.
- de Wit, C.T., Goudriaan, J., 1974. Simulation of ecological processes. Simulation monographs. Centre for Agricultural Publishing and Documentation (Pudoc). Wageningen, Netherlands.
- de Wit, C.T., Huisman, H., Rabbinge, R., 1987. Agriculture and its environment: are there other ways? *Agric. Systems* 23, 211–236.
- Wolf, J., Evans, L.G., Semenov, M.A., Eckerstein, H., Iglesias, A., 1996. Comparison of wheat simulation models under climate change I. Model calibration and sensitivity analysis. *Clim. Res.* 7, 253–270.
- Yiridoe, E.K., Voroney, R.P., Weersink, A., 1997. Impact of alternative farm management practices on nitrogen pollution of groundwater: evaluation and application of CENTURY model. *J. Environ. Quality* 26, 1255–1263.
- Zadoks, J.C., 1989. EPIPE, a computer-based decision support system for pest and disease control in wheat: its development and implementation in Europe. In: Leonard, K.J., Fry, W.E. (Eds.), *Plant Disease Epidemiology*, Vol. 2: Genetics, Resistance, and Management. McGraw-Hill, New York, pp. 3–29.
- Zadoks, J.C., Rijsdijk, F.H., Rabbinge, R., 1984. EPIPE: a systems approach to supervised control of pests and diseases of wheat in the Netherlands. In: Conway, G.R. (Ed.), *Pest and Pathogen Control: Strategic, Tactical, and Policy Models*. Wiley, New York, pp. 344–351.

The DSSAT cropping system model[☆]

J.W. Jones^{a,*}, G. Hoogenboom^b, C.H. Porter^a, K.J. Boote^a,
W.D. Batchelor^c, L.A. Hunt^d, P.W. Wilkens^e, U. Singh^e, A.J. Gijsman^a,
J.T. Ritchie^f

^a Agricultural and Biological Engineering Department, P.O. Box 110570, University of Florida, Gainesville, FL, USA

^b Department of Biological and Agricultural Engineering, University of Georgia, 165 Gordon Futral Court, Griffin, GA 30223, USA

^c Agricultural and Biosystems Engineering, 219b Davidson Hall, Iowa State University, Ames, IA 50011, USA

^d Department of Plant Agriculture, Crop Science Building, University of Guelph, Guelph, Ont., Canada N1G 2W1

^e International Fertilizer Development Center, Muscle Shoals, AL, USA

^f Department of Crop and Soil Science, Michigan State University, East Lansing, MI, USA

Abstract

The decision support system for agrotechnology transfer (DSSAT) has been in use for the last 15 years by researchers worldwide. This package incorporates models of 16 different crops with software that facilitates the evaluation and application of the crop models for different purposes. Over the last few years, it has become increasingly difficult to maintain the DSSAT crop models, partly due to fact that there were different sets of computer code for different crops with little attention to software design at the level of crop models themselves. Thus, the DSSAT crop models have been re-designed and programmed to facilitate more efficient incorporation of new scientific advances, applications, documentation and maintenance. The basis for the new DSSAT cropping system model (CSM) design is a modular structure in which components separate along scientific discipline lines and are structured to allow easy replacement or addition of modules. It has one Soil module, a Crop Template module which can simulate different crops by defining species input files, an interface to add individual crop models if they have the same design and interface, a Weather module, and a module for dealing with competition for light and water among the soil, plants, and atmosphere. It is also designed for incorporation into various application packages, ranging from those that help researchers adapt and test the CSM to those that operate the DSSAT–CSM to simulate production over time and space for different purposes. In this paper, we describe this new DSSAT–CSM design as well as approaches used to model the primary scientific components (soil, crop, weather, and management). In addition, the paper describes data requirements and methods used for model evaluation. We provide an overview of the hundreds of published studies in which the DSSAT crop models have been used for various applications. The benefits of the new, re-designed DSSAT–CSM will provide considerable opportunities to its developers and others in the scientific community for greater cooperation in interdisciplinary research and in the application of knowledge to solve problems at field, farm, and higher levels.

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* Corresponding author. Tel.: +1-352-392-1864x289; fax: +1-352-392-4092

E-mail address: jjones@agen.ufl.edu (J.W. Jones).

1. Introduction

Information needs for agricultural decision making at all levels are increasing rapidly due to increased demands for agricultural products and increased pressures on land, water, and other natural resources. The generation of new data through traditional agronomic research methods and its publication are not sufficient to meet these increasing needs. Traditional agronomic experiments are conducted at particular points in time and space, making results site- and season-specific, time consuming and expensive. Unless new data and research findings are put into formats that are relevant and easily accessible, they may not be used effectively. The decision support system for agrotechnology transfer (DSSAT) was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project (IBSNAT, 1993; Tsuji, 1998; Uehara, 1998; Jones et al., 1998), to facilitate the application of crop models in a systems approach to agronomic research. Its initial development was motivated by a need to integrate knowledge about soil, climate, crops, and management for making better decisions about transferring production technology from one location to others where soils and climate differed (IBSNAT, 1993; Uehara and Tsuji, 1998). The systems approach provided a framework in which research is conducted to *understand* how the system and its components function. This understanding is then integrated into models that allow one to *predict* the behavior of the system for given conditions. After one is confident that the models simulate the real world adequately, computer experiments can be performed hundreds or even thousands of times for given environments to determine how to best *manage* or *control* the system. DSSAT was developed to operationalize this approach and make it available for global applications. The DSSAT helps decision-makers by reducing the time and human resources required for analyzing complex alternative decisions (Tsuji et al., 1998). It also provides a framework for scientific cooperation through research to integrate new knowledge and apply it to research questions.

Prior to the development of the DSSAT, crop models were available, but these were used mostly in labs where they were created. For example, the original crop models implemented in DSSAT, the CERES models for maize (Jones and Kiniry, 1986) and wheat (Ritchie and Otter, 1985) and the SOYGRO soybean (Wilkerson et al., 1983) and PNUTGRO peanut (Boote et al., 1986) models, were already enjoying early successes. Those models required different file and data structures and had different modes of operation. Because the IBSNAT project aimed to provide a framework for cropping system analysis, these crop models had to be revised to make them compatible regarding data inputs and application modes. The decision to make these models compatible led to the design of the DSSAT and the ultimate development of compatible models for additional crops, such as potato, rice, dry beans, sunflower, and sugarcane (Hoogenboom et al., 1994a; Jones et al., 1998; Hoogenboom et al., 1999). In DSSAT v3.5, the latest release at the time this paper was written, there are models for 16 different crops and a bare fallow simulation.

The DSSAT is a collection of independent programs that operate together; crop simulation models are at its center (Fig. 1). Databases describe weather, soil, experiment conditions and measurements, and genotype information for applying the models to different situations. Software helps users prepare these databases and compare simulated results with observations to give them confidence in the models or to determine if modifications are needed to improve accuracy (Uehara, 1989; Jones et al., 1998). In addition, programs contained in DSSAT allow users to simulate options for crop management over a number of years to assess the risks associated with each option. DSSAT was first released (v2.1) in 1989; additional releases were made in 1994 (v3.0) (Tsuji et al., 1994) and 1998 (v3.5) (Hoogenboom et al., 1999).

The DSSAT is currently undergoing major revisions, not in its aim but in its design. One major reason for this re-design is that each individual crop model in DSSAT v3.5 had its own soil model components. Although simulation of crop rotations was possible in that version, the

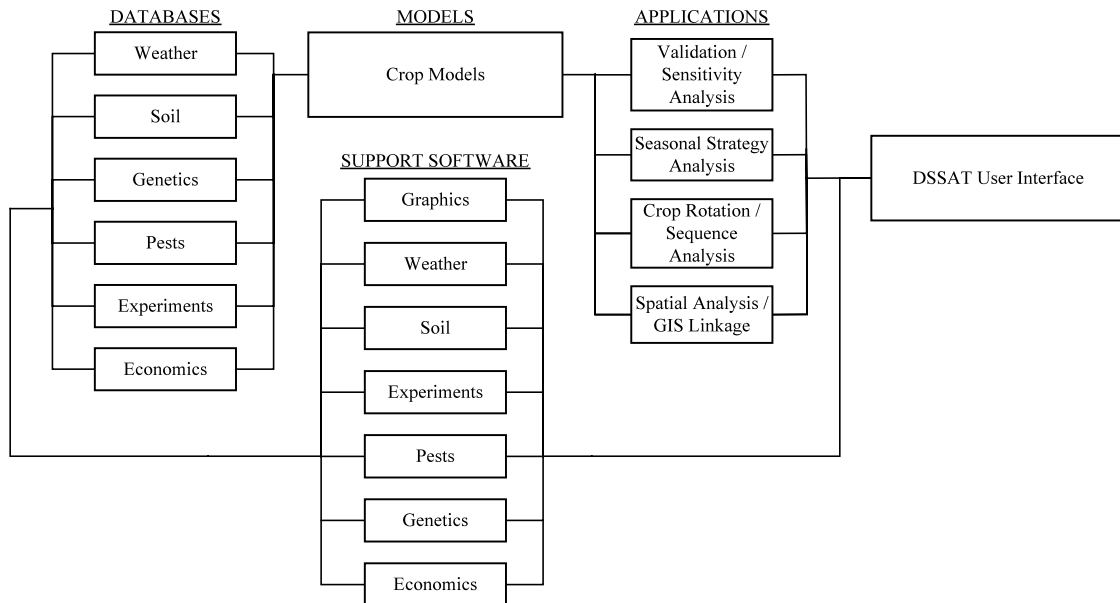


Fig. 1. Diagram of database, application, and support software components and their use with crop models for applications in DSSAT v3.5.

approach that was used was fraught with many problems regarding programming, compatibility of soil models, and potential bugs in different sets of code. At the heart of the DSSAT revisions is a new cropping system model (DSSAT–CSM), which incorporates all crops as modules using a single soil model. This was accomplished by completely redesigning the crop models, starting with CROPGRO, using a modular structure (Jones et al., 2001). This design was motivated to a large extent by the modular features of APSIM (McCown et al., 1996), but it uses the approach developed by van Kraalingen (1990, 1991, 1995), Kraalingen et al. (2003) in the FSE/FST software for programming the behavior of each module. The new CSM now contains models of 16 crops derived from the old DSSAT CROPGRO and CERES models (maize, wheat, soybean, peanut, rice, potato, tomato, drybean, sorghum, millet, pasture, chickpea, cowpea, velvetbean, brachiaria grass, and faba bean).

The aims of the DSSAT–CSM are (1) to simulate monocrop production systems considering weather, genetics, soil water, soil carbon and nitrogen, and management in single or multiple

seasons and in crop rotations at any location where minimum inputs are provided, (2) to provide a platform for easily incorporating modules for other abiotic and biotic factors, such as soil phosphorus and plant diseases, (3) to provide a platform that allows one to easily compare alternative modules for specific components to facilitate model improvement, evolution, and documentation, and (4) to provide a capability for easily introducing the CSM into additional application programs in a modular, well documented way. The purpose of this paper is to describe the DSSAT–CSM, its design, data requirements, evaluation and applications.

2. Overall description of the DSSAT cropping system model

The DSSAT–CSM simulates growth, development and yield of a crop growing on a uniform area of land under prescribed or simulated management as well as the changes in soil water, carbon, and nitrogen that take place under the cropping system over time. The DSSAT–CSM is

structured using the modular approach described by Jones et al. (2001) and Porter et al. (2000). The most important features of our approach are:

- It separates modules along disciplinary lines,
- It defines clear and simple interfaces for each module,
- It enables individual components to be plugged in or unplugged with little impact on the main program or other modules, i.e. for comparison of different models or model components,
- It facilitates documentation and maintenance of code,
- It enables modules written in different programming languages to be linked together,
- It allows for easy integration into different types of application packages due to the well defined and documented interface to the modules,
- It allows for evolution to integrate other components, such as livestock and intercropping, through well defined module interfaces, and
- It facilitates cooperation among different model development groups where each can focus on specific modules as building blocks for expanding the scope and utility of the CSM. All co-authors of this paper actively contributed to the overall design of DSSAT–CSM, provided modules, and are responsible for maintenance of specific modules.

The DSSAT–CSM has a main driver program, a land unit module, and modules for the primary components that make up a land unit in a cropping system (Fig. 2). The Primary modules are for weather, soil, plant, soil–plant–atmosphere interface, and management components. Collectively, these components describe the time changes in the soil and plants that occur on a single land unit in response to weather and management. In contrast to earlier versions of DSSAT and its crop models, the DSSAT–CSM incorporates models of all crops within one set of code allowing all crops to utilize the same soil model components. This design feature greatly simplifies the simulation of crop rotations since soil processes operate continuously, and different

crops are planted, managed, and harvested according to cropping system information provided as inputs to the model.

Each module has six operational steps, as shown in Fig. 2 (run initialization, season initialization, rate calculations, integration, daily output, and summary output). The main program controls when each of these steps is active, and when each module performs the task that is called for. This feature, an adaptation of van Kraalingen's (1991, 1995) work, allows each module to read its own inputs, initialize itself, compute rates, integrate its own state variables, and write outputs completely independent from the operation of other modules. Only a few 'interface' variables are communicated to and from each module. This allows one to 'unplug' a module and replace it with a different one as long as it communicates the same variables to the rest of the modules, even if the parameters, state variables, and module input files are different. State variables are written after integration to represent the state of the system at the end of the day, and initial values are written during initialization for day 0. More details of this modular design can be found in Porter et al. (2000).

Different types of applications are accomplished in DSSAT–CSM by using different modes to call the land unit module on a daily basis; the mode is specified as a command line argument when the model is run. The basic mode provides for interactive sensitivity analysis and comparison of simulated vs. observed field data. A second mode of operation simulates crops over a number of years of weather using the same soil initial conditions. This mode allows one to evaluate the effects of uncertain future weather conditions on decisions made when all soil initial conditions are known. A third mode operates the cropping system modules to simulate crop rotations over a number of years, and soil conditions are initialized only at the very start of the simulation. A fourth mode operates the CSM to simulate one or more crops over space (i.e. for precision agriculture, land use management or other spatial-based applications). One can also completely replace the main driver for other applications, thereby providing a highly flexible approach for development of additional applications and user interfaces

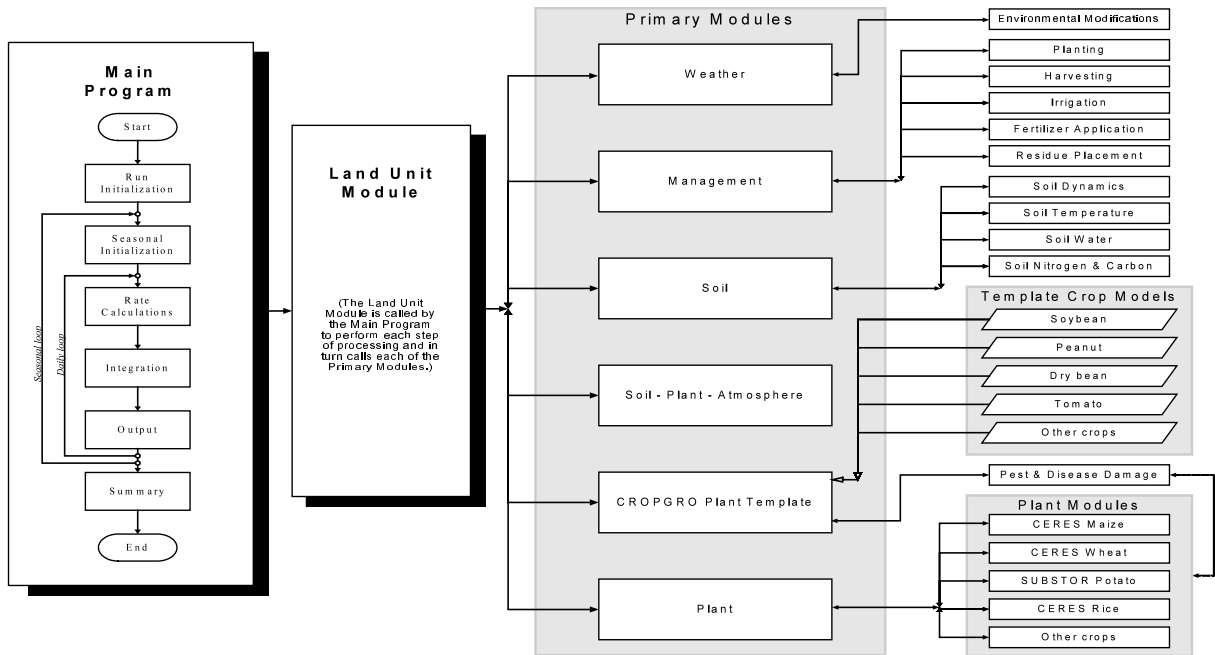


Fig. 2. Overview of the components and modular structure of the DSSAT-CSM.

without having to modify code for any other module. The application driver communicates with only one module—the Land Unit module as shown in Fig. 2. The Land Unit Module provides the interface between the application driver (main program) and all of the components that interact in a uniform area of land.

Table 1 lists the primary and sub modules currently used in the CSM and summarizes their functions. There are two important points to be made about this table. First, sub modules operate exactly like Primary modules. Each sub module will usually perform six steps, and thus it can be replaced by another module that can operate with its defined input interface variables and produce the defined module output interface variables. Thus, the concept of ‘interface’ variables is critical to the modular approach used in DSSAT-CSM. There can be additional levels of sub modules, each behaving the same way. For example, the CERES-Maize sub module could have a phenology sub module. One could unplug this phenology module, for example, and introduce a new one, if desired, without changing the rest of the CERES-Maize module. Any module or sub module can

also have other subroutines as needed; there are no technical restrictions about how simple or complex a module should be.

The second important point is that there are two different ways of introducing new crops into the DSSAT-CSM. One can introduce a new module for a crop by interfacing it with the Plant module. This is the approach that was used to interface the CERES and other models, which were operated as stand-alone crop models in DSSAT v3.5, such as potato, cassava, sugarcane, and sunflower. In this approach, a model developer would create the code for the crop growth module, adhering to the interface for the Plant module described below, and simply add it to the rest of the code. An advantage of this approach is that it enables one to easily test a model from outside the DSSAT group. The second way to introduce a new crop is through the use of a Crop Template approach. This can be implemented with the CROPGRO approach and allows users to modify values in a species Crop Template file without changing any code. The CROPGRO development team has used this approach in creating models for different species, including faba bean (Boote et al., 2002),

Table 1
Summary description of modules in the DSSAT–CSM

Modules	Sub modules	Behavior
Main program (DSSAT–CSM)		Controls time loops,, determines which modules to call based on user input switches, controls print timing for all modules
Land unit		Provides a single interface between cropping system behavior and applications that control the use of the cropping system. It serves as a collection point for all components that interact on a homogenous area of land
Weather		Reads or generates daily weather parameters used by the model. Adjusts daily values if required, and computes hourly values
Soil	Soil dynamics	Computes soil structure characteristics by layer. This module currently reads values from a file, but future versions can modify soil properties in response to tillage, etc
	Soil temperature module	Computes soil temperature by layer
	Soil water module	Computes soil water processes including snow accumulation and melt, runoff, infiltration, saturated flow and water table depth. Volumetric soil water content is updated daily for all soil layers. Tipping bucket approach is used
	Soil nitrogen and carbon module	Computes soil nitrogen and carbon processes, including organic and inorganic fertilizer and residue placement, decomposition rates, nutrient fluxes between various pools and soil layers. Soil nitrate and ammonium concentrations are updated on a daily basis for each layer
SPAM		Resolves competition for resources in soil–plant–atmosphere system. Current version computes partitioning of energy and resolves energy balance processes for soil evaporation, transpiration, and root water extraction
CROPGRO Crop Template module		Computes crop growth processes including phenology, photosynthesis, plant nitrogen and carbon demand, growth partitioning, and pest and disease damage for crops modeled using the CROPGRO model Crop Template (soybean, peanut, dry bean, chickpea, cowpea, faba bean, tomato, Macuna, Brachiaria, Bahiagrass)
Individual plant growth modules	CERES-Maize; CERES-Wheat; CERES-Rice; SubStor-Potato; Other plant models	Modules that simulate growth and yield for individual species. Each is a separate module that simulates phenology, daily growth and partitioning, plant nitrogen and carbon demands, senescence of plant material, etc
Management operations module	Planting	Determines planting date based on read-in value or simulated using an input planting window and soil, weather conditions
	Harvesting	Determines harvest date, based on maturity, read-in value or on a harvesting window along with soil, weather conditions
	Irrigation	Determines daily irrigation, based on read-in values or automatic applications based on soil water depletion
	Fertilizer	Determines fertilizer additions, based on read-in values or automatic conditions
	Residue	Application of residues and other organic material (plant, animal) as read-in values or simulated in crop rotations

brachiaria grass (Giraldo et al., 1998), tomato (Scholberg et al., 1997), chickpea (Singh and Virmani, 1994) and velvet bean (Hartkamp et al., 2002), for example. A major advantage of this approach is that working with the Crop Template will no doubt be less prone to errors.

3. Component descriptions

The main program reads information from the DSSAT standard file that describes a particular experiment or situation to be simulated (Hunt et al., 2001) and sets a number of variables for controlling a simulation run. It initiates the simulation by setting the DYNAMIC variable for initializing the run and calls the Land Unit module. It then starts a crop season time loop and calls the Land Unit module for initializing variables that must be set at the start of each season. After initialization of the seasonal loop, the main program starts a daily loop and calls the Land Unit module three times in sequence, first to compute rates, secondly to integrate, and finally to report daily outputs. After a crop season is completed, it calls the Land Unit module to produce season-end variables and to create summary output files. A summary of these operations is presented in Fig. 2. The main program provides these timing and simulation control variables to all modules.

The Land Unit module calls each of the primary cropping system modules shown in Fig. 2 each day. At the start of each new crop season, it obtains management information from the DSSAT input file. The Land Unit and Primary modules link to sub modules, and thus are used to aggregate processes and information describing successive components of the cropping system. For example, the Soil module has four sub modules that integrate soil water, soil carbon and nitrogen, soil temperature and soil dynamics processes. The Plant module has sub modules for various crops. Below, we describe these modules and sub modules, emphasizing those for simulating soil and plant growth processes and their interactions. Table 2 shows the variables that are currently passed from each of the Primary modules to the

Land Unit module, excluding the timing and control variables. These interface variables are available for any primary module since they are passed into the Land Unit module.

3.1. Weather module

The main function of the Weather module is to read or generate daily weather data. It reads in daily weather values (maximum and minimum air temperatures, solar radiation and precipitation, relative humidity and wind speed when available), from the daily weather file. Hourly weather values are computed for use by some modules that require them. This module generates daily weather data using the WGEN (Richardson, 1981, 1985) or SIMMETEO (Geng et al., 1986, 1988) weather generators. It also can modify daily weather variables for studying climate change or simulating experiments in which solar radiation, rainfall, maximum and minimum temperatures, day length, and/or atmospheric CO₂ concentrations were set at constant values or increased/decreased relative to their read-in values. Based on the inputs provided from the management file, the Weather module knows whether to just read-in daily values or to generate or modify them (using the Environmental Modification sub module). The variables listed in Table 2a are passed through its interface.

3.2. Soil module

The soil in the land unit is represented as a one-dimensional profile; it is homogenous horizontally and consists of a number of vertical soil layers. The Soil module integrates information from four sub modules: soil water, soil temperature, soil carbon and nitrogen, and soil dynamics. Table 2b defines the variables produced by this module for use in other modules. The soil dynamics module is designed to read-in soil parameters for the land unit and to modify them based on tillage, long-term changes in soil carbon, or other field operations. The soil dynamics module currently reads in soil properties from a file. Descriptions of the other three sub modules of Soil are given below.

Table 2

Definition of all interface variables showing the primary modules in which they are computed and provided as outputs in the current version of DSSAT–CSM

Variable	Definition	Variable	Definition
<i>(a) Weather module (WEATHR) outputs</i>			
CLOUDS	Relative cloudiness factor (0–1)	TAV	Average annual air temperature (°C) (used with TAMP to calculate soil temperature)
CO ₂	Atmospheric carbon dioxide concentration (μmol[CO ₂]/mol[air])	TDEW	Dew point temperature (°C)
DAYL	Day length on day of simulation (from sunrise to sunset) (h)	TGRO(I)	Hourly air temperature (°C)
PAR	Daily photosynthetically active radiation or photon flux density (moles[quanta]/(m ² d))	TMAX	Maximum daily temperature (°C)
RAIN	Daily total precipitation (mm)	TMIN	Minimum daily temperature (°C)
SRAD	Daily total solar radiation (MJ/(m ² d))	WINDSP	Wind speed (km/d)
TAMP	Amplitude of annual air temperature (°C) (used to calculate soil temperature)	XLAT	Latitude (°)
<i>(b) Soil module (SOIL) outputs</i>			
BD(L)	Bulk density, soil layer L (g[soil]/cm ³ [soil])	PH(L)	pH in soil layer L
DLAYR(L)	Thickness of soil layer L (cm)	SAT(L)	Soil water content in layer L at saturation (cm ³ [water]/cm ³ [soil])
DUL(L)	Soil water content at drained upper limit in soil layer L (cm ³ [water]/cm ³ [soil])	SRFTEMP	Temperature of soil surface litter (°C)
LL(L)	Soil water content in soil layer L at lower limit of plant extractable soil water (cm ³ [water]/cm ³ [soil])	ST(L)	Soil temperature in soil layer L (°C)
NH ₄ (L)	Ammonium N in soil layer L (μg[N]/g[soil])	SW(L)	Soil water content in layer L (cm ³ [water]/cm ³ [soil])
NLAYR	Actual number of soil layers	SWDELTS (L)	Change in soil water content due to drainage in layer L (cm ³ [water]/cm ³ [soil])
NO ₃ (L)	Nitrate in soil layer L (μg[N]/g[soil])	WINF	Water available for infiltration-rainfall plus net irrigation minus runoff (mm/d)
<i>(c) Plant growth module outputs (from CROPGRO Crop Template and PLANT Modules)</i>			
NSTRES	Nitrogen stress factor (1 = no stress, 0 = max stress)	UNO3(L)	Rate of root uptake of NO ₃ (kg[N]/(ha d))
RLV(L)	Root length density for soil layer L (cm[root]/cm ³ [soil])	XHLAI	Healthy LAI (m ² [leaf]/m ² [ground])
SENCLN(I, J)	Daily senesced plant matter. I = 0 for surface, 1 for soil; J = 1 for C, 2 for lignin, 3 for N (g[C,N,or lignin]/(m ² d))	XLAI	LAI (m ² [leaf]/m ² [ground])
STGDOY(I)	Day when plant stage I occurred (YYDDDD)(YRDOY)	YREMRG	Day of emergence (YYDDDD)
UNH ₄ (L)	Rate of root uptake of NH ₄ (kg[N]/(ha d))	YRNR8	Harvest maturity date (YYDDDD)(YRDOY)
<i>(d) SPAM outputs</i>			
EO	Potential ET rate (mm/d)	SWDELTX(L)	Change in soil water content due to root water uptake in layer L (cm ³ [water]/cm ³ [soil])
EOP	Potential plant transpiration rate (mm/d)	TRWU	Actual daily root water uptake over soil profile (cm/d)
FDINT	Light interception by leaves	TRWUP	Potential daily root water uptake over soil profile (cm/d)
FLOW(L)	Unsaturated soil water flow: + = upward, – = downward (cm/d)		
<i>(e) Operations management module outputs (OPMGMT)</i>			
FERTYPE	Fertilizer type for current application	RESSRF	Residue left on surface of soil (kg[residue]/ha)
FERDEPTH	Fertilizer incorporation depth on current day of simulation (cm)	RESNIT	N concentration of the residue for current application (%)

Table 2 (Continued)

Variable	Definition	Variable	Definition
FERNIT	Amount of nitrogen in fertilizer applied on current day of simulation (kg[N]/ha)	RESDEPTH	Incorporation depth of newly added residues (cm)
HAREND	End of season or harvest date (YYDDD)	RESTYPE	Residue type for current application
IRRAMT	Irrigation amount for today (mm/d)	YRPLT	Planting date (YYDDD)
RESSOL	Amount of residue applied to the soil (kg[dry matter]/ha)		

3.2.1. Soil water sub module

The soil water balance model developed for CERES-Wheat by Ritchie and Otter, (1985) was adapted for use by all of the DSSAT v3.5 crop models (Jones and Ritchie, 1991; Jones, 1993; Ritchie, 1998). This one-dimensional model computes the daily changes in soil water content by soil layer due to infiltration of rainfall and irrigation, vertical drainage, unsaturated flow, soil evaporation, and root water uptake processes. In the new DSSAT–CSM, soil evaporation, plant transpiration, and root water uptake processes were separated out into a soil–plant–atmosphere module (SPAM) to create more flexibility for expanding and maintaining the model. Otherwise, the water balance model in DSSAT–CSM is the same as in DSSAT v3.5 individual crop models, and individual processes are modeled using the same logic and equations. The soil has parameters that describe its surface conditions and layer-by-layer soil water holding and conductivity characteristics (Table 2b). The model uses a ‘tipping bucket’ approach for computing soil water drainage when a layer’s water content is above a drained upper limit parameter. Upward unsaturated flow is also computed using a conservative estimate of the soil water diffusivity and differences in volumetric soil water content of adjacent layers (Ritchie, 1998).

Soil water infiltration during a day is computed by subtracting surface runoff from rainfall that occurs on that day. The SCS method (Soil Conservation Service, 1972) is used to partition rainfall into runoff and infiltration, based on a ‘curve number’ that attempts to account for texture, slope, and tillage. The modification to this method that was developed by Williams et al. (1984) is used in the model; it accounts for layered soils and soil water content at the time when rainfall occurs.

When irrigation is applied, the amount applied is added to the amount of rainfall for the day to compute infiltration and runoff. Drainage of liquid water through the profile is first calculated based on an overall soil drainage parameter assumed to be constant with depth. The amount of water passing through any layer is then compared with the saturated hydraulic conductivity of that layer, if this parameter is provided. If the saturated hydraulic conductivity of any layer is less than computed vertical drainage through that layer, actual drainage is limited to the conductivity value, and water accumulates above that layer. This feature allows the model to simulate poorly drained soils and perched water tables. For example, a soil may have a layer with very low or no drainage at the bottom of the profile. Vertical drainage from the profile would not occur or it would be very low, limited by the saturated hydraulic conductivity value of the bottom layer.

Evaporation of water from the soil surface and root water uptake (transpiration) from each layer are computed in the SPAM and communicated to this soil water balance module. Each day, the soil water content of each layer is updated by adding or subtracting daily flows of water to or from the layer due to each process.

3.2.2. Soil carbon and nitrogen balance sub module

The DSSAT–CSM has two options to simulate the soil organic matter (SOM) and nitrogen balance. The original SOM model in DSSAT v3.5 (Godwin and Jones, 1991; Godwin and Singh, 1998), based on the PAPRAN model of Seligman and Van Keulen (1981), was converted into a modular structure and retained in the new DSSAT–CSM. Additionally, a SOM module developed by Gijsman et al. (2002), based on the

CENTURY model (Parton et al., 1988, 1994), is included. This CENTURY-based module was added to facilitate simulation of soil organic sequestration potential for different crop rotations over long time periods after initializing soil C and other variables only once at the start of the simulation. The main differences are that the CENTURY-based module (i) divides the SOM in more fractions, each of which has a variable C:N ratio and can mineralize or immobilize nutrients, (ii) it has a residue layer on top of the soil, and (iii) the decomposition rate is texture dependent. In both SOM modules, organic matter decomposition depends on soil temperature and water content. Because of the widespread use of the CENTURY model and interest in its use in CSMs, we focus on this component in this section. This version is more appropriate for use in low input agricultural systems, for example those that use green manure where the surface layer is crucial. Gijsman et al. (2002) showed that this new component greatly improved the accuracy of simulating the long-term changes in soil carbon in the Rothamsted bare fallow experiment.

The CENTURY-based module distinguishes three types of SOM: (1) easily decomposable (microbial) SOM1, (2) recalcitrant SOM2, which contains lignin and cell walls, and (3) an almost inert SOM3. At initialization of the simulation, the fractional ratio of these three pools is set, with SOM1 of only about 2% of total SOM, while SOM2 and SOM3 vary with the management history of the soil (grassland or cultivated) and the degree of depletion. The improved SOM module also allows one to perform more realistic simulations on carbon sequestration, i.e. the build up of soil organic C under different management systems.

Most of the interface input variables to the soil carbon and nitrogen balance modules are soil properties and variables computed in the soil water and soil temperature sub modules. Transport of N through the soil to deeper layers is based on water flux values obtained from the soil water module. The only interface variable from the Plant module is the array of plant mass being senesced and abscised onto the soil surface daily. The output variables sent to other modules are ammo-

nium and nitrate nitrogen in each soil layer (Table 2b).

3.2.3. Soil temperature sub module

The soil temperature model currently in the DSSAT–CSM was originally derived from the EPIC model (Williams et al., 1984; Jones et al., 1991) and is the same as the one in the CERES and CROPGRO models in DSSAT v3.5. Soil temperature is computed from air temperature and a deep soil temperature boundary condition that is calculated from the average annual air temperature and the amplitude of monthly mean temperatures. It also includes a simple approach to calculate the impact of solar radiation and albedo on the soil surface temperature. However, it does not consider differences in soil wetness or surface conditions. Soil temperature is used to modify plant processes (emergence) and SOM decomposition. Additional details on this component are in Jones and Kiniry (1986) in the description of the CERES-Maize model.

3.3. Soil–plant–atmosphere module

This module computes daily soil evaporation and plant transpiration. The current version was originally developed by Ritchie (1972) and was used in all of the DSSAT v3.5 crop models as part of the soil water balance. This module brings together soil, plant and atmosphere inputs and computes light interception by the canopy, potential evapotranspiration (ET) as well as actual soil evaporation and plant transpiration (Table 2d). It also computes the root water uptake of each soil layer. The daily weather values as well as all soil properties and current soil water content, by layer, are required as input. In addition, leaf area index (LAI) and root length density for each layer are needed.

The module first computes daily net solar radiation, taking into account the combined soil and plant canopy albedo. It calculates potential ET using one of two current options. The default Priestley and Taylor (1972) method requires only daily solar radiation and temperature, and was described in detail by Ritchie (1972), Ritchie and Otter, (1985) and Jones and Ritchie (1991). The

Penman-FAO (Doorenbos and Pruitt, 1977) method for computing potential ET can optionally be used to better account for arid or windy conditions, but weather data files must include wind and humidity data. We have also created options for using the Penman–Monteith (Monteith, 1986) method for daily potential ET calculations and for using hourly energy balance (unpublished).

The potential ET is partitioned into potential soil evaporation based on the fraction of solar energy reaching the soil surface, based on a negative exponential function of LAI, and potential plant transpiration. Actual soil evaporation is based on a two-stage process (Ritchie, 1972). After the soil surface is first wetted due to either rainfall or irrigation, evaporation occurs at the potential rate until a cumulative soil evaporation amount since wetting is reached. Then, a soil-limiting daily soil evaporation amount is computed as a square root function of time since stage one ended. Actual soil evaporation is the minimum of the potential and soil-limiting calculations on a daily basis. If evaporation is less than potential soil evaporation, this difference is added back to potential plant transpiration to account for the increased heat load on the canopy when the soil surface is dry (Ritchie, 1972).

To determine whether the soil or atmosphere limits plant transpiration, potential root water uptake is computed by calculating a maximum water flow to roots in each layer and summing these values (Ritchie and Otter, 1985; Ritchie, 1998; Jones and Ritchie, 1991). These calculations account for root length density in each layer and the soil water content in the layer. The equation that computes potential root water uptake in each layer is an approximation to the radial flow equation, where assumptions are made about soil texture effect on hydraulic conductivity, root diameter, and a maximum water potential difference between roots and the soil. The actual plant transpiration is then computed as the minimum of potential plant transpiration and the potential root water uptake. Thus, the atmosphere can limit transpiration by low solar radiation and cool temperatures, the canopy can limit it by low LAI, and the soil can limit it by low soil water

content, low root length density, and their distributions relative to each other.

This method for computing ET has provided an excellent functional approach for determining water stress in the plant without explicitly modeling water status in the plant component. The ratio of actual ET to potential ET, if less than 1.0, indicates that stomatal conductance would have had to be decreased sometimes during the day to prevent plant desiccation. This ratio is typically used in the Plant modules to reduce photosynthesis in proportion to relative decreases in transpiration. Similarly, a ratio of potential root water uptake and potential transpiration is used to reduce plant turgor and expansive growth of crops. The rationale for this is that as soil water becomes more limiting, turgor pressure in leaves would decrease and affect leaf expansion before photosynthesis is reduced. In the current Plant modules this ratio is set to 1.5.

3.4. Template crop module (CROPGRO)

The CROPGRO Crop Template module in DSSAT–CSM is the same as that described by Boote et al. (1998a), although its components were modified to fit the modular structure. The interface variables linking this module (and the Plant module where CERES and other individual crops are modeled) to other modules are defined in Table 2c. CROPGRO was created after our earlier experience in adapting SOYGRO to PNUTGRO and BEANGRO (Hoogenboom et al., 1994b) suggested to us the value of having one common program with values from files providing information for each species to be modeled. CROPGRO was then developed as a generic approach for modeling crops in the sense that it has one common source code, yet it can predict the growth of a number of different crops. Currently, it simulates ten crops; including seven grain legumes (soybean (*Glycine max* L. Merr.); peanut (*Arachis hypogaea* L.); dry bean (*Phaseolus vulgaris* L.); chickpea; cowpea; velvet bean and faba bean (*Vicia faba* L.)), and non-legumes such as tomato (*Lycopersicon esculentum* Mill.) (Scholberg et al., 1997; Boote et al., 1998a,b). This versatility is

Table 3
Summary of types of parameters used in the Crop Template approach

Section	Description
Photosynthesis	Coefficients for partitioning at emergence and final growth stage, stem senescence during water stress, and nodule growth Functions that define leaf N and temperature effects on photosynthesis
Respiration	Respiration parameters associated with various growth processes 'Maximum', 'normal growth', and 'final' protein concentrations of leaf, stem, root, shell, seed, and nodule tissues
Plant composition values	Carbohydrate–cellulose, lipid, lignin, organic acid concentration of leaf, stem, root, shell, seed, and nodule tissues Effects of temperature on seed lipid concentration
Carbon and nitrogen mining parameters	Coefficients for carbohydrate reserves in stem tissue Fraction of new leaf, stem, root and shell tissue growth that is available carbohydrate Mobilization rates of carbohydrate and protein from vegetative tissue
Nitrogen fixation parameters	Nodule growth and senescence parameters Arrays that define the effects of temperature, soil water, and nodule age on nitrogen fixation and nodule growth
Plant growth and partitioning parameters	Dry matter partitioning to leaf, stem, and root as function of vegetative stage Coefficients for partitioning at emergence, final growth stage, stem senescence, during water stress, and nodule growth Parameters that define leaf expansion response to temperature and solar radiation Initial root depth and length, root water uptake parameters Relative effects of temperature on pod set, seed growth and relative change in partitioning Relative effects of soil water content on peanut pegging and pod addition
Senescence factors	Senescence parameters related to vegetative stage, freeze damage, nitrogen mobilization, drought, canopy self shading
Phenology parameters	Curves that define temperature effect on vegetative, early reproductive, and late reproductive development Parameters for each growth stage: preceding stage, photoperiod function, temperature function, temperature and water sensitivity, N & P sensitivity
Canopy height and width growth parameters	Internode length and canopy width increase as a function of plant vegetative stage Internode elongation as a function of temperature and photosynthetic photon flux density

These parameters are contained in a separate species file for each crop using the Crop Template approach of the DSSAT–CSM

achieved through input files that define species traits.

An overview of the types of parameters contained in the species file is given in Table 3. Each species file contains information on base temperatures (T_b) and optimum temperatures (T_{opt}) for developmental processes (rate of emergence, rate of leaf appearance, and rate of progress toward flowering and maturity) and growth processes (photosynthesis, nodule growth, N_2 -fixation, leaf

expansion, pod addition, seed growth, N mobilization, etc.). The file also includes information on photosynthesis, N_2 -fixation, tissue composition, growth and maintenance respiration coefficients.

The CROPGRO Crop Template provides for ecotype and cultivar traits to be defined in read-in files. Table 4 lists cultivar coefficients and definitions (Boote et al., 1998a). Cultivar differences are created by 15 'cultivar' traits. The cultivar traits include two daylength sensitivity traits, five im-

Table 4

Genetic coefficients used in the CROPGRO Crop Template module for modeling different cultivars

Trait	Definition of trait
ECO#	Code for the ecotype to which this cultivar belongs (see *.eco file)
CSDL	Critical short day length below which reproductive development progresses with no daylength effect (for short day plants) (h)
PPSEN	Slope of the relative response of development to photoperiod with time (positive for short day plants) (1/h)
EM-FL	Time between plant emergence and flower appearance (R1) (photothermal days)
FL-SH	Time between first flower and first pod (R3) (photothermal days)
FL-SD	Time between first flower and first seed (R5) (photothermal days)
SD-PM	Time between first seed (R5) and physiological maturity (R7) (photothermal days)
FL-LF	Time between first flower (R1) and end of leaf expansion (photothermal days)
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 vpm CO ₂ , and high light (mg CO ₂ /(m ² s))
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm ² /g)
SIZELF	Maximum size of full leaf (three leaflets) (cm ²)
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell
WTPSD	Maximum weight per seed (g)
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)
SDPDV	Average seed per pod under standard growing conditions (#seed/pod)
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)
<i>Frequently used important traits from the ecotype file</i>	
RIPRO	Increase in daylength sensitivity after anthesis (CSDL decreases by this amount (h))
FL-VS	Time from first flower to last leaf on main stem (photothermal days)
THRESH	The maximum ratio of (seed/(seed+shell)) at maturity causes seed to stop growing as their dry weight increases until shells are filled in a cohort
SDPRO	Fraction protein in seeds (g[protein]/g[seed])
SDLIP	Fraction oil in seeds (g[oil]/g[seed])

Also included are definitions of frequently used traits from the ecotype file.

portant life cycle ‘phase’ durations, light-saturated leaf photosynthesis, vegetative traits, and reproductive traits. There are 19 traits in the ecotype file that were proposed to vary less often, such as thermal time to emergence and first leaf stages, but some traits from this file have been used frequently to characterize cultivars.

Phenology is an important component of the CROPGRO Crop Template approach. This component uses information from the species file, which contains cardinal temperature values, as well as information from the cultivar and ecotype files, which contain physiological day durations for respective life cycle phases. Life cycle progress through any given phase depends on a physiological day accumulator as a function of temperature and day length, in many cases. Crops like soybean are sensitive to day length, whereas other crops such as peanut are not. When the physiological day accumulator reaches a value defined by a

threshold given in the cultivar file, a new growth stage is triggered. A physiological day can be thought of as equivalent to one calendar day if temperatures are optimum 24 h per day and day length is below the critical short or long day length requirement, depending on species sensitivity. The species file also contains coefficients that indicate the effect of water or nitrogen deficit on rate of life cycle progress. These coefficients may vary with life cycle phase; for example, water deficit may slow the onset of reproductive growth but accelerate reproductive growth after beginning seed fill. The species file also allows different cardinal temperatures for pre-anthesis development compared to post-anthesis reproductive development. For additional information on phenology in CROPGRO see papers by Boote et al. (1998a,b), Grimm et al. (1993, 1994), Piper et al. (1996a,b), Mavromatis et al. (2001).

Crop photosynthesis can be calculated by two options: (1) daily canopy photosynthesis, similar

to radiation use efficiency models, or (2) hourly hedgerow light interception and leaf-level photosynthesis. The daily canopy photosynthesis option, modified from the method used in SOYGRO V5.4 (Jones et al., 1989), predicts daily gross photosynthesis as a function of daily irradiance for a full canopy, which is then multiplied by factors 0–1 for light interception, temperature, leaf nitrogen status, and water deficit. There are additional adjustments for CO₂ concentration, specific leaf weight, row spacing, and cultivar. The hourly hedgerow photosynthesis light interception approach is described by Boote and Pickering (1994). On an hourly time step during each day, interception and absorption of direct and diffuse light components are computed based upon canopy height and width, LAI, leaf angle, row direction, latitude, day of year, and time of day (Boote and Pickering, 1994). Photosynthesis of sunlit and shaded leaves is computed hourly using the asymptotic exponential response equation, where quantum efficiency and light-saturated photosynthesis rate variables are dependent on CO₂ and temperature (Boote and Pickering, 1994). Hourly canopy photosynthesis on a land area basis is computed from the sum of sunlit and shaded leaf contributions by multiplying sunlit and shaded leaf photosynthetic rates by their respective LAIs. The hourly time loop is handled completely by the subroutine that uses this approach; gross photosynthesis is integrated hourly to provide a daily total value for use by other subroutines in the CROPGRO module.

Growth of new tissues depends on daily available carbohydrate, partitioning to different tissues, and respiration costs of tissue synthesis. During vegetative growth, the model follows a partitioning pattern dependent on vegetative growth stage, but modified by water deficit and nitrogen deficiency. Partitioning coefficients for leaf, stem, and root are defined in the species Crop Template file. Beginning at flowering, cohorts of flowers, pods, and seeds are added daily. These cohorts have an explicit assimilate demand per day depending on genetic potential and temperature. Reproductive tissues have first priority for assimilate over vegetative tissues, up to a maximum reproductive partitioning factor. This factor may be less than 1.0 for indeterminate plants (such as peanut and

tomato) and 1.0 for determinate plants, indicating that reproductive tissue eventually can utilize 100% of the assimilate. Leaf area expansion depends on leaf weight growth and specific leaf area, where the latter depends on temperature, light, and water deficit. Leaf expansion during reproductive growth is terminated by decrease of assimilate allocated to leaf growth and by reaching a phase that terminates leaf expansion. During seed fill, nitrogen is mobilized from vegetative tissues. As a result photosynthesis declines and leaf abscission increases. Protein and carbohydrate mobilized from vegetative tissue contribute to seed growth while photosynthesis declines. Growth respiration and conversion efficiency follow the approach of Penning de Vries and van Laar (1982) where the glucose cost for respiration and for condensation are computed as a function of the composition of each tissue. The species file contains the glucose cost to synthesize protein, lipid, lignin, organic acid, cellulose-carbohydrate, and mineral fractions as well as the approximate composition of each tissue. Maintenance respiration depends on temperature as well as gross photosynthesis and total crop mass minus protein and oil in the seed. Maintenance respiration is subtracted from gross daily photosynthesis to give available carbohydrates for new tissue growth. Details on these relationships and sources of data used in their development have been published by various authors (Wilkerson et al., 1983; Boote et al., 1986; Jones et al., 1989; Boote and Pickering, 1994; Boote et al., 1997, 1998a,b, 2002).

3.5. *Individual crop module interface (plant module)*

The individual crop module interface serves the same function as the CROPGRO Crop Template module in that it has the same interface variables (Table 2), linking plant growth dynamics to the other modules in the DSSAT–CSM. However, it is designed to link modules that describe growth, development and yield for individual crops. This module links in, for example, the CERES models from DSSAT v3.5 after modifications were made to fit the modular structure. We have implemented several of the individual models from DSSAT v3.5

Table 5
Growth stages simulated by the DSSAT CERES-maize, wheat and barley models

Maize	Wheat	Barley
Germination	Germination	Germination
Emergence	Emergence	Emergence
End of juvenile		
Floral induction	Terminal spikelet End ear growth	Maximum primordia End ear growth
75% Silking		
Beginning grain fill	Beginning grain fill	Beginning grain fill
Maturity	Maturity	Maturity
Harvest	Harvest	Harvest

(maize, wheat, sorghum, millet, barley, and rice) as well as potato (Hoogenboom et al., 1999; Ritchie et al., 1998; Singh et al., 1998), and we are converting others. One could add additional crops by adhering to the modular structure and providing the interface variables defined in Table 2. Here,

Table 6
Genetic coefficients for the DSSAT CERES-Maize, Wheat and Barley models

<i>(A) Maize</i>	
P1	Degree days (base 8 °C) from emergence to end of juvenile phase
P2	Photoperiod sensitivity coefficient (0–1.0)
P5	Degree days (base 8 °C) from silking to physiological maturity
G2	Potential kernel number
G5	Potential kernel growth rate mg/(kernel d)
PHINT	Degree days required for a leaf tip to emerge (phyllchron interval) (°C d)
<i>(B) Wheat and barley</i>	
P1D	Photoperiod sensitivity coefficient (% reduction/h near threshold)
P1V	Vernalization sensitivity coefficient (%/d of unfulfilled vernalization)
P5	Thermal time from the onset of linear fill to maturity (°C d)
G1	Kernel number per unit stem + spike weight at anthesis (#/g)
G2	Potential kernel growth rate (mg/(kernel d))
G3	Tiller death coefficient. Standard stem + spike weight when elongation ceases (g)
PHINT	Thermal time between the appearance of leaf tips (°C d)

we summarize how crop growth is computed for three crops (maize, wheat, and barley).

The CERES-Maize, Wheat and Barley models were modified for integration into the modular DSSAT–CSM. For these CERES models, the plant life cycle is divided into several phases, which are similar among the crops (Table 5). Rate of development is governed by thermal time, or growing degree-days (GDD), which is computed based on the daily maximum and minimum temperatures. The GDD required to progress from one growth stage to another are either defined as a user input (Table 6), or are computed internally based on user inputs and assumptions about duration of intermediate stages. Cultivar-specific inputs for all DSSAT–CSM CERES models are presented in absolute terms for consistency, a convention change from that followed previously for wheat and barley for which relative values were used. The number of GDD occurring on a calendar day is a function of a triangular or trapezoidal function defined by a base temperature, one or two optimum temperatures, and a maximum temperature above which development does not occur. Daylength may affect the total number of leaves formed by altering the duration of the floral induction phase, and thus, floral initiation. Daylength sensitivity is a cultivar-specific user input. Currently, only temperature and, in some cases, daylength, drive the accumulation of GDD; drought and nutrient stresses currently have no effect. During the vegetative phase, emergence of new leaves is used to limit leaf area development until after a species-dependent number of leaves have appeared. Thereafter, vegetative branching can occur, and leaf area development depends on the availability of assimilates and specific leaf area. Leaf area expansion is modified by daily temperature GDD, and water and nitrogen stress.

Daily plant growth is computed by converting daily intercepted photosynthetically active radiation into plant dry matter using a crop-specific radiation use efficiency parameter. Light interception is computed as a function of LAI, plant population, and row spacing. The amount of new dry matter available for growth each day may also be modified by the most limiting of water or

nitrogen stress, and temperature, and is sensitive to atmospheric CO₂ concentration. Above ground biomass has priority for carbohydrate, and at the end of each day, carbohydrate not used for above ground biomass is allocated to roots. Roots must receive, however, a specified stage-dependent minimum of the daily carbohydrate available for growth. Leaf area is converted into new leaf weight using empirical functions.

Kernel numbers per plant are computed during flowering based on the cultivar's genetic potential, canopy weight, average rate of carbohydrate accumulation during flowering, and temperature, water and nitrogen stresses. Potential kernel number is a user-defined input for specific cultivars. Once the beginning of grain fill is reached, the model computes daily grain growth rate based on a user-specified cultivar input (Table 6) defined as the potential kernel growth rate (mg/(kernel d)). Daily growth rate is modified by temperature and assimilate availability. If the daily pool of carbon is insufficient to allow growth at the potential rate, a fraction of carbon can be remobilized from the vegetative to reproductive sinks each day. Kernels are allowed to grow until physiological maturity is reached. If the plant runs out of resources, however, growth is terminated prior to physiological maturity. Likewise, if the grain growth rate is reduced below a threshold value for several days, growth is also terminated. Readers are referred to other papers for additional details on these CERES models ((Jones and Kiniry, 1986; Ritchie and Otter, 1985; Ritchie et al., 1998).

3.6. Management module

The management module determines when field operations are performed by calling sub modules. Currently, these operations are planting, harvesting, applying inorganic fertilizer, irrigating and applying crop residue and organic material. These operations can be specified by users in the standard 'experiment' input file (Hunt et al., 2001). Users specify whether any or all of the operations are to be automatic or fixed based on input dates or days from planting. Conditions that cause automatic planting within the interval of time are soil water content averaged over a

specified depth (i.e. 30 cm) and soil temperature at a specified depth to be between specified limits. Harvesting can occur on given dates, when the crop is mature, or when soil water conditions in the field are favorable for machine operation. Irrigation can be applied on specific dates with specified irrigation amount or can be controlled by the plant available water. If plant available water drops below a specified fraction of water holding capacity in an irrigation management depth, an irrigation event is triggered. The irrigation amount applied can be either a fixed amount or it can refill the profile to the management depth. Similarly, fertilizer can be applied on fixed dates in specified amounts, or the applications can optionally be controlled by plant needs for nitrogen via the nitrogen stress variable from the Plant module. Crop residue and organic fertilizer, such as manure, is applied either at the start of simulation, after harvesting the crop or on fixed dates similar to inorganic fertilizer applications. These management options allow users a great deal of flexibility for simulating experiments that were conducted in the past for model evaluation and improvement and for simulating optional management systems for different applications. The management file also provides scope to define multiple crops and management strategies for crop rotations and sequencing.

3.7. Pest module

The Pest module was developed for the CROPGRO models by Batchelor et al. (1993), following the approach described by Boote et al. (1983, 1993). It allows users to input field observations and scouting data on insect populations or damage to different plant parts, disease severity on different plant tissues, and physical damage to plants or plant components to simulate the effects of specified pest and diseases on growth and yield. Feedbacks on plant growth processes are through leaf area reduction, assimilate loss, loss of leaves, fruit, stems, or roots, and inactivation of the photosynthetic capacity of leaves (Boote et al., 1983). This feature has been used successfully for soybean, peanut, and tomato in the past (e.g. Boote et al., 1983, 1993; Batchelor et al., 1993),

Table 7

Contents of minimum data sets for operation and evaluation of the DSSAT–CSM

<i>(a) For operation of model</i>	
Site	Latitude and longitude, elevation; average annual temperature; average annual amplitude in temperature Slope and aspect; major obstruction to the sun (e.g. nearby mountain); drainage (type, spacing and depth); surface stones (coverage and size)
Weather	Daily global solar radiation, maximum and minimum air temperatures, precipitation
Soil	Classification using the local system and (to family level) the USDA-NRCS taxonomic system Basic profile characteristics by soil layer: in situ water release curve characteristics (saturated drained upper limit, lower limit); bulk density, organic carbon; pH; root growth factor; drainage coefficient
Initial conditions	Previous crop, root, and nodule amounts; numbers and effectiveness of rhizobia (nodulating crop) Water, ammonium and nitrate by soil layer
Management	Cultivar name and type Planting date, depth and method; row spacing and direction; plant population Irrigation and water management, dates, methods and amounts or depths Fertilizer (inorganic) and inoculant applications Residue (organic fertilizer) applications (material, depth of incorporation, amount and nutrient concentrations) Tillage Environment (aerial) adjustments Harvest schedule
<i>(b) For evaluation of models</i>	
	Date of emergence Date of flowering or pollination (where appropriate) Date of onset of bulking in vegetative storage organ (where appropriate) Date of physiological maturity LAI and canopy dry weight at three stages during the life cycle Canopy height and breadth at maturity Yield of appropriate economic unit (e.g. kernels) in dry weight terms Canopy (above ground) dry weight to harvest index (plus shelling percentage for legumes) Harvest product individual dry weight (e.g. weight per grain, weight per tuber) Harvest product number per unit at maturity (e.g. seeds per spike, seeds per pod) Harvest product number per unit at maturity (e.g. seeds per spike, seeds per pod) Soil water measurements vs. time at selected depth intervals Soil nitrogen measurements vs. time Soil C measurements vs. time, for long-term experiments Damage level of pest (disease, weeds, etc.) infestation (recorded when infestation first noted, and at maximum) Number of leaves produced on the main stem N percentage of economic unit N percentage of non-economic parts

and now this capability is accessible to all crops modeled in the DSSAT–CSM.

4. Data requirements

The DSSAT models require the minimum data set for model operation. The contents of such a dataset have been defined based on efforts by

workers in IBSNAT and ICASA (Jones et al., 1994; Hunt and Boote, 1998; Hunt et al., 2001), and are shown in Table 7. They encompass data on the site where the model is to be operated, on the daily weather during the growing cycle, on the characteristics of the soil at the start of the growing cycle or crop sequence, and on the management of the crop (e.g. seeding rate, fertilizer applications, irrigations).

Required weather data (Table 7a) encompass daily records of total solar radiation incident on the top of the crop canopy, maximum and minimum air temperature above the crop, and rainfall. However, it is recognized that all required weather data for a particular site and a particular time period are often not available. In such cases, the integrity of the minimum data set is maintained by calculating surrogate values or using data from nearby sites. To calculate surrogate values, statistics of the climate at a particular site are necessary and may thus be required.

The DSSAT–CSM requires information on the water holding characteristics of different soil layers. It needs a root weighting factor that accommodates the impact of several adverse soil factors on root growth in different soil layers, such as soil pH, soil impedance, and salinity. Additional soil parameters are needed for computing surface runoff, evaporation from the soil surface, and drainage (Ritchie, 1972). Initial values of soil water, nitrate and ammonium are needed as well as an estimate of the above- and below-ground residues from the previous crop. All aspects of crop management including modifications to the environment (e.g. photoperiod extension) as imposed in some crop physiology studies, are needed. Typical crop management factors include planting date, planting depth, row spacing, plant population, fertilization, irrigation and inoculation. Plant bed configuration and bund height is also necessary for some crops. The DSSAT–CSM also requires coefficients for the genotypes involved (Hunt, 1993; Ritchie, 1993), as described earlier with examples in Tables 4 and 6.

5. Software implementation, distribution policy

The DSSAT–CSM is a new implementation of the individual crop models contained in DSSAT v3.5. Its first release was in June 2002 where it was used in a course on application of CSMs at the University of Florida. Thus, although this version of the DSSAT models has not achieved widespread distribution yet, it is the latest release of the widely used DSSAT suite of crop models in a much more integrated format that was designed in

part for better capabilities for simulating cropping systems. At the time of publication, this DSSAT–CSM was available from the same source as DSSAT v3.5, as described below.

For over 5 years, DSSAT v3.5 DSSAT (Tsuji et al., 1994; Hoogenboom et al., 1999) has been distributed through the International Consortium for Agricultural Systems Applications (ICASA) for a small fee; order forms are at the ICASA web site (www.ICASAnet.org). ICASA supports an open code policy and encourages collaborating scientists to evaluate and improve the source code. Source code of the cropping systems models is available upon request for registered users of DSSAT. ICASA also maintains a list server to exchange information between users and developers of DSSAT. Currently there are more than 325 members of this list server. Information on how to subscribe to the DSSAT list server and archives of frequently asked questions can also be found at the ICASA web site. Technical support is provided by the individual developers of the CSM and is normally conducted via electronic mail. ICASA considers DSSAT to be an open platform and encourages active participation by the users' community to help with the improvement and advancement of its various models, modules, tools and application programs.

6. Model evaluation and testing

Evaluation involves comparison of model outputs with real data and a determination of suitability for an intended purpose. It is useful to think of model evaluation as a documentation of its accuracy for specific predictions in specified environments, with appropriate consideration given to possible errors in input variables or evaluation data. Essential parts of any minimum data set for evaluation are: (1) a complete record of the information required to run the model (Table 7a), and (2) field information on the aspect(s) for which the model is being validated (Table 7b). The data sets should not have been used previously for calibration and should represent the complete array of environments and crop sequences for which the model will be applied. In

the past, it has often been difficult to obtain enough data sets for effective evaluation, and to this end the DSSAT community has endeavoured to assemble a collection of datasets that can be used on an ongoing basis for model evaluation. Testing over diverse regions is valuable to expose models to new and different environments and test model robustness as [Piper et al. \(1998\)](#) did.

DSSAT model developers and other scientists have tested the models against various single factors, such as water, nitrogen, cultivar or planting date choice, and temperature. Since the DSSAT–CSM has just been released, we describe here evaluation of the crop models as they existed in the previous versions of DSSAT, the most recent being DSSAT v3.5. This is appropriate since component models in DSSAT–CSM are the same as those in DSSAT v3.5, reprogrammed and integrated together. The only new addition was the incorporation of the CENTURY module to facilitate more accurate cropping system analysis ([Gijsman et al., 2002](#)). Testing of these models has occurred at the level of processes, in terms of seasonal dynamics of leaf area, crop biomass, or ET over time, or in terms of final yield variables such as total biomass or grain yield. Statements of adequacy of model prediction include calculation of standard errors, root mean square error, and slope and intercept of regression of observed vs. predicted variables. Additionally, many studies have evaluated model performance, particularly yield, relative to observations from farmers' fields or other tests of cropping systems where many factors may vary (e.g. [Boote et al., 1989](#)). This latter approach was used in the international study of climate change impacts on agriculture described by [Rosenzweig et al. \(1995\)](#). In that study, researchers first evaluated model performance using data from cropping systems currently used in their respective countries, then used the models to assess the potential impacts of climate change on their cropping systems using different climate scenarios. Many of the studies referenced in [Table 8](#) evaluated the models for the applications shown.

Recent examples of model evaluation for two crops (corn and soybean) demonstrate the use of different model evaluation approaches for different purposes. [Braga \(2000\)](#) evaluated the ability of

the CERES–Maize model to accurately describe the spatial variability in maize yields over 2 years for use in precision agriculture research and decision support. He precisely measured soil water holding parameters in 40 locations in a farmer's field in Michigan, including initial conditions at planting during each of 2 years. [Fig. 3](#) shows a comparison of simulated vs. observed maize yields for the 40 locations over 2 years, showing that the model reproduced observed grain yields for these conditions when accurate soil, weather and cultivar information was available. [Mavromatis et al. \(2002\)](#) demonstrated the value of using routinely collected data from yield trials for both estimating cultivar characteristics and for evaluation. They used yield trial data from Georgia and North Carolina to show the robustness of the CROPGRO–Soybean model predictions across regions. They first used the yield trial data from Georgia to estimate cultivar coefficients for a number of cultivars, then used coefficients estimated from North Carolina yield trial data to predict the performance of the same cultivars in Georgia ([Fig. 4](#)). Results in [Fig. 4\(b\)](#) demonstrate the ability of the CROPGRO–Soybean model in DSSAT to predict soybean yields in environments different from those used to estimate the coefficients; on average simulated yields were within 2.5% of mean observed yields at each location.

Another important issue in model testing involves evaluation of simulations under different conditions as models undergo modifications during maintenance or enhancements. Modifications to some scientific relationships in a model may cause unexpected responses or bugs in the code that may go unnoticed unless a rigorous testing procedure is carried out. During the creation of the DSSAT–CSM, modifications to the original CERES and CROPGRO code were required, so software was developed to automatically compare simulated results from the new modular models with those obtained from the latest released versions in DSSAT v3.5 (C. Porter, unpublished). This software invokes two versions of models for the same crop (e.g. soybean) as changes are made to make sure that results are the same or to understand the reasons for changes that occur as a result of modifications. A standard set of real

Table 8

List of various types of applications of the DSSAT crop models and example references that describe these applications in detail, organized by continent on which the studies were conducted

Region	Type of application	References
Africa	Crop management	Fechter et al. (1991), Mbabaliye and Wojtkowski (1994), Vos and Mallett (1987), Wafula (1995)
	Fertilizer management	Jagtap et al. (1999), Singh et al. (1993), Thornton et al. (1995), Keating et al. (1991)
	Irrigation management	Kamel et al. (1995), MacRobert and Savage (1998)
	Precision management	Booltink et al. (2001)
	Climate change	Muchena and Iglesias (1995)
	Climate variability	Phillips et al. (1998)
	Food security	Pisani (1987), Thornton et al. (1997)
Asia	Crop management	Alagarwamy et al. (2000), Jintrawet (1995), Singh et al. (1994a,b), Salam et al. (2001)
	Fertilizer management	Godwin et al. (1994)
	Irrigation management	Hundal and Prabhjyot-Kaur (1997)
	Pest management	Luo et al. (1997), Pinnschmidt et al. (1995)
	Climate change	Jinghua and Erda (1996), Lal et al. (1998, 1999), Luo et al. (1995, 1998), Singh and Godwin (1990)
	Climate variability	Alcila and Ritchie (1990), Gadgil et al. (1999)
	Yield forecasting	Kaur and Hundal (1999), Singh et al. (1999)
Europe	Sustainability	Singh et al. (1999a,b)
	Crop management	Hunkár (1994), Pfeil et al. (1992a,b), Ruiz-Nogueira et al. (2001), Sau et al. (1999), Zalud et al. (2000)
	Fertilizer management	Gabrielle and Kengni (1996), Gabrielle et al. (1998), Zalud et al. (2001)
	Irrigation management	Ben Nouna et al. (2000), Castrignano et al. (1998), Gerdes et al. (1994)
	Tillage management	Castrignano et al. (1997)
	Variety evaluation	Brisson et al. (1989), Colson et al. (1995)
	Precision farming	Booltink and Verhagen (1997), Bootink et al. (2001)
	Environmental pollution	Kovács and Németh (1995)
	Climate change	Alexandrov and Hoogenboom (2001), Iglesias et al. (2000), Semenov et al. (1996), Wolf et al. (1996)
	Yield forecasting	Landau et al. (1998), Saarikko (2000)
North America	Sustainability	Hoffmann and Ritchie (1993)
	Crop management	Egli and Bruening (1992), Jame and Cutforth (1996), Sexton et al. (1998)
	Fertilizer management	Beckie et al. (1995), Hodges (1998)
	Irrigation management	Epperson et al. (1993), Hook (1994), McClendon et al. (1996), Steele et al. (2000), Swaney et al. (1983)
	Pest management	Barbour et al. (1994), Barbour and Bridges (1995), Batchelor et al. (1993), Boote et al. (1993), Lacey et al. (1989), Mishoe et al. (1984)
	Tillage management	Andales et al. (2000)
	Variety evaluation	Irmak et al. (1999), Manrique et al. (1990), Mavromatis et al. (2001), Piper et al. (1996a,b, 1998)
	Genomics	Boote and Tollenaar (1994), Boote et al. (2001), Hoogenboom et al. (1997), White and Hoogenboom (1996)

Table 8 (Continued)

Region	Type of application	References
Central and South America	Precision agriculture	Han et al. (1995), Sadler et al. (2000), Paz et al. (1998, 1999), Irmak et al. (2001), Paz et al. (2001a,b)), Seidl et al. (2001)
	Environmental pollution	Gerakis and Ritchie (1998), Pang et al. (1998)
	Climate change	Hatch et al. (1999), Mearns et al. (2001), Rosenzweig and Tubiello (1996), Southworth et al. (2000), Tubiello et al. (1995, 2001), Boote et al. (1997)
	Climate variability	Hansen and Jones (2000), Jones et al. (2000), Mearns et al. (1996)
	Yield forecasting	Carbone (1993), Carbone et al. (1996), Chipanshi et al. (1997, 1999), Duchon (1986), Georgiev and Hoogenboom (1999), Moulin and Beckie (1993)
	Sustainability	Hasegawa et al. (1999, 2000), Quemada and Cabrera (1995), Wagner-Riddle et al. (1997)
	Space technology	Fleisher et al. (2000)
	Education	Cabrera (1994), Meisner et al. (1991)
	Crop management	Savin et al. (1995), Travasso and Magrin (1998)
	Irrigation management	Heinemann et al. (2000)
	Precision management	Booltink et al. (2001)
	Variety evaluation	Castelan Ortega et al. (2000), Ferreyra et al. (2000), White et al. (1995)
	Climate change	Baethgen (1997), Conde et al. (1997), Diaz et al. (1997), Magrin et al. (1997), Maytin et al. (1995)
	Climate variability	Messina et al. (1999), Podesta et al. (2002), Ferreyra et al. (2001), Royce et al. (2002)
	Yield forecasting	Meira and Guevara (1997), Travasso et al. (1996)
	Sustainability	Bowen et al. (1992)
	Education	Ortiz (1998)

and hypothetical experiments are simulated, covering a wide range of conditions, to compare with observed data and to evaluate responses to temperature, solar radiation, planting date, and other factors. This software was used in our efforts to

develop the modular DSSAT–CSM to ensure that the scientific integrity of the models was maintained. This software will be made available in the next release of DSSAT so that researchers can test any changes that they might make to the models. The DSSAT–CSM developers will use it for quality control purposes in maintaining and revising the model.

7. Example applications

The DSSAT crop models have been widely used over the last 15 years by many researchers for many different applications. Many of these applications have been done to study management options at study sites, including fertilizer, irrigation, pest management, and site-specific farming. These applications have been conducted by agricultural researchers from different disciplines, frequently working in teams to integrate cropping

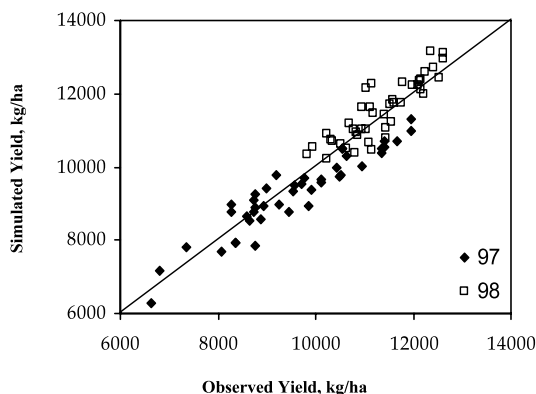


Fig. 3. Simulated versus observed maize grain yield over two years using field-measured, spatially varying soil parameters in Michigan (Braga, 2000).

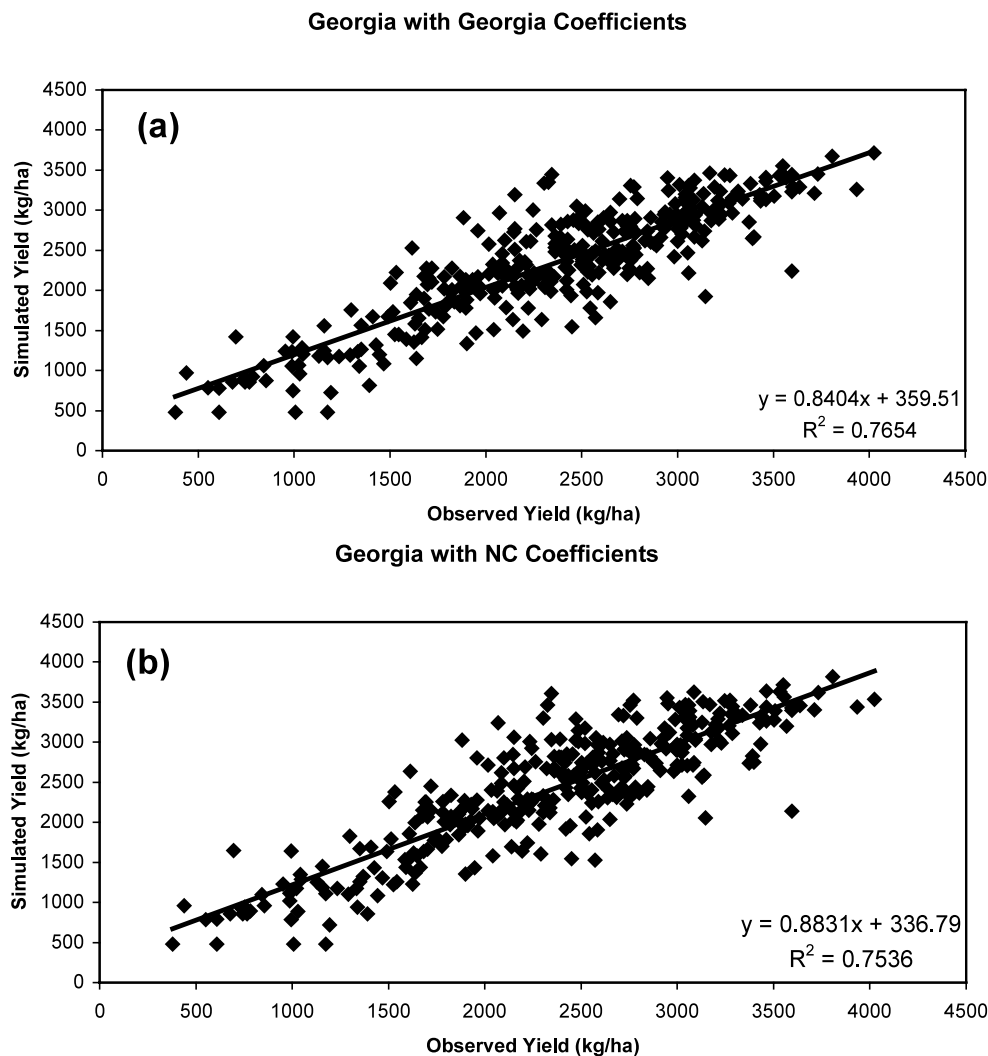


Fig. 4. Simulated vs. observed yields for soybean yield trials in Georgia in which (a) Georgia data were used to estimate cultivar coefficients, and (b) North Carolina data were used to estimate cultivar coefficients (Mavromatis et al., 2002).

systems analysis using models with field agronomic research and socioeconomic information to answer complex questions about production, economics, and the environment.

An important aspect of many of these studies is a consideration that weather influences the performance of crops, interacting in complex ways with soil and management. Researchers have thus applied these models to study uncertainty in crop production associated with weather variability and the associated economic risks that farmers face

under such climate variability. Researchers from all continents have used these models in studying potential impacts of climate change on agricultural production (Rosenzweig et al., 1995). The models have also been widely used in studying the potential use of climate forecasts for improving management of different cropping systems, and the value and risks associated with the use of this information. Table 8 lists references that describe some of these applications, organized by continent and application topic.

In addition to research applications, the DSSAT and its crop models have been used in teaching, both in continuing education courses and in formal university courses at graduate and undergraduate levels (Tsuji et al., 1998). There also have been attempts to use these models in advising farmers (through extension services and the private sector). In one application, described by Welch et al. (2002), an agricultural company has implemented versions of three of the DSSAT v3.5 models in a comprehensive farmer support software package that is being used by private consultants. This software package, called PCYield, includes CROPGRO-Soybean, CERES-Maize and CERES-Wheat models. PCYield is available to clients of the company via the Internet along with daily weather data for specific farm locations. It has a very simple user interface to allow private crop consultants to operate them for any of their farmer clients (<http://www.mPower3.com>).

The applications referred to in Table 8 provide a broad overview of the many studies that have used the DSSAT and its crop models. These were conducted before the new modular DSSAT–CSM was developed. Thus, many of these applications have focused on single crops instead of cropping systems. Since the DSSAT–CSM simulates crop and soil processes the same as DSSAT v3.5 (except for the new CENTURY-based soil C and N module), the current version has the same scientific capabilities that were used in most of these previous studies. However, the new DSSAT–CSM opens the way for more effective research on cropping systems (Gijsman et al., 2002), and it opens the way for more effective scientific improvements than ever before due to overcoming many hurdles imposed by the structure of previous versions.

8. Closing the loop between development and application

As shown in the previous section, researchers have been applying DSSAT crop models for many purposes. However, as more experience has been gained by the scientific community in using these

models, the demands have increased beyond those that motivated many of these studies. In many past studies, researchers accepted the crop and soil models in DSSAT as they were, but many studies showed that improvements were needed in various parts of the models. In some cases, researchers modified the code to create their own versions of crop models, but such efforts were complicated by the design of the models themselves and by the lack of adequate documentation in some cases. The re-design of the DSSAT–CSM was undertaken to help overcome some of these problems as well as to facilitate an efficient evolution for broader and more advanced applications in the future. Although the DSSAT–CSM is new, researchers are already adding new modules for pest dynamics (J. Koo, personal communication), models for new crops (O. Daza, personal communication). We expect that the modular structure, open code, testing software, the documentation, and instructions for modifying or adding modules and embedding DSSAT–CSM into other software will help close the gap between development and research applications. This includes the use of CSMs for policy; our experience indicates that researchers will be part of the process of cropping system applications for informing policy makers.

A more difficult issue is, however, the gap that exists between CSMs and their applications for decision support at a farm level. There are scientific and technical reasons for this gap. Many CSMs currently do not include factors that may limit growth and yield of crops grown under field conditions, such as different pests or other soil constraints. Gaining an understanding of these factors, how they interact with environment and management, and expanding model capabilities to include them is a challenge for agricultural scientists (Boote et al., 1996). Even if all of these factors were included in models, there would still be enormous difficulties in providing data inputs necessary to simulate these factors and their effects on crop production at a site. Our own experience with PCYield (Welch et al., 2002) indicated that crop consultants will use CSMs if they add value to the services that consultants provide to farmers, are easy to use, inexpensive in terms of dollar and time costs, and have ready

access to farm-specific and industry-specific information. Although some progress was made to overcome some impediments, such as access to daily weather data for specific farms (Welch et al., 2002) and software for calculating genetic coefficients using yield trial data (Mavromatis et al., 2001, 2002) others still exist. Technically, the major impediments are access to accurate site-specific soil and management information as well as high quality software that addresses relevant issues and appropriately embeds CSMs. However, the use of CSMs in software for decision support may be more constrained by social factors (McCown, 2001). Overcoming these constraints are likely to require consistent social interactions between advisors who use models and people to whom they give advice.

Looking ahead, we envision many applications in which the DSSAT–CSM will be integrated with other models and information for many research purposes. We are already developing special drivers for integrating the CSM with GIS for diagnosing causes of yield variability in precision agriculture fields (Paz et al., 2001a; Irmak et al., 2001) and for prescribing variable management (Paz et al., 2001b) and for linking with other models, such as for water quality and mixed crop-livestock farming system analysis. The DSSAT–CSM will continue to evolve as these new applications are developed and as we learn how to effectively incorporate other factors for more comprehensive agricultural systems analyses.

References

- Alagarwamy, G., Singh, P., Hoogenboom, G., Wani, S.P., Pathak, P., Virmani, S.M., 2000. Evaluation and application of the CROPGRO-Soybean simulation model in vertic ineptisol. *Agricultural Systems* 63, 19–32.
- Alexandrov, V.A., Hoogenboom, G., 2001. The impact of climate variability and change on crop yield in Bulgaria. *Agricultural and Forest Meteorology* 104, 315–327.
- Alocilja, E.C., Ritchie, J.T., 1990. The application of SIMOPT2:RICE to evaluate profit and yield-risk in upland-rice production. *Agricultural Systems* 33, 315–326.
- Andales, A.A., Batchelor, W.D., Anderson, C.E., Farnham, D.E., Whigham, D.K., 2000. Incorporating tillage effects into soybean model. *Agricultural Systems* 66, 69–98.
- Baethgen, W.E., 1997. Vulnerability of the agricultural sector of Latin America to climate change. *Climate Research* 9, 1–7.
- Barbour, J.C., Bridges, D.C., 1995. A model of competition for light between peanut (*Arachis hypogaea*) and broadleaf weeds. *Weed Science* 43 (2), 247–257.
- Barbour, J.C., Bridges, D.C., Nesmith, D.S., 1994. Peanut acclimation to simulated shading by weeds. *Agronomy Journal* 86 (5), 874–880.
- Batchelor, W.D., Jones, J.W., Boote, K.J., Pinnschmidt, H.O., 1993. Extending the use of crop models to study pest damage. *Transactions of the ASAE* 36 (2), 551–558.
- Beckie, H.J., Moulin, A.P., Campbell, C.A., Brandt, S.A., 1995. Testing effectiveness of four simulation models for estimating nitrates and water in two soils. *Canadian Journal of Soil Sciences* 75, 135–143.
- Ben Nouna, B., Katerji, N., Mastrorilli, M., 2000. Using the CERES-Maize model in a semi-arid Mediterranean environment. Evaluation of model performance. *European Journal of Agronomy* 13 (4), 309–322.
- Booltink, H.W.G., Verhagen, J., 1997. Using decision support systems to optimize barley management on spatial variable soil. In: Kropff, M., et al. (Eds.), *Applications of Systems Approaches at the Field Level*, vol. 2. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 219–233.
- Booltink, H.W.G., van Alphen, B.J., Batchelor, W.D., Paz, J.O., Stoorvogel, J.J., Vargas, R., 2001. Tools for optimizing management of spatially-variable fields. *Agricultural Systems* 70, 445–476.
- Boote, K.J., Batchelor, W.D., Jones, J.W., Pinnschmidt, H., Bourgeois, G., 1993. Pest damage relations at the field level. In: Penning de Vries, F.W.T., et al. (Eds.), *Systems Approaches for Agricultural Development*. Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Boote, K.J., Bennett, J.M., Jones, J.W., Jowers, H.E., 1989. On-farm testing of peanut and soybean models in Florida. ASAE P No. 89-4040. *Am. Soc. Agr. Engr. (ASAE)*, St. Joseph, MI, pp. 54.
- Boote, K.J., Jones, J.W., Hoogenboom, G., 1998a. Simulation of crop growth: CROPGRO model. In: Peart, R.M., Curry, R.B. (Eds.), *Agricultural Systems Modeling and Simulation* (Chapter 18). Marcel Dekker, Inc, New York, pp. 651–692.
- Boote, K.J., Jones, J.W., Hoogenboom, G., Pickering, N.B., 1998b. The CROPGRO model for grain legumes. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, pp. 99–128.
- Boote, K.J., Jones, J.W., Pickering, N.B., 1996. Potential uses and limitations of crop models. *Agronomie Journal* 88, 704–716.
- Boote, K.J., Minguez, M.I., Sau, F., 2002. Adapting the CROPGRO-legume model to simulate growth of faba bean. *Agronomy Journal* 94, 743–756.
- Boote, K.J., Pickering, N.B., 1994. Modeling photosynthesis of row crop canopies. *HortScience* 29, 1423–1434.
- Boote, K.J., Kropff, M.J., Bindraban, P.S., 2001. Physiology and modeling of traits in crop plants: implications for genetic improvement. *Agricultural Systems* 70, 395–420.

- Boote, K.J., Jones, J.W., Mishoe, J.W., Berger, R.D., 1983. Coupling pests to crop growth simulators to predict yield reductions. *Phytopathology* 73 (11), 1581–1587.
- Boote, K.J., Jones, J.W., Mishoe, J.W., Wilkerson, G.G., 1986. Modeling growth and yield of groundnut. *Agrometeorology of Groundnut: Proceedings of an International Symposium, ICRISAT Sahelian Center, Niamey, Niger. 21–26 Aug, 1985, ICRISAT, Patancheru, A.P. 502 324, India*, pp. 243–254.
- Boote, K.J., Pickering, N.B., Allen, L.H., Jr., 1997. Plant modeling: advances and gaps in our capability to project future crop growth and yield in response to global climate change. In: Allen, L.H., Jr., Kirkham, M.B., Olszyk, D.M., Whitman, C.E. (Eds.), *Advances in Carbon Dioxide Effects Research (Special Publication No. 61)*. ASA-CSSA-SSSA, Madison, WI, pp. 179–228.
- Boote, K.J., Tollenaar, M., 1994. Modeling genetic yield potential. In: Boote, K.J., Bennett, J.M., Sinclair, T.R., Paulsen, G.M. (Eds.), *Physiology and Determination of Crop Yield*. ASA-CSSA-SSSA, Madison, WI, pp. 533–565.
- Bowen, W.T., Jones, J.W., Thornton P.K., 1992. Crop simulation as a potential tool for evaluating sustainable land management. *Utilization of Soil Survey Information for Sustainable Land Use Proceedings: 11–24 July*.
- Braga, R., 2000. Predicting the spatial pattern of grain yield under water limiting conditions. PhD Dissertation, Agricultural and Biological Engineering Department, University of Florida, Gainesville, FL, pp. 176.
- Brisson, N., Bona, S., Bouniols, A., 1989. A soybean crop simulation model: validation and adaptation to varieties cultivated in southern Europe. *Agronomie* 9, 27–36.
- Cabrera, M.L., 1994. N-show: an educational computer program that displays dynamic graphs of nitrogen in soil. *Journal of Natural Resources and Life Science Education* 23 (1), 43–45.
- Carbone, G.J., 1993. Considerations of meteorological time-series in estimating regional-scale crop yield. *Journal of Climate* 6 (8), 1607–1615.
- Carbone, G.J., Narumalani, S., King, M., 1996. Application of remote sensing and GIS technologies with physiological crop models. *American Society for Photogrammetry and Remote Sensing* 62 (2), 171–179.
- Castrignano, A., Colucci, R., Degiorgio, D., Rizzo, V., Stelluti, M., 1997. Tillage effects on plant extractable soil–water in a silty clay vertisol in southern Italy. *Soil and Tillage Research* 40 (3–4), 227–237.
- Castrignano, A., Katerji, N., Karam, F., Mastroiilli, M., Hamdy, A., 1998. A modified version of CERES-Maize model for predicting crop response to salinity stress. *Ecological Modelling* 111 (2–3), 107–120.
- Castelan Ortega, O.A., Fawcett, R.H., Arriaga Jordan, C.M., Smith, A.J., 2000. Evaluation of the CERES-Maize model in simulating Campesino farmer yields in the highlands of central Mexico. *Experimental Agriculture* 36 (4), 479–500.
- Chipanshi, A.C., Ripley, E.A., Lawford, R.G., 1997. Early prediction of spring wheat yields in Saskatchewan from current and historical weather data using the CERES-wheat model. *Agricultural and Forest Meteorology* 84 (3–4), 223–232.
- Chipanshi, A.C., Ripley, E.A., Lawford, R.G., 1999. Large-scale simulation of wheat yields in a semi-arid environment using a crop-growth model. *Agricultural Systems* 59 (1), 57–66.
- Colson, J., Bouniols, A., Jones, J.W., 1995. Soybean reproductive development: adapting a model for European cultivars. *Agronomy Journal* 87, 1129–1139.
- Conde, C., Liverman, D., Flores, M., Ferrer, R., Araujo, R., Betancourt, E., Villarreal, G., Gay, C., 1997. Vulnerability of rainfed maize crops in Mexico to climate change. *Climate Research* 9, 17–23.
- Diaz, R.A., Magrin, G.O., Travasso, M.I., Rodriguez, R.O., 1997. Climate change and its impact on the properties of agricultural soils in the Argentinean rolling pampas. *Climate Research* 9, 25–30.
- Doorenbos, J., Pruitt, W.D., 1977. Guidelines for predicting crop water requirements. Food and Agriculture Organization of the United Nations, Rome. *Irrigation and Drainage Paper No. 24*.
- Duchon, C.E., 1986. Corn yield prediction using climatology. *Journal of Climate and Applied Meteorology* 25 (5), 581–590.
- Egli, D.B., Bruening, W., 1992. Planting date and soybean yield: evaluation of environmental effects with a crop simulation model: SOYGRO. *Agricultural and Forest Meteorology* 62 (1–2), 19–29.
- Epperson, J.E., Hook, J.E., Mustafa, Y.R., 1993. Dynamic programming for improving irrigation scheduling strategies of maize. *Agricultural Systems* 42, 85–101.
- Fechter, J., Allison, B.E., Sivakumar, M.V.K., van der Ploeg, R.R., Bley, J., 1991. An evaluation of the SWATRER and CERES-Millet models for southwest Niger. In: Sivakumar, M.V.K., Wallace, J.S., Renard, C., Giroux, C. (Eds.), *Soil Water Balance in the Sudano-Sahelian Zone*. International Association of Hydrological Sciences, Wallingford, pp. 505–513.
- Ferreira, R.A., Pachepsky, L.B., Collino, D., Acock, B., 2000. Modeling peanut leaf gas exchange for the calibration of crop models for different cultivars. *Ecological Modelling* 131 (2–3), 285–298.
- Ferreira, R.A., Podesta, G.P., Messina, C.D., Letson, D., Dardanelli, J., Guevera, E., Meira, S., 2001. A linked-modeling framework to estimate maize production risk associated with ENSO-related climate variability in Argentina. *Agricultural and Forest Meteorology* 107, 177–192.
- Fleisher, D.H., Cavazzoni, J., Giacomelli, G.A., Ting K.C., 2000. Adaption of SUBTOR for hydroponic, controlled environment white potato production. *ASAE Paper 00-4089*. American Society of Agricultural Engineers, St. Joseph, MI.
- Gabrielle, B., Kengni, L., 1996. Analysis and field-evaluation of the CERES models' soil components: nitrogen transfer and transformations. *Soil Science Society of American Journal* 60, 142–149.

- Gabrielle, B., Denoroy, P., Gosse, G., Justes, E., Andersen, M.N., 1998. Development and evaluation of a CERES-type model for winter oilseed rape. *Field Crops Research* 57 (1), 95–111.
- Gadgil, S., Seshagiri Rao, P.R., Sridhar, S., 1999. Modelling impact of climate variability on rainfed groundnut. *Current Science* 76, 557–569.
- Geng, S., Penning de Vries, F.W.T., Supit, I., 1986. A simple method for generating daily rainfall data. *Agricultural and Forest Meteorology* 36, 363–376.
- Geng, S., Auburn, J., Brandstetter, E., Li, B., 1988. A program to simulate meteorological variables. Documentation for SIMMETEO. Agronomy Report No. 204. University of California, Davis Crop Extension, Davis, CA.
- Georgiev, G.A., Hoogenboom, G., 1999. Near real-time agricultural simulations on the web. *Simulation* 73 (1), 22–28.
- Gerakis, A., Ritchie, J.T., 1998. Simulation of atrazine leaching in relation to water-table management using the CERES model. *Journal of Environmental Management* 52, 241–258.
- Gerdes, G., Allison, B.E., Pereira, L.S., 1994. Overestimation of soybean crop transpiration by sap flow measurements under field conditions in central Portugal. *Irrigation Science* 14 (3), 135–139.
- Giraldo, L.M., Lizcano, L.J., Gijsman, A.J., Rivera, B., Franco, L.H., 1998. Adaptation of the DSSAT model for simulation of *Brachiaria decumbens* production. *Pasturas Tropicales* 20, 2–12.
- Gijsman, A.J., Hoogenboom, G., Parton, W.J., Kerridge, P.C., 2002. Modifying DSSAT for low-input agricultural systems, using a soil organic matter—residue module from CENTURY. *Agronomy Journal* 94 (3), 462–474.
- Godwin, D.C., Jones, C.A., 1991. Nitrogen dynamics in soil–plant systems. In: Hanks, J., Ritchie, J.T. (Eds.), *Modeling Plant and Soil Systems* (Agronomy monograph no. 31). ASA, CSSA, and SSSA, Madison, WI, pp. 287–321.
- Godwin, D.C., Singh, U., 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production. System Approaches for Sustainable Agricultural Development*. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 55–77.
- Godwin, D.C., Meyer, W.S., Singh, U., 1994. Simulation of the effect of chilling injury and nitrogen supply on floret fertility and yield in rice. *Australian Journal Experimental Agricultural* 34, 921–926.
- Grimm, S.S., Jones, J.W., Boote, K.J., Herzog, D.C., 1994. Modeling the occurrence of reproductive stages after flowering for four soybean cultivars. *Agronomy Journal* 86, 31–38.
- Grimm, S.S., Jones, J.W., Boote, K.J., Hesketh, J.D., 1993. Parameter estimation for predicting flowering date of soybean cultivars. *Crop Science* 33, 137–144.
- Han, S., Evans, R.G., Hodges, T., Rawlins, S.L., 1995. Linking a geographic information system with a potato simulation model for site-specific crop management. *Journal of Environmental Quality* 24, 772–777.
- Hansen, J.W., Jones, J.W., 2000. Scaling-up crop models for climate variability applications. *Agricultural Systems* 65, 43–72.
- Hartkamp, A.D., Hoogenboom, G., White, J.W., 2002. Adaptation of the CROPGRO growth model to velvet bean as a green manure cover crop: I. Model development. *Field Crops Research* 78 (1), 9–25.
- Hasegawa, H., Bryant, D.C., Denison, R.F., 2000. Testing CERES model predictions of crop growth and N dynamics, in cropping systems with leguminous green manures in a Mediterranean climate. *Field Crops Research* 67 (3), 239–255.
- Hasegawa, H., Labavitch, J.M., McGuire, A.M., Bryant, D.C., Denison, R.F., 1999. Testing CERES model predictions of N release from legume cover crop residue. *Field Crops Research* 63, 255–267.
- Hatch, U., Jagtap, S., Jones, J., Lamb, M., 1999. Potential effects of climate change on agricultural, water use in the southeast US. *Journal of the American Water Resources Association* 35, 1551–1561.
- Heinemann, A.B., Hoogenboom, G., Georgiev, G.A., de Faria, R.T., Frizzzone, J.A., 2000. Center pivot irrigation management optimization of dry beans in humid areas. *Transactions of the ASAE* 43 (6), 1507–1516.
- Hoffmann, F., Ritchie, J.T., 1993. Model for slurry and manure in CERES and similar models. *Journal Agronomy and Crop Science* 170, 330–340.
- Hodges, T., 1998. Water and nitrogen applications for potato: commercial and experimental rates compared to a simulation model. *Journal of Sustainable Agriculture* 13, 79–90.
- Hoogenboom, G., Wilkens, P.W., Thornton, P.K., Jones, J.W., Hunt, L.A., Imamura, D.T., 1999. Decision support system for agrotechnology transfer v3.5. In: Hoogenboom, G., Wilkens, P.W., Tsuji, G.Y. (Eds.), *DSSAT version 3, vol. 4* (ISBN 1-886684-04-9). University of Hawaii, Honolulu, HI, pp. 1–36.
- Hoogenboom, G., White, J.W., Acosta-Gallegos, J., Gaudiel, R.G., Myers, J.R., Silbernagel, M.J., 1997. Evaluation of a crop simulation model that incorporates gene action. *Agronomy Journal* 89 (4), 613–620.
- Hoogenboom, G., Jones, J.W., Wilkens, P.W., Batchelor, W.D., Bowen, W.T., Hunt, L.A., Pickering, N.B., Singh, U., Godwin, D.C., Baer, B., Boote, K.J., Ritchie, J.T., White, J.W., 1994a. Crop models. In: Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), *DSSAT Version 3, vol. 2*. University of Hawaii, Honolulu, HI, pp. 95–244.
- Hoogenboom, G., White, J.W., Jones, J.W., Boote, K.J., 1994b. BEANGRO: A process-oriented dry bean model with a versatile user interface. *Agronomy Journal* 86, 182–190.
- Hook, J.E., 1994. Using crop models to plan water withdrawals for irrigation in drought years. *Agricultural Systems* 45, 271–289.
- Hundal, S.S., Prabhjyot-Kaur, 1997. Application of the CERES-Wheat model to yield predictions in the irrigated

- plains of the Indian Punjab. *Journal of Agricultural Science* 129, 13–18.
- Hunkár, M., 1994. Validation of crop simulation model CERES-Maize. *Quarterly Journal of Hungarian Meteorology Series* 98, 37–46.
- Hunt, L.A., 1993. Designing improved plant types: a breeder's viewpoint. In: Penning de Vries, F., Teng, P., Metselaar, K. (Eds.), *Systems Approaches for Agricultural Development*. Kluwer Academic Press, Boston, pp. 3–17.
- Hunt, L.A., Boote, K.J., 1998. Data for model operation, calibration, and evaluation. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, pp. 9–39.
- Hunt, L.A., White, J.W., Hoogenboom, G., 2001. Agronomic data: advances in documentation and protocols for exchange and use. *Agricultural Systems* 70, 477–492.
- Iglesias, A., Rosenzweig, C., Pereira, D., 2000. Agricultural impacts of climate change in Spain: developing tools for a spatial analysis. *Global Environmental Change* 10, 69–80.
- International Benchmark Sites Network for Agrotechnology Transfer. 1993. *The IBSNAT Decade*. Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, Hawaii.
- Irmak, A., Jones, J.W., Mavromatis, T., Welch, S.M., Boote, K.J., Wilkerson, G.G., 1999. Evaluating methods for simulating soybean cultivar responses using cross validation. *Agronomy Journal* 92, 1140–1149.
- Irmak, A., Jones, J.W., Batchelor, W.D., Paz, J.O., 2001. Linking multiple layers of information for diagnosing causes of spatial yield variability. *Trans. ASAE* 45 (3), 839–849.
- Jagtap, S.S., Abamu, F.J., Kling, J.G., 1999. Long-term assessment of nitrogen and variety technologies on attainable maize yields in Nigeria using CERES-maize. *Agricultural Systems* 60, 77–86.
- Jame, Y.W., Cutforth, H.W., 1996. Crop growth-models for decision-support systems. *Canadian Journal of Plant Science* 76 (1), 9–19.
- Jinghua, W., Erda, L., 1996. The impacts of potential climate change and climate variability on simulated maize production in China. *Water, Air and Soil Pollution* 92, 75–85.
- Jintrawet, A., 1995. A decision support system for rapid assessment of lowland rice-based cropping alternatives in Thailand. *Agricultural Systems* 47, 245–258.
- Jones, C.A., Kiniry, J.R., 1986. *CERES-Maize: A Simulation Model of Maize Growth and Development*. Texas A&M University Press, College Station, Texas.
- Jones, C.A., Dyke, P.T., Williams, J.R., Kiniry, J.R., Benson, V.W., Griggs, R.H., 1991. EPIC: an operational model for evaluation of agricultural sustainability. *Agricultural Systems* 37, 341–350.
- Jones J.W. Ritchie, J.T., 1991. Crop growth models In: Hoffman, G.J., Howell, T.A., Solomon, K.H. (Eds.), *Management of Farm Irrigation Systems*, American Society for Agricultural Engineering, pp. 63–89.
- Jones, J.W., 1993. Decision support systems for agricultural development. In: Penning de Vries, F., Teng, P., Metselaar, K. (Eds.), *Systems Approaches for Agricultural Development*. Kluwer Academic Press, Boston, pp. 459–471.
- Jones, J.W., Boote, K.J., Hoogenboom, G., Jagtap, S.S., Wilkerson, G.G., 1989. SOYGRO V5.42, Soybean Crop Growth Simulation Model. User's Guide. *Fl. Agric. Exp. Sta., Journal No. 8304*. University of Florida, Gainesville, pp. 53.
- Jones, J.W., Tsuji, G.Y., Hoogenboom, G., Hunt, L.A., Thornton, P.K., Wilkens, P.W., Imamura, D.T., Bowen, W.T., Singh, U., 1998. Decision support system for agrotechnology transfer; DSSAT v3. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 157–177.
- Jones, J.W., Hansen, J.W., Royce, F.S., Messina, C.D., 2000. Potential benefits of climate forecasting to agriculture. *Agriculture Ecosystems and Environment* 82, 169–184.
- Jones, J.W., Hunt, L.A., Hoogenboom, G., Godwin, D.C., Singh, U., Tsuji, G.Y., Pickering, N.B., Thornton, P.K., Bowen, W.T., Boote, K.J., Ritchie, J.T., 1994. Input and output files. In: Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), *Decision Support System for Agrotechnology Transfer (DSSAT) Version 3, vol. 2*. University of Hawaii, Honolulu, HI, pp. 1–94.
- Jones, J.W., Keating, B.A., Porter, C.H., 2001. Approaches to modular model development. *Agricultural Systems* 70, 421–443.
- Kamel, A., Schroeder, K., Sticklen, J., Rafea, A., Salah, A., Schulthess, U., Ward, R., Ritchie, J.T., 1995. Integrated wheat crop management based on generic task knowledge-based systems and CERES numerical-simulation. *AI Applications* 9 (1), 17–28.
- Kaur, P., Hundal, S.S., 1999. Forecasting growth and yield of groundnut (*Arachis hypogaea*) with a dynamic simulation model 'PNUTGRO' under Punjab conditions. *Journal of Agricultural Science* 133, 167–173.
- Keating, B.A., Godwin, D.G., Watiki, J.M., 1991. Optimising nitrogen inputs in response to climatic risk. In: Muchow, R.C., Bellamy, J.A. (Eds.), *Climatic Risk in Crop Production-Models and Management for the Semi-arid Tropics and Subtropics*. CAB International, Wallingford.
- Kovács, G.T., Németh, T., 1995. Testing simulation models for the assessment of crop production and nitrate leaching in Hungary. *Agricultural Systems* 49, 385–397.
- Kraalingen, D.W.G. van, 1990. The FORTRAN version of CSMP MACROS (Modules for Annual Crop Simulation). Simulation reports CABO-TT; nr. 21. Centre for Agrobiological Research and Department of Theoretical Production Ecology, Agricultural University, Wageningen, the Netherlands.
- Kraalingen, D.W.G. van, 1991. The FSE system for crop simulation. Simulation reports CABO-TT; nr. 23. Centre for Agrobiological Research and Department of Theoretical Production Ecology, Agricultural University, Wageningen, the Netherlands.

- Kraalingen, D.W.G. van. 1995. The FSE system for crop simulation, version 2.1. Quantitative Approaches in Systems Analysis, No. 1, C.T. de Wit Graduate School for Production Ecology and Resource Conservation, Wageningen University, The Netherlands, pp. 58.
- Kraalingen, D.W.G. van, Rappoldt C., Van Laar, H.H., 2003. The Fortran simulation translator, a simulation language. *European Journal of Agronomy* 18, 359–361.
- Lacey, D.K., McClendon, R.W., Hook, J.E., Todd, J.W., Womack, H., 1989. Express: An Expert Simulation System for Peanut Insect Pest Management (ASAE Paper 89-7574). American Society of Agricultural Engineers, St Joseph, Michigan.
- Lal, M., Singh, K.K., Rathore, L.S., Srinivasan, G., Saseendran, S.A., 1998. Vulnerability of rice and wheat yields in NW India to future changes in climate. *Agricultural and Forest Meteorology* 89, 101–114.
- Lal, M., Singh, K.K., Srinivasan, G., Rathore, L.S., Naidu, D., Tripathi, C.N., 1999. Growth and yield responses of soybean in Madhya Pradesh, India to climate variability and change. *Agricultural and Forest Meteorology* 93 (1), 53–70.
- Landau, S., Mitchell, R.A.C., Barnett, V., Colls, J.J., Craigon, J., Moore, K.L., Payne, R.W., 1998. Testing winter wheat simulation models' predictions against observed UK grain yields. *Agricultural and Forest Meteorology* 89 (2), 85–99.
- Luo, Y., Tebeest, D.O., Teng, P.S., Fabellar, N.G., 1995. Simulation studies on risk analysis of rice leaf blast epidemics associated with global climate-change in several Asian countries. *Journal of Biogeography* 22 (4–5), 673–678.
- Luo, Y., Teng, P.S., Fabellar, N.G., Tebeest, D.O., 1997. A rice-leaf blast combined model for simulation of epidemics and yield loss. *Agricultural Systems* 53 (1), 27–39.
- Luo, Y., Teng, P.S., Fabellar, N.G., TeBeest, D.O., 1998. The effects of global temperature change on rice leaf blast epidemics: a simulation study in three agroecological zones. *Agriculture Ecosystems and Environment* 68, 187–196.
- MacRobert, J.F., Savage, M.J., 1998. The use of a crop simulation model for planning wheat irrigation in Zimbabwe. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 205–220.
- Magrin, G.O., Travasso, M.I., Diaz, R.A., Rodriguez, R.O., 1997. Vulnerability of the agricultural systems of Argentina to climate change. *Climate Research* 9, 31–36.
- Manrique, L.A., Hodges, T., Johnson, B.S., 1990. Genetic variables for potato. *American Potato Journal* 67 (10), 669–683.
- Mavromatis, T., Boote, K.J., Jones, J.W., Irmak, A., Shinde, D., Hoogenboom, G., 2001. Developing genetic coefficients for crop simulation models with data from crop performance trials. *Crop Science* 41, 40–51.
- Mavromatis, T., Boote, K.J., Jones, J.W., Wilkerson, G.G., Hoogenboom, G., 2002. Repeatability of model genetic coefficients derived from soybean performance trials cross different states. *Crop Sci.* 42, 76–89.
- Maytin, C.E., Acevedo, M., Jaimez, R., Andressen, R., Harwell, M.A., Robock, A., Azocar, A., 1995. Potential effects of global climatic-change on the phenology and yield of maize in Venezuela. *Climatic Change* 29 (2), 189–211.
- Mbabaliye, T., Wojtkowski, P.A., 1994. Problems and perspectives on the use of a crop simulation model in an African research station. *Experimental Agriculture* 30, 441–446.
- Mearns, L.O., Mavromatis, T., Tsvetsinskaya, E., Hays, C., Easterling, W., 2001. Comparative responses of EPIC and CERES crop models to high and low spatial resolution climate change scenarios. *Journal of Geophysical Research* 104, 6623–6646.
- Mearns, L.O., Rosenzweig, C., Goldberg, R., 1996. The effect of changes in daily and interannual climatic variability of CERES-Wheat: a sensitivity study. *Climatic Change* 32, 257–292.
- Messina, C.C., Hansen, J.W., Hall, A.J., 1999. Land allocation conditioned on El Nino-Southern Oscillation phases in the Pampas of Argentina. *Agricultural Systems* 60, 197–212.
- McClendon, R.W., Hoogenboom, G., Seigner, I., 1996. Optimal control and neural networks applied to peanut irrigation management. *Transactions of the ASAE* 39 (1), 275–279.
- McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P., Freebairn, D.M., 1996. APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. *Agricultural Systems* 50, 255–271.
- McCown, R.L., 2001. Learning to bridge the gap between science-based decision support and the practice of farming: evolution in paradigms of model-based research and intervention from design to dialogue. *Australian Journal of Agricultural Research* 52, 549–571.
- Meira, S., Guevara, E., 1997. Application of SOYGRO in Argentina. In: Kropff, M.J., et al. (Eds.), *Applications of System Approaches at the Field Level, v.2*. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 235–242.
- Meisner, C.A., Karnok, K.J., McCrimmon, J.N., 1991. Using crop models in a beginning crop science laboratory. *Journal of Agronomic Education* 20, 157–158.
- Mishoe, J.W., Jones, J.W., Swaney, D.P., Wilkerson, G.G., 1984. Using crop and pest models for management applications. *Agricultural Systems* 15, 153–170.
- Monteith, J.L., 1986. How do crops manipulate water supply and demand? *Philosophical Transactions of the Royal Society London A* 316, 245–259.
- Moulin, A.P., Beckie, H.J., 1993. Evaluation of the CERES and EPIC models for predicting spring wheat grain yield over time. *Canadian Journal Plant Sciences* 73, 713–719.
- Muchena, P., Iglesias, A., 1995. Vulnerability of maize yields to climate change in different farming sectors in Zimbabwe. In: Rosenzweig, C., Allen, L.H., Harper, L.A., Hollinger, S.E., Jones, J.W. (Eds.), *Climate Change and Agriculture: Analysis of Potential International Impacts* (ASA Special

- Publication 59). American Society of Agronomy, Madison, Wisconsin, pp. 229–239.
- Ortiz, R.A., 1998. Crop simulation models as an educational tool. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 383–388.
- Pang, X.P., Gupta, S.C., Moncrief, J.F., Rosen, C.J., Cheng, H.H., 1998. Evaluation of nitrate leaching potential in Minnesota glacial outwash soils using the CERES-Maize model. *Journal of Environmental Quality* 27 (1), 75–85.
- Penning de Vries, F.W.T., van Laar, H.H., 1982. Simulation of growth processes and the model BACROS. In: Penning de Vries, F.W.T., van Laar, H.H. (Eds.), *Simulation of Plant Growth and Crop Production*. PUDOC, Wageningen, The Netherlands, pp. 114–136.
- Parton, W.J., Stewart, J.W.B., Cole, C.V., 1988. Dynamics of C, N, P and S in grassland soils: a model. *Biogeochemistry* 5, 109–131.
- Parton, W.J., Ojima, D.S., Cole, C.V., Schimel, D.S., 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In: Bryant, R.B., Arnold, R.W. (Eds.), *Quantitative Modeling of Soil Forming Processes* (Special Publication 39). SSSA, Madison, WI, pp. 147–167.
- Paz, J.O., Batchelor, W.D., Colvin, T.S., Logsdon, S.D., Kaspar, T.C., Karlen, D.L., 1998. Analysis of water stress effects causing spatial yield variability. *Transactions of the ASAE* 41, 1527–1534.
- Paz, J.O., Batchelor, W.D., Babcock, B.A., Colvin, T.S., Logsdon, S.D., Kaspar, T.C., Karlen, D.L., 1999. Model-based technique to determine variable rate nitrogen for corn. *Agricultural Systems* 61, 69–75.
- Paz, J.O., Batchelor, W.D., Tylka, G.L., Hartzler, R.G., 2001a. A modeling approach to quantifying the effects of spatial soybean yield limiting factors. *Trans. ASAE* 44 (5), 1329–1334.
- Paz, J.O., Batchelor, W.D., Tylka, G.L., 2001b. Estimating potential economic return for variable rate management in soybeans. *Trans. ASAE* 44 (5), 1335–1341.
- Pfeil, E.V., Hundertmark, W., Thies, F.D., Widmoser, P., 1992a. Calibration of the simulation model 'Ceres Wheat' under conditions of soils with shallow watertable and temperate climate. Part 1: limitations in the applicability of the original model and necessary modifications. *Zeitschrift fuer Pflanzenernähr Bodenk* 155, 323–326.
- Pfeil, E.V., Hundertmark, W., Thies, F.D., Widmoser, P., 1992b. Calibration of the simulation model 'Ceres Wheat' under conditions of soils with shallow watertable and temperate climate. Part 2: verification of the modified model 'Ceres Wheat'. *Zeitschrift fuer Pflanzenernähr Bodenk* 155, 327–331.
- Phillips, J.G., Cane, M.A., Rosenzweig, C., 1998. ENSO, seasonal rainfall patterns and simulated maize yield variability in Zimbabwe. *Agricultural and Forest Meteorology* 90, 39–50.
- Pinnschmidt, H.O., Batchelor, W.D., Teng, P.S., 1995. Simulation of multiple species pest damage in rice using CERES-rice. *Agricultural Systems* 48, 193–222.
- Piper, E.L., Boote, K.J., Jones, J.W., Grimm, S.S., 1996a. Comparison of two phenology models for predicting flowering and maturity date of soybean. *Crop Science* 36, 1606–1614.
- Piper, E.L., Boote, K.J., Jones, J.W., 1998. Evaluation and improvement of crop models using regional cultivar trial data. *Applied Engineering in Agriculture* 14, 435–446.
- Piper, E.L., Smit, M.A., Boote, K.J., Jones, J.W., 1996b. The role of daily minimum temperature in modulating the development rate to flowering in soybean. *Field Crop Research* 47, 211–220.
- Pisani, du A., 1987. The CERES-MAIZE model as a potential tool for drought assessment in South Africa. *Water SA* 13 (3), 159–164.
- Podesta, G., Letson, D., Messina, C.D., Royce, F., Ferreyra, R.A., Jones, J.W., Jones, J.W., Llovet, I., Grondona, M., O'Brien, J.J., 2002. Use of ENSO-related climate information in agricultural decision making in Argentina. *Agricultural Systems* (in press).
- Porter, C., Jones, J.W., Braga, R., 2000. An approach for modular crop model development. International Consortium for Agricultural Systems Applications, 2440 Campus Rd., 527 Honolulu, HI 96822, pp. 13. Available from <http://www.icasanet.org/modular/index.html>.
- Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large scale parameters. *Monthly Weather Review* 100, 81–92.
- Quemada, M., Cabrera, M.L., 1995. CERES-N model predictions of nitrogen mineralized from cover crop residues. *Soil Science Society of American Journal* 59, 1059–1065.
- Richardson, C.W., 1981. Stochastic simulation of daily precipitation, temperature, and solar radiation. *Water Resources Research* 17 (1), 182–190.
- Richardson, C.W., 1985. Weather simulation for crop management models. *Transactions of the ASAE* 28 (5), 1602–1606.
- Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Research* 8, 1204–1213.
- Ritchie, J.T., 1993. Genetic specific data for crop modeling. In: Penning de Vries, F., Teng, P., Metselaar, K. (Eds.), *Systems Approaches for Agricultural Development*. Kluwer Academic Press, Boston, pp. 77–93.
- Ritchie, J.T., 1998. Soil water balance and plant stress. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 41–54.
- Ritchie, J.T., Otter, S., 1985. Description and performance of CERES-Wheat: a user-oriented wheat yield model. In: ARS Wheat Yield Project. ARS-38. Natl Tech Info Serv, Springfield, Missouri, pp. 159–175.
- Ritchie, J.T., Singh, U., Godwin, D.C., Bowen, W.T., 1998. Cereal growth, development and yield. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding*

- Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 79–98.
- Rosenzweig, C., Tubiello, F.N., 1996. Effects of changes in minimum and maximum temperature on wheat yields in the central US—a simulation study. *Agricultural and Forest Meteorology* 80 (2–4), 215–230.
- Rosenzweig, C., Allen, L.H., Jr., Jones, J.W., Tsuji, G.Y., Hildebrand, P. (Eds.), *Climate Change and Agriculture: Analysis of Potential International Impacts* (ASA Special Publication No. 59). Amer. Soc. Agron., Madison, WI 1995, p. 382.
- Royce, F.S., Jones, J.W., Hansen, J.W., 2002. Model-Based Optimization of Crop Management for Climate Forecast Applications. *Trans. ASAE* 44 (5), 1319–1327.
- Ruiz-Nogueira, B., Boote, K.J., Sau, F., 2001. Calibration and use of CROPGRO-soybean model for improving soybean management under rainfed conditions. *Agricultural Systems* 68 (2), 151–173.
- Saarikko, R.A., 2000. Applying a site based crop model to estimate regional yields under current and changed climates. *Ecological Modelling* 131 (2–3), 191–206.
- Sadler, E.J., Gerwig, B.K., Evans, D.E., Busscher, W.J., Bauer, P.J., 2000. Site-specific modeling of corn yield in the SE coastal plain. *Agricultural Systems* 64, 189–207.
- Salam, M.U., Jones, J.W., Kobayashi, K., 2001. Predicting nursery growth and transplanting shock in rice. *Experimental Agriculture* 37, 65–81.
- Sau, F., Boote, K.J., Ruiz-Nogueira, B., 1999. Evaluation and improvement of CROPGRO-soybean model for a cool environment in Galicia, northwest Spain. *Field Crops Research* 61, 273–291.
- Savin, R., Satorre, E.H., Hall, A.J., Slafer, G.A., 1995. Assessing strategies for wheat cropping in the monsoonal climate of the Pampas using the CERES-Wheat simulation model. *Field Crops Research* 42, 81–91.
- Scholberg, J.M.S., Boote, K.J., Jones, J.W., McNeal, B.L., 1997. Adaptation of the CROPGRO model to simulate the growth of field-grown tomato. In: Kropff, M.J., et al. (Eds.), *Systems Approaches for Sustainable Agricultural Development: Applications of Systems Approaches at the Field Level*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 133–151.
- Seidl, M.S., Batchelor, W.D., Fallick, J.B., Paz, J.O., 2001. GIS-crop model based decision support system to evaluate corn and soybean prescriptions. *Applied Engineering in Agriculture* 17 (5), 721–728.
- Seligman, N.C., Van Keulen, H., 1981. PAPRAN: a simulation model of annual pasture production limited by rainfall and nitrogen. In: Frissel, M.J., Van Veen, J.A. (Eds.), *Simulation of Nitrogen Behaviour of Soil-Plant Systems*. Centrum voor Landbouwpublikaties en Landbouwdocumentatie (PUDOC), Wageningen, Netherlands, pp. 192–221.
- Semenov, M.A., Wolf, J., Evans, L.G., Eckersten, H., Iglesias, A., 1996. Comparison of wheat simulation models under climate change. II. Application of climate change scenarios. *Climate Research* 7, 271–281.
- Sexton, P.J., Batchelor, W.D., Boote, K.J., Shibles, R., 1998. Evaluation of CROPGRO for prediction of soybean nitrogen balance in a Midwestern environment. *Transactions of the ASAE* 41, 1543–1548.
- Singh, K.K., Kumar, R., Mall, R.K., Rathore, L.S., Sanker, U., Gupta, B.R.D., 1999. Soybean (*Glycine max*) yield prediction from current and historical weather data using CROPGRO model. *Indian Journal of Agricultural Sciences* 69 (9), 639–643.
- Singh, P., Boote, K.J., Virmani, S.M., 1994a. Evaluation of the groundnut model PNUTGRO for crop response to plant population and row spacing. *Field Crops Research* 39, 163–170.
- Singh, P., Boote, K.J., Rao, Y.A., Iruthayaraj, M.R., Sheik, A.M., Hundal, S.S., Narang, R.S., 1994b. Evaluation of the groundnut model PNUTGRO for crop response to water availability, sowing dates, and seasons. *Field Crops Research* 39, 147–162.
- Singh, P., Alagarswamy, G., Hoogenboom, G., Pathak, P., Wani, S.P., Virmani, S.M., 1999a. Soybean–chickpea rotation on verticceptisols: 2. Long-term simulation of water balance and crop yields. *Field Crops Research* 63, 225–236.
- Singh, P., Alagarswamy, G., Pathak, P., Wani, S.P., Hoogenboom, G., Virmani, S.M., 1999b. Soybean–chickpea rotation on verticceptisols: 1. Effect of soil depth and landform on light interception, water balance and crop yields. *Field Crops Research* 63, 211–224.
- Singh, U., Godwin, D.C., 1990. Modelling the impact of climate change on agricultural production in the South Pacific. In: Hughes, P.J., McGregor, G. (Eds.), *Global Warming-Related Effects on Agriculture and Human Health and Comfort in the South Pacific*. South Pacific Regional Environment Programme, New Guinea, pp. 521–537.
- Singh, U., Thornton, P.K., Saka, A.R., Dent, J.B., 1993. Maize modeling in Malawi: a tool for soil fertility research and development. In: Penning de Vries, F.W.T., et al. (Eds.), *Systems Approaches for Agricultural Development*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 253–273.
- Singh, P., Virmani, S.M., 1994. Modeling growth and yield of chickpea (*Cicer arietinum* L.). *Field Crops Research* 46, 1–29.
- Singh, U., Matthews, R.B., Griffin, T.S., Ritchie, J.T., Hunt, L.A., Goenaga, R., 1998. Modeling growth and development of root and tuber crops. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 129–156.
- Soil Conservation Service (SCS) 1972. *National Engineering Handbook*, Hydrology Section 4, Chapters 4–10.
- Southworth, J., Randolph, J.C., Habeck, M., Doering, O.C., Pfeifer, R.A., Rao, D.G., Johnston, J.J., 2000. Consequences of future climate change and changing climate variability on maize yields on the midwestern United States. *Agriculture Ecosystems and Environment* 82, 139–158.

- Steele, D.D., Stegman, E.C., Knighton, R.E., 2000. Irrigation management for corn in the northern Great Plains, USA. *Irrigation Science* 19, 107–114.
- Swaney, D.P., Jones, J.W., Boggess, W.G., Wilkerson, G.G., Mishoe, J.W., 1983. Real-time irrigation decision analysis using simulation. *Transactions of the ASAE* 26, 562–568.
- Thornton, P.K., Saka, A.R., Singh, U., Kumwenda, J.D.T., Brink, J.E., Dent, J.B., 1995. Application of a maize crop simulation model in the central region of Malawi. *Experimental Agriculture* 31, 213–226.
- Thornton, P.K., Bowen, W.T., Ravelo, A.C., Wilkens, P.W., Farmer, G., Brock, J., Brink, J.E., 1997. Estimating millet production for famine early warning: an application of crop simulation modelling using satellite and ground-based data in Burkina Faso. *Agricultural and Forest Meteorology* 83, 95–112.
- Travasso, M.I., Magrin, G.O., 1998. Utility of CERES-Barley under Argentine conditions. *Field Crops Research* 57, 329–333.
- Travasso, M.I., Caldiz, D.O., Saluzzo, J.A., 1996. Yield prediction using the substor-potato model under Argentinian conditions. *Potato Research* 39, 305–312.
- Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), Decision Support System for Agrotechnology Transfer (DSSAT) Version 3. University of Hawaii, Honolulu, Hawaii 1994.
- Tsuji, G.Y., 1998. Network management and information dissemination for agrotechnology transfer. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 367–381.
- Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding options for agricultural production. Systems Approaches for Sustainable Agricultural Development*. Kluwer Academic Publishers, Dordrecht, The Netherlands 1998, p. 400.
- Tubiello, F.N., Rosenzweig, C., Volk, T., 1995. Interactions of CO₂ temperature and management practices: simulations with a modified version of CERES-Wheat. *Agricultural Systems* 49, 135–152.
- Tubiello, F.N., Rosenzweig, C., Kimball, B.A., Pinter, P.J., Jr., Wall, G.W., Hunsaker, D.J., LaMorte, R.L., Garcia, R.L., 2001. Testing CERES-wheat with free-air carbon dioxide enrichment (FACE) experiment data: CO₂ and water interactions. *Agronomy Journal* 91, 247–255.
- Uehara, G., 1989. Technology transfer in the tropics. *Outlook Agricultural* 18, 38–42.
- Uehara, G., 1998. Synthesis. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options For Agricultural Production*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 389–392.
- Uehara, G., Tsuji, G.Y., 1998. Overview of IBSNAT. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options For Agricultural Production*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 1–7.
- Vos, de R.N., Mallett, J.B., 1987. Preliminary evaluation of two maize (*Zea mays* L.) growth-simulation models. *South African Journal of Plant Soil* 4 (3), 131–136.
- Wafula, B.M., 1995. Applications of crop simulation in agricultural extension and research in Kenya. *Agricultural Systems* 49, 399–412.
- Wagner-Riddle, C., Gillespie, T.J., Hunt, L.A., Swanton, C.J., 1997. Modeling a rye cover crop and subsequent soybean yield. *Agronomy Journal* 89, 208–218.
- Welch, S.M., Jones, J.W., Brennan, M.W., Reeder, G., Jacobson, B.M., 2002. PCYield: Model-Based Decision Support for PRIVATE Soybean Production. *Agricultural Systems* 74 (1), 79–98.
- White, J.W., Hoogenboom, G., 1996. Simulating effects of genes for physiological traits in a process-oriented crop model. *Agronomy Journal* 88, 416–422.
- White, J.W., Hoogenboom, G., Jones, J.W., Boote, K.J., 1995. Evaluation of the dry bean model BEANGRO V1.01 for crop production research in a tropical environment. *Experimental Agriculture* 31, 241–254.
- Wilkerson, G.G., Jones, J.W., Boote, K.J., Ingram, K.T., Mishoe, J.W., 1983. Modeling soybean growth for crop management. *Transactions of the ASAE* 26, 63–73.
- Williams, J.R., Jones, C.A., Dyke, P.T., 1984. A modeling approach to determining the relationships between erosion and soil productivity. *Transactions of the ASAE* 27, 129–144.
- Wolf, J., Evans, L.G., Semenov, M.A., Eckersten, H., Iglesias, A., 1996. Comparison of wheat simulation models under climate change. I. Model calibration and sensitivity analyses. *Climate Research* 7, 253–270.
- Zalud, Z., Trnka, M., Dubrovsky, M., 2000. Change of spring barley production potential using crop model CERES-Barley. *Rostlinna Vyroba* 46 (9), 423–428.
- Zalud, Z., Stralkova, R., Pokorny, E., Podesvova, J., 2001. Estimation of winter wheat nitrogen stress using the CERES crop model. *Rostlinna Vyroba* 47 (6), 253–259.

CropSyst, a cropping systems simulation model

Claudio O. Stöckle^{a,*}, Marcello Donatelli^b, Roger Nelson^a

^a *Department of Biological Systems Engineering, Washington State University, Pullman, WA 99164-6120, USA*

^b *ISCI (Research Institute for Industrial Crops), Via di Corticella 133, 40128 Bologna, Italy*

Abstract

CropSyst is a multi-year, multi-crop, daily time step cropping systems simulation model developed to serve as an analytical tool to study the effect of climate, soils, and management on cropping systems productivity and the environment. CropSyst simulates the soil water and nitrogen budgets, crop growth and development, crop yield, residue production and decomposition, soil erosion by water, and salinity. The development of CropSyst started in the early 1990s, evolving to a suite of programs including a cropping systems simulator (CropSyst), a weather generator (ClimGen), GIS-CropSyst cooperator program (ArcCS), a watershed model (CropSyst Watershed), and several miscellaneous utility programs. CropSyst and associated programs can be downloaded free of charge over the Internet. One key feature of CropSyst is the implementation of a generic crop simulator that enables the simulation of both yearly and multi-year crops and crop rotations via a single set of parameters. Simulations can last a fraction of a year to hundreds of years. The model has been evaluated in many world locations by comparing model estimates to data collected in field experiments. CropSyst has been applied to perform risk and economic analyses of scenarios involving different cropping systems, management options, and soil and climatic conditions. An extensive list of references related to model development, evaluation, and application is provided.

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1. Introduction

CropSyst is a multi-year, multi-crop, daily time step cropping systems simulation model developed to serve as an analytical tool to study the effect of climate, soils, and management on cropping systems productivity and the environment. Emphasis

has been placed on developing a user-friendly interface, providing links to GIS software, a weather generator, and other utility programs.

CropSyst simulates the soil water budget, soil-plant nitrogen budget, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and salinity. These processes are affected by weather, soil characteristics, crop characteristics, and cropping system management options including crop rotation, cultivar selection, irrigation, nitrogen fertilization, soil and irrigation

* Corresponding author. Tel.: +1-509-335-3826; fax: +1-509-335-2722

E-mail address: stockle@wsu.edu (C.O. Stöckle).

water salinity, tillage operations, and residue management.

The development of CropSyst started in the early 1990s. The motivation for its development was based on the observation that there was a niche in the demand for cropping systems models, particularly those featuring crop rotation capabilities, which was not properly served. Efficient cooperation among researchers from several world locations, a free distribution policy, active cooperation of model developers and users in specific projects, and careful attention to software design from the onset allowed for rapid and cost-effective progress. Another important factor was the advantage of learning from a rich history of crop modeling efforts.

The first examples of crop growth models, mostly intended for use by the agriculture research community, were available during the 1970s (e.g. de Wit et al., 1970; Arkin et al., 1976). Applications oriented to management or field decision-making (irrigation scheduling, pest and disease control, etc.) appeared in the early 1980s (e.g. Wilkerson et al., 1983; Swaney et al., 1983). On-farm applications of models were also reported (e.g. Lindemann et al., 1987; McKinion et al., 1988). Models such as SUCROS and others associated with the 'School of de Wit' (Bouman et al., 1996) as well as those of the CERES (Ritchie et al., 1998) and CROPGRO (Boote et al., 1998) families of models had a significant impact on the crop modeling community.

For the analysis of cropping systems, the ability to simulate crop rotations is important. Models of the CROPGRO and CERES families, placed under the common umbrella of DSSAT (Jones et al., 1998) can be used in rotation configurations. However, the DSSAT approach has been slow in adopting a more generic simulation platform that would allow users to easily integrate these models and simulate crop rotations (Jones et al., 2001). The EPIC model (Williams et al., 1984) provides a simple but effective generic multi-crop simulation approach suitable for the analysis of crop rotations and cropping systems. However, the model has limitations due to the simplicity of its crop growth descriptions and related biophysical processes.

CropSyst was designed to draw from the conceptual strengths of EPIC, but including a more process-oriented approach to the simulation of crop growth and its interaction with management and the surrounding environment. In addition, a stronger emphasis on software design was a clear departure from the EPIC and DSSAT approaches. Attention to a balance between the incorporation of sound science in the models and the utilization of adequate software design practices has been a trait of CropSyst since the beginning of its development. In this regard, it shares somewhat common objectives with APSIM (McCown et al., 1996; Keating et al., 2003), a modeling approach that has evolved to place substantial resources in the development of quality software engineering practices.

2. CropSyst components and modeling approach

CropSyst is a suite of programs designed to work co-operatively, providing users with a set of tools to analyze the productivity and the environmental impact of crop rotations and cropping systems management at various temporal and spatial scales. The main components of the CropSyst Suite are: CropSyst parameter editor, a cropping systems simulator (CropSyst model), a weather generator (ClimGen), a GIS-CropSyst simulation co-operator (ArcCS), a watershed analysis tool (CropSyst Watershed), and several utility programs.

2.1. CropSyst parameter editor

The parameter editor serves as the main user interface to the CropSyst Suite package. The user interface provides editors for setting and modifying CropSyst parameters, running the model, and viewing the output. The various components and utilities can be selected or accessed from menus and buttons on the tool bar.

2.2. CropSyst

The cropping systems simulator is the core of the suite of programs. It contains all the necessary

objects, procedures, and functions to simulate the productivity of crops and crop rotations in response to weather, soil and management. A description of the main processes in CropSyst is given in [Section 3](#). The model simulates a *single land block fragment*. A land block fragment represents a biophysically homogeneous unit area with a uniform management regimen. Simulation scenarios for land block fragments are created by preparing parameter files describing the climate, soil, crops and crop management. A simulation control file identifies and links all the input files, provides initial conditions, selects optional simulation modules, and specifies the scenario to be simulated.

2.3. *ClimGen*

Long-term series of daily weather data are often required for the probabilistic analysis of weather-impacted systems (e.g. cropping systems management, hydrologic studies, environmental studies, and others). Weather generators are computer programs that use existing weather data to determine generation parameters, which in turn are used to generate long series of daily climatic data. The statistical properties of the generated data are expected to be similar to those of the actual data.

ClimGen is a weather generator that uses principles similar to those in WGEN ([Richardson and Wright, 1984](#)), but with significant modifications and additions. ClimGen generates precipitation, daily maximum and minimum temperature, solar radiation, air humidity, and wind speed. All generation parameters are calculated for each site of interest, allowing the program to be applied to any world location. Additional features allow users to estimate atmospheric vapor pressure deficit and solar radiation from existing temperature records. The performance of ClimGen has been evaluated in several studies ([Stöckle et al., 1998](#); [Acutis et al., 1998, 1999](#); [Castellvi and Stöckle, 2002](#); [Castellvi et al., 2002](#)).

2.4. *ArcCS*

ArcCS facilitates GIS-based CropSyst simulation projects by using polygons derived from

ARCVIEW or Arc/Info GIS. Each polygon represents a land block fragment. ArcCS uses the polygon attribute table produced by the GIS software to identify, generate and run a simulation scenario for each unique land block fragment. A new polygon attribute table of CropSyst output variables is generated, which can be used by Arc/Info or ARCVIEW to produce maps of the CropSyst outputs. Annual and harvest outputs are used in statistical analyses to produce output maps for the mean, coefficient of variation, and cumulative probability distributions for any of the variables selected by the user.

2.5. *CropSyst watershed*

CropSyst Watershed is an extension of CropSyst and ArcCS capabilities where land block fragments, defined as raster cells in a grid instead of polygons, are hydrologically connected. As in the ArcCS module, the watershed model will compose a simulation scenario for each grid cell. CropSyst Watershed uses ARCVIEW for Windows and its Spatial Analyst extension as geographical base. The Spatial Analyst for ARCVIEW allows users to define watershed boundaries and drainage network from digital elevation models data. In addition, it provides tools to rasterize and overlay polygon-based combination maps (produced by ArcCS) that represent unique combinations of soils, land use, management, and other characteristics within the watershed. CropSyst simulations are run for each cell, starting with the uppermost cells and continuing with lower elevations until the entire watershed is covered.

2.6. *Miscellaneous utility programs*

In addition to the main components, the CropSyst Suite package includes utility programs to estimate soil hydraulic parameters ([Acutis and Donatelli, 2003](#)) and global solar radiation ([Donatelli et al., 2003](#)), and for statistical comparisons of model estimates and measured data ([Fila et al., 2003](#)). It also includes a dynamic link library that can be integrated in other models to calculate reference crop evapotranspiration ([Donatelli et al., 2002a](#)).

3. Model description

The CropSyst model is intended for crop growth simulation over a single land block fragment with uniform soil, weather, crop rotation and management. Growth is described at the level of whole plant and organs. Integration is performed with daily time steps using the Euler's method. An overall description of the model follows.

3.1. Water budget

The water budget in the model includes precipitation, irrigation, runoff, interception, water infiltration, water redistribution in the soil profile, deep percolation, crop transpiration, and evaporation. Water redistribution in the soil can be simulated by a simple cascading approach or a numerical solution of the Richard's soil flow equation (Campbell, 1985; Ross and Bristow, 1990). Boundary conditions allow for flux or saturated upper boundary and for free drainage or saturated (water table) lower boundaries.

CropSyst offers two options to calculate reference crop ET (ET_0): the Penman–Monteith model (Monteith, 1965) and the Priestley–Taylor model (Priestley and Taylor, 1972). The implementation of the Penman–Monteith model follows the methodology suggested by FAO (Allen et al., 1998). This option requires daily maximum and minimum temperature, solar radiation, maximum and minimum relative humidity (or dew-point temperature), and wind speed. The Priestley–Taylor model only requires temperature and radiation data, but the user must provide an appropriate value of the Priestley–Taylor constant. ClimGen allows users to estimate daily solar radiation and humidity from temperature, and to generate daily wind data, provided that at least 2 years of complete daily records are available. Potential crop ET is determined by multiplying ET_0 by a crop coefficient (K_c). Ground coverage by the crop determines the partitioning into potential crop transpiration and potential soil evaporation. Actual transpiration and soil evaporation depend on water availability in the soil profile explored by roots and soil surface, respectively (Stöckle and Jara, 1998; Jara and Stöckle, 1999).

3.2. Nitrogen budget

The mineral N budget in CropSyst includes separate budgets for nitrate and ammonium. Processes include N transformations, ammonium sorption, symbiotic N fixation, crop N demand and crop N uptake. Nitrogen transformations (net mineralization, nitrification, and denitrification) and ammonium sorption follow the approach presented by Stöckle and Campbell (1989) while symbiotic N fixation is based on Bouniols et al. (1991).

Crop N uptake was modeled by adapting the approach presented by Godwin and Jones (1991), where N uptake is determined as the minimum of crop nitrogen demand and potential nitrogen uptake. Crop nitrogen demand is the amount of nitrogen the crop needs to meet growth requirements plus its deficiency demand. The deficiency demand is the difference between the crop maximum and actual nitrogen concentration.

The water and nitrogen budgets interact to produce a simulation of N transport within the soil. Other chemical budgets such as salinity also interact with the water balance. All balances are checked during a simulation, and errors are reported.

3.3. Crop phenology

The simulation of crop development is based on thermal time, which is the required daily accumulation of average air temperature above a base temperature and below a cutoff temperature to reach given growth stages. The accumulation of thermal time may be accelerated by water stress. This can be conceptualized as a response to increased crop temperature. Relations between air and crop temperatures for stressed and unstressed crops, expressed as a function of the vapor pressure deficit of the atmosphere, can be found in the infrared thermometry literature (e.g., Jackson, 1982).

When simulations for a particular crop or cultivar are conducted over contrasting locations or for a wide range of planting dates, thermal time alone may not be a good predictor of development. Vernalization and photoperiod require-

ments may need to be considered (Ritchie and NeSmith, 1991).

3.4. Biomass accumulation

Fig. 1 shows a flowchart describing the approach used in CropSyst to calculate daily biomass accumulation. The core of these calculations is the determination of unstressed (potential) biomass growth based on crop potential transpiration and on crop intercepted PAR. This potential growth is

then corrected by water and nitrogen limitations, if any, to determine actual daily biomass gain.

Given the common pathway in leaves for carbon and vapor exchange, there is a conservative relationship between crop transpiration and biomass production. Thus, the potential daily biomass production can be calculated as (Tanner and Sinclair, 1983):

$$B_{PT} = \frac{K_{BT} T_P}{VPD} \quad (1)$$

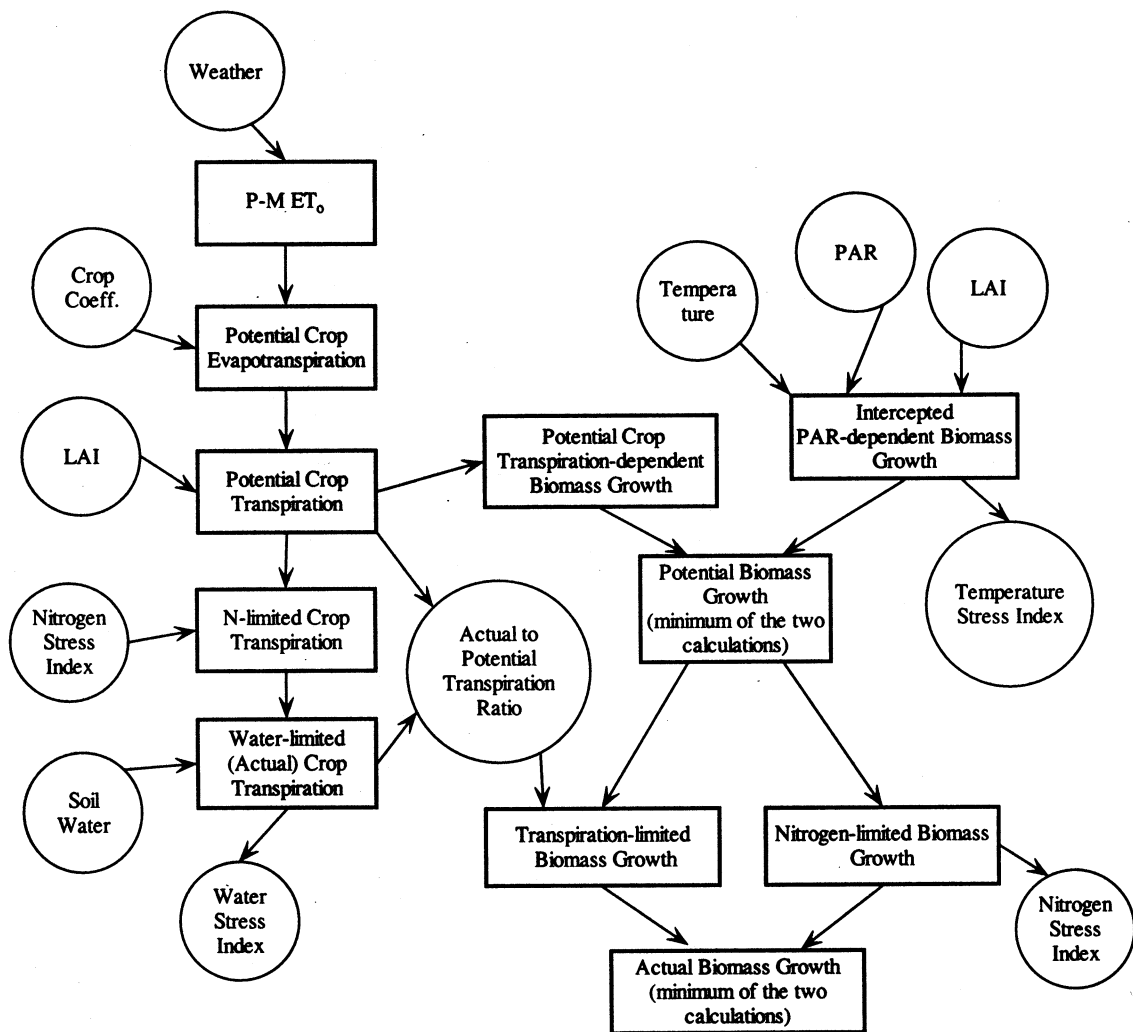


Fig. 1. Flowchart of biomass growth calculations in CropSyst.

where B_{PT} is the crop potential transpiration-dependent biomass production ($\text{kg m}^{-2} \text{day}^{-1}$), T_P is crop potential transpiration ($\text{kg m}^{-2} \text{day}^{-1}$), VPD is the daytime mean atmospheric vapor pressure deficit (kPa), and K_{BT} is a biomass-transpiration coefficient (kPa). Values for the latter parameter are available in the literature (Tanner and Sinclair, 1983; Loomis and Connors, 1992).

The Tanner–Sinclair relationship becomes unstable at low VPD values; in fact it would predict infinite growth at near zero VPD. To overcome this problem, a second estimate of unstressed biomass production is calculated following Monteith (1977):

$$B_{IPAR} = eIPAR \quad (2)$$

where B_{IPAR} is the intercepted PAR-dependent biomass production ($\text{kg m}^{-2} \text{day}^{-1}$), e is the radiation-use efficiency (kg MJ^{-1}) and IPAR is the daily amount of crop-intercepted photosynthetically active radiation ($\text{MJ m}^{-2} \text{day}^{-1}$).

Values for the parameter e in Eq. (2) are available in the literature (e.g. Kiniry et al., 1989). However, these values tend to present significant variability. For the approach implemented in CropSyst, it is important to select values from experiments with unstressed crops and conducted under low VPD environments. Although the parameter e includes the effect of the temperature regime prevailing during its experimental determination, temperature limitations during early growth are normally not accounted for. This may result in overprediction of biomass production during early growth at low temperature, particularly in the case of winter crops or early sown spring crops. A temperature limitation factor is included in CropSyst to correct the value of e during early growth, which is assumed to increase linearly (from 0 to 1) as air temperature fluctuates from the base temperature for development to an optimum temperature for early growth.

During each simulation day, the potential biomass production for the day (B_P) is taken as the minimum of B_{PT} and B_{IPAR} . This value is used as basis to calculate water and nitrogen-limited biomass growth (actual daily biomass production).

To determine water limitations, the effect of nitrogen deficiency on crop transpiration must be estimated. This effect is accounted for by increasing canopy resistance (Van Keulen and Seligman, 1987). For each simulation day, maximum (N_{\max}), critical (N_{crit}), and minimum (N_{\min}) plant nitrogen concentrations are calculated. N_{\max} is the maximum attainable plant N concentration, N_{crit} is the critical plant N concentration (kg kg^{-1}) below which biomass growth is reduced, and N_{\min} is the minimum plant nitrogen concentration (kg kg^{-1}) at which biomass growth stops. The values of N_{\max} , N_{crit} and N_{\min} fluctuate throughout the growing season as a function of accumulated biomass, following the concept of growth dilution (e.g., Greenwood et al., 1990). More details on this are given by Stöckle et al. (1997).

At plant N concentrations between N_{\max} and N_{crit} , canopy resistance (r_c in day m^{-1}) remains unchanged (unstressed r_c value), but r_c increases at N concentrations between N_{crit} and N_{\min} as follows:

$$r_{\text{cNS}} = \frac{r_c}{\left[1 - \frac{N_{\text{crit}} - N_c}{N_{\text{crit}} - N_{\min}}\right]} \quad (3)$$

where r_{cNS} is N stressed canopy resistance (day m^{-1}), whose value is constrained to an arbitrary maximum representing canopy resistance with closed stomata, and N_c is the current plant nitrogen concentration (kg kg^{-1}). N-limited crop transpiration (T_N) is then calculated by reducing potential transpiration in response to changes in r_c .

$$T_N = T_P \frac{+ \gamma(1 + r_c/r_a)}{\Delta + \gamma(1 + r_{\text{cNS}}/r_a)} \quad (4)$$

where Δ is the slope of the saturation vapor pressure function of temperature ($\text{kPa } ^\circ\text{C}^{-1}$), γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), and r_a is aerodynamic resistance to vapor transfer (day m^{-1}). See Allen et al. (1998) for more information on these parameters.

Water-limited or actual crop transpiration (T_A) is determined by the ability of the crop to uptake soil water to match the requirement set by T_N (which is equal to potential crop transpiration

when N is not limiting). T_A is calculated as outlined by Stöckle and Jara (1998). Transpiration-limited biomass growth (B_T) is then given by:

$$B_T = B_P \left[\frac{T_A}{T_P} \right] \quad (5)$$

where B_T is in $\text{kg m}^{-2} \text{day}^{-1}$, B_P is the potential biomass growth for the day ($\text{kg m}^{-2} \text{day}^{-1}$), and T_A/T_P is the ratio of actual to potential transpiration.

Nitrogen-limited biomass growth (B_N) is calculated as follows:

$$B_N = B_T \left[1 - \frac{N_{\text{crit}} - N_c}{N_{\text{crit}} - N_{\text{min}}} \right] \quad (6)$$

where B_N is in $\text{kg m}^{-2} \text{day}^{-1}$. For plant N concentrations between the N_{max} and N_{crit} , biomass growth is not affected by the plant nitrogen status.

3.5. Leaf area development

The increase of leaf area during the vegetative period, expressed as leaf area per unit soil area (leaf area index, LAI), is calculated as a function of biomass accumulation:

$$\text{LAI} = \frac{\text{SLAB}}{1 + pB} \quad (7)$$

where LAI is in $\text{m}^2 \text{m}^{-2}$, B is accumulated aboveground biomass (kg m^{-2}), SLA is the specific leaf area ($\text{m}^2 \text{kg}^{-1}$), and p is a partition coefficient ($\text{m}^2 \text{kg}^{-1}$) controlling the fraction of biomass apportioned to leaves (a value of zero apportions all biomass to leaves).

The derivative of Eq. (7) with respect to biomass gives the change of LAI per unit change of biomass. Thus, the amount of new LAI produced in each simulation day is a function of the biomass production on that day. The end of the vegetative period marks the end of new LAI production. Leaf area duration, expressed in thermal time units (degree-days), is assigned to each unit of daily LAI produced. When a given daily LAI portion completes its duration, it is removed from current LAI, effectively simulating the process of leaf senes-

cence. Water stress corrections are applied to both daily leaf area production and leaf area duration.

3.6. Root growth

Root growth in CropSyst is described in terms of root depth and root density, the latter calculated for each soil layer. Root depth is synchronized with leaf area growth, eventually reaching a specified maximum value (Rd_{max}) unless severe water or nitrogen limitations are present. Root density is assumed zero at a soil depth equal to the current root depth, and increases linearly to a maximum at a depth near the soil surface. The slope of this linear increase is given by the ratio of maximum root density to Rd_{max} . For shallow soils, only roots in actual soil layers extract water and nitrogen.

3.7. Yield

Yield simulation depends on total biomass accumulated at physiological maturity (B_{PM}) and the harvest index (HI = harvestable yield/above-ground biomass):

$$Y = B_{\text{PM}} \text{HI} \quad (8)$$

where Y is yield (kg m^{-2}) and B_{PM} is also in kg m^{-2} . The harvest index is determined using as base an unstressed harvest index modified according to stress intensity (water and nitrogen) and crop sensitivity to stress during flowering and grain filling.

3.8. Crop growth response to elevated atmospheric CO_2

Two parameters in CropSyst define potential crop growth in response to water use and radiation capture: K_{BT} and e (Eqs. (1) and (2), respectively). In order to establish the effect of elevated atmospheric CO_2 on growth, values of these parameters under specified atmospheric CO_2 concentrations are required.

Determining the rate of change of these parameters in response to changes in CO_2 concentration requires complex carbon assimilation models that are not suitable for application at the crop-

ping systems scale. Therefore, the implementation in CropSyst relies on experimental evidence of crop growth responses to CO₂. These experiments report the percent increase of growth under a specified atmospheric CO₂ concentration compared to growth at a baseline concentration. This information is processed using a modified version of the approach introduced by Stöckle et al. (1992).

3.9. Crop rotations

CropSyst simulations are performed using a daily time step within a period specified by start and ending dates. During this period, state variables such as residue biomass (surface and incorporated into the soil), evapotranspiration, soil water content, soil N content (nitrate and ammonium), soil organic matter and others are updated daily regardless if a growing crop is present or not (fallow). Crops and their corresponding management are initiated during this period according to a sequence given by a crop rotation template.

4. Data requirements

Five input data files are required to run CropSyst: Simulation Control, Location, Soil, Crop, and Management files. Separation of files allows for an easier link of CropSyst simulations with GIS software. Definitions, usage, and range of variation of all parameters required by CropSyst are given in the User's Manual (Stöckle and Nelson, 2000), and they are also available in the Help facility of the model interface.

The Simulation Control file combines the different types of input files as desired to produce specific simulation runs. It specifies the start and ending day of the simulation and the crop rotation to be simulated, and sets the values of all parameters requiring initialization. Also, inputs to this file allow users to switch on/off the simulation of soil erosion, soil salinity, nitrogen and CO₂ effects on crop growth, and to select soil water redistribution and runoff models.

The Location file includes information such as latitude, weather file code name and directories,

rainfall intensity parameters, selection of ET models (Penman–Monteith or Priestley–Taylor) and associated parameters, and generalized information on wind for locations where daily wind data are not available.

The Soil file includes surface soil cation exchange capacity and pH for the estimation of ammonia volatilization, parameters for the SCS curve number approach (US Soil Conservation Service, 1972) for runoff calculation, and parameters for the Revised Soil Loss Equation (Renard et al., 1997) for erosion calculation. For each soil layer, thickness and texture must be specified. Based on this information, pedotransfer functions (Saxton et al., 1986) are used to calculate bulk density, volumetric water content at water potentials of –33 kPa (Field Capacity) and –1500 kPa (Wilting Point), and air entry potential and Campbell *b* value for the relationship between volumetric water content and water potential (Campbell, 1985). Whenever available, actual measurements instead of values estimated from texture can be used.

The Management file includes scheduled and automatic management events. Management events can be scheduled using actual date, relative date (relative to year of planting), or using synchronization with phenological events (e.g., number of days after flowering). Scheduled events include irrigation (application date, amount, and salinity concentration), nitrogen fertilization (application date, amount, source, and application mode), tillage operations, and residue management. The automatic event manager (irrigation and nitrogen fertilization) checks continuously the soil water and nitrogen content and it can be specified to provide management for maximum growth or to implement deficit strategies.

The Crop file allows users access to a common set of parameters to represent different crops and crop cultivars. This is a key feature of CropSyst. The file is structured in the following sections: phenology (thermal time requirements to reach specific growth stages), morphology (Maximum LAI, root depth, specific leaf area, leaf area duration, and other parameters defining canopy and root characteristics), growth (transpiration-biomass coefficient, radiation-use efficiency, stress

response parameters, etc.), residue (decomposition and shading parameters for crop residues), Nitrogen (defining crop N demand and root uptake), harvest index (unstressed harvest index and stress sensitivity parameters), salinity tolerance, and CO₂-elevation response.

Crop parameters are the only input data that require calibration within a narrow range to properly represent specific crops and cultivars. However, those parameters defining the bulk of the crop response to the environment and management can be determined through field experiments. These parameters are the transpiration-biomass coefficient (Tanner and Sinclair, 1983), the radiation-use efficiency (Monteith, 1977), the specific leaf area, the stem/leaf partitioning coefficient, and the leaf area duration. In addition, thermal time requirements for different crop development stages can also be recorded from field observations. The basic experimental data set must include growing season evolution of biomass (leaves and stem), LAI, intercepted PAR, soil water, seasonal daily weather, total biomass at harvest and yield.

5. Software implementation and distribution policy

The model code is written in C++, and can be used on WINDOWS or UNIX-based platforms. An advanced user-friendly interface allows users to easily manipulate input files, verify input parameters for range errors and cross-compatibility, create simulations, execute single and batch run simulations, customize outputs, produce text and graphical reports, and link to spreadsheet programs. Simulations can be customized to invoke only those modules of interest for a particular application (e.g., erosion and nitrogen simulation can be disabled if not desired), producing more efficient runs and simplifying model parameterization. The model is fully documented (Stöckle and Nelson, 2000, last update), and the manual is also available as a help utility in the CropSyst interface. The CropSyst executable program, manual, tutorials, and utility programs can be retrieved free of charge directly over the internet at <http://www.bsyes.wsu.edu/cropsyst> or <http://www.isci.it/tools>. However, the source code is not distributed,

eliminating the risk of ending up with many versions of the model.

5.1. Programming framework

CropSyst development has emphasized runtime performance using a conventional monolithic simulation engine approach incorporating all simulation elements in a single program at compile time. The normal object oriented features and coding conventions of the C++ language provide a straightforward and consistent simulation model development environment. New features and capabilities can be added and the overall logical framework of the model can be changed quickly.

Recent simulation model framework design efforts are attempting to develop a modular simulation engine with the primary goal of offering model developers and users the ability to augment an existing model or construct new models by plugging in modules at run time within a simulation development environment, sometimes allowing the modules to be written in a variety of programming languages. Often the modular design is an attempt to work around the software design and maintenance limitations of non-object oriented programming languages such as FORTRAN, C and dialects of BASIC. Such systems often require significant overhead in terms of both run time performance and coding to support modular model construction and data exchange protocols.

In CropSyst, modular programming is achieved by using C++ wrapper classes to encapsulate sub-models that can even be written in other programming languages. Many of the CropSyst sub-model objects are independent. The crop, soil, residue, evapotranspiration and weather objects can and have been used in other simulation models and programs. The entire cropping system model in CropSyst, itself being a C++ object class, can be used directly in other simulation models written in C++. Thus, CropSyst has been used as a sub-model in a regional scale land use optimization program (Rivington et al., 2001) and a whole farm simulation model (Chen et al., 2002).

5.2. User interface

One of the principles adopted early on was that the user interface would organize the parameters into data sets that could be pulled together to quickly produce new simulation runs via a simulation control file. Parameters are divided into location specific, crop specific, soil specific, and management parameters. One of the most fundamental aspects of the CropSyst structure is the mapping of input parameter values to user input screen representation to data storage files to simulation model objects in the program.

Simulation scenarios are constructed by selecting a soil and location and building crop rotations with sowing dates and an optional temporally dynamic management schedule associated with the crop. The scenario can also specify initial soil profile conditions, provide optional water table observations (to create an interpolated water table), and an optional schedule of soil profile recalibration data points.

5.3. Input file formats

For most parameter files, CropSyst uses a text file format similar to the Window INI file format. Parameters can be organized into sections allowing a logical structure that can more closely match the organization of parameters in the program. The format is extensible. New parameters can be added to the model, but allowing users to still use their old parameter files without modification. Adding new parameters requires modification of only a couple of lines of code and does not require reorganization of a database or utilities to reformat a database. Parameters not used by the model, additional data, and comments can be stored in the file even if not currently used by the model.

Recently, the code for reading parameter files has been further separated from the model's scientific code using a 'Data source/Data record' model, greatly reducing the amount of code required to read and write parameter files, and allowing the ability to store parameters in relational databases such as dBase and Oracle.

In addition to the parameter files, the only other input file is for weather data. The weather files

consist of a simple space delimited text file table with daily weather values organized one day per line, one file per year. Four formats are currently recognized. Text files are easy to read and to generate from databases. However, they also have several disadvantages. To address these disadvantages, CropSyst now uses the 'Universal Environmental Database' (UED) binary file format for storing input weather data (as well as output results). This, coupled with an object oriented class for accessing the data, significantly reduces the size of the weather data files and improves runtime performance. The UED format also provides facilities for efficiently annotating the database with comments and unit specification.

5.4. Event driven modeling

To accommodate the dynamic nature of management practices in the simulation of long-term crop rotation scenarios, operations for both simulated management and simulation output options are presented to the model as dated events and/or operation modes. The simulation control parameters specify a list of sowing events and associated management event tables. These tables are loaded at runtime to build a dynamic event queue for all operations that occur during the simulation. Most objects are created dynamically in response to management operation events. For example a crop object will be created when a planting event is reached and will be disposed after harvest is processed.

Events can be set to occur on specific dates, dates relative to the planting date, or synchronized to the phenologic development of the crop or to the occurrence of specified conditions (e.g., automatic irrigation). Some events may propagate additional events that are added to the event queue; for example, a crop-planting event with an associated management file will add events for the management when the crop is planted. This flexibility allows CropSyst to be used in a predictive mode to model management practices based on crop conditions rather than fixed schedules.

All events can also be set to occur on specific dates. This allows CropSyst to be used in a

calibrative mode to check the model against conditions that actually occurred either in actual farming scenarios or research studies. Fixed dates can either be set as actual dates, or relative to the year in the rotation, or set to occur every year on the same date.

6. Model testing and examples of applications

6.1. Evaluation of models and its limitations

Model evaluation is conventionally made by comparing simulation outputs with data collected from the ‘real world’ system represented by the model. However, such evaluations can be limited by several factors, making it somewhat difficult to establish the true performance of models. Detailed information on the initial conditions of the system is required to conduct these comparisons, information that it is not always available or is confounded by significant spatial variability under typical field situations. Model evaluation is increasingly difficult as the system under consideration becomes more complex, as is the case with crop rotations and cropping systems evaluated over several years. In such a case, many types of data are required to test the various processes simulated by the model. Furthermore, not all model outputs of interest can be evaluated because the corresponding measurements are difficult or unfeasible to obtain.

Another problem in model evaluation is the choice of quantitative indices used to evaluate model performance. These statistical indices normally rely on one-to-one (simulated vs. measured) comparisons, neglecting measurement errors and other sources of variation inherent to field experiments. Moreover, discrepancies between simulated and measured values in time series are not properly evaluated, greatly penalizing simulation outputs that have even a modest time shift with respect to measured data. Attempts to overcome some of these problems have been recently, proposed (Donatelli et al., 2002c).

6.2. Evaluation of CropSyst

The CropSyst model has been evaluated under a variety of conditions. By design, CropSyst only includes processes or relationships that are not site specific; indeed they are expected to work under most agricultural situations. However, several features of the model (e.g., organization of output variables, output handling, management events synchronization) have been modified or developed to facilitate these evaluations. The inclusion of processes such as salinity and water table effects, elevated CO₂ responses, and others have resulted from user–developer interactions prompted by model evaluations and applications. However, the basic algorithms for crop growth and development, and for simulating water and nitrogen balances have not been changed.

Examples of the performance of CropSyst in the simulation of biomass production and yield in response to water and nitrogen of single crops, over a single season and under experimental conditions are summarized in [Tables 1 and 2](#). In these experiments, the treatments imposed provided a large array of conditions from dry to fully irrigated and from low soil available nitrogen to well supplied conditions. In these evaluations, the indicators of performance were the root mean square errors (RMSE), the ratio of RMSE to the observed mean (an indication of the relative magnitude of the error), and the Willmott index of agreement (*d*) that takes on values from 0 to 1.0, with an index of 1.0 indicating perfect agreement (Willmott, 1982).

Examples of model performance in the simulation of evapotranspiration are shown in [Table 3](#). [Jara and Stöckle \(1999\)](#) conducted a more detailed evaluation of the simulation of crop water uptake. Simulated daily crop water uptake was compared with measurements of sap flow and soil water content for maize growing at Prosser, Washington, under a wet and a dry irrigation treatment, and with soil water content measurements for non-irrigated maize at Davis, California. For the wet treatment at Prosser, the RMSE for water uptake was 0.27–0.28 mm day^{−1} (~7% of the observed mean). For the dry treatment, the simulation accuracy decreased to a RMSE of 0.33–0.38

Table 1

Statistical comparisons of observed and simulated responses to water treatments for four crops and four locations (Stöckle et al., 1994, 1997)

Crop	Location		<i>N</i>	Obs mean (kg/ha)	Sim mean (kg/ha)	RMSE (kg/ha)	RMSE / Obs mean	<i>d</i>
Maize	Davis, CA and Ft Collins, CO	Grain yield	28	9831	9026	724	0.081	0.950
		Biomass	28	16 460	16 808	1246	0.076	0.954
	Auzeville, France	Grain yield	9	8026	7847	1707	0.213	0.963
		Biomass	9	19 038	18 358	2921	0.153	0.966
Wheat	Logan, UT	Grain yield	18	4100	4261	443	0.108	0.979
		Biomass	18	8033	8460	1121	0.140	0.961
Sorghum	Auzeville, France	Grain yield	8	7601	8055	896	0.118	0.967
		Biomass	8	16 684	17 358	1139	0.068	0.985
Soybean	Auzeville, France	Grain yield	9	2828	2804	381	0.135	0.970

N, number of data point; Obs, observed value; Sim, simulated value; RMSE, root mean square error; *d*, index of agreement.

mm day⁻¹ (~9–10% of the observed mean). The time evolution of water uptake depicted well the measured sap flow. The RMSE for water content by soil layer ranged from 0.011 to 0.024 m³ m⁻³ (5–9% of observed means) for Prosser and Davis experiments.

Simulations of N requirement and crop N uptake were evaluated using data collected at the Auzeville experiment station of INRA near Toulouse, France. These simulations resulted in a relationship between biomass at harvest and N uptake that correctly described an upper boundary (other limiting factors were not included in the

simulations) for all observed data points. Detailed evaluation of biomass, leaf area, water uptake, and nitrogen uptake evolution throughout a complete growing season has also shown a reasonable performance of the model (e.g., Pala et al., 1996; Stöckle and Debaeke, 1997).

The capability of the model to simulate crop rotations was evaluated at sites in Northern and Southern Italy (Donatelli et al., 1996a). Simulated yields of different cropping systems were evaluated for seven consecutive years, generally showing good results with the exception of the simulation of summer crops following barley harvest (second

Table 2

Statistical comparisons of observed and simulated responses to water and nitrogen treatments for wheat at two locations (Stöckle et al., 1994; Pala et al., 1996)

Crop	Location		<i>N</i>	Obs mean (kg/ha)	Sim mean (kg/ha)	RMSE (kg/ha)	RMSE / Obs mean	<i>d</i>
Wheat	Logan, UT	Grain yield	30	4946	4963	383	0.077	0.975
		Biomass	30	10 293	10 339	786	0.076	0.996
Wheat (Cham 1) ^a	Northern Syria	Grain yield	16	2180	2410	550	0.250	0.920
		Biomass	16	7310	7090	870	0.120	0.960
Wheat (Hourani) ^a	Northern Syria	Grain yield	16	1750	2080	560	0.320	0.900
		Biomass	16	7190	7140	1030	0.140	0.920

N, number of data point; Obs, observed value; Sim, simulated value; RMSE, root mean square error; *d*, index of agreement.

^a Cham 1 and Hourani correspond to improved and local varieties, respectively.

Table 3

Statistical comparisons of observed and simulated seasonal evapotranspiration for four crops and two locations (Stöckle et al., 1997; Pala et al., 1996)

Crop	Location	<i>N</i>	Obs mean (mm)	Sim mean (mm)	RMSE (mm)	RMSE/Obs mean	<i>d</i>
Wheat (Cham 1) ^a	Northern Syria	16	311	298	29	0.090	0.950
Wheat (Hourani) ^a		16	319	314	30	0.090	0.950
Sorghum	Auzeville, France	5	372	409	54	0.144	0.786
Soybean		6	412	443	42	0.102	0.956
Maize		6	416	414	13	0.031	0.997

N, number of data point; Obs, observed value; Sim, simulated value; RMSE, root mean square error; *d*, index of agreement.

^a Cham 1 and Hourani correspond to improved and local varieties, respectively.

crops in the same growing season). A long-term 4-year rotation with different levels of mineral and organic fertilization was used to evaluate the model in Northern Italy (Berti et al., 2001). The results were satisfactory for the overall systems evaluated, and for winter wheat, maize, and sugar beet crops, whereas the simulation of soybeans was not satisfactory. In southeastern Australia, the model simulated well phenology, biomass, yield and water budget components of wheat, field pea and mustard (Diaz-Ambrona et al., 2001). An unpublished test by Diaz-Ambrona et al. also showed that the model simulated well the yield of farmer-grown wheat crops in the region between 1998 and 2000 (measured vs. simulated yield: $r^2 = 0.72$, $RMSE = 0.21 \mu g \text{ ha}^{-1}$) (Sadras, 2002).

CropSyst performed well in simulating rice systems implemented in Northern Italy (Bocchi et al., 2001) with early varieties at high yield levels. In contrast, further work in model development appeared to be needed to simulate flooded rice. Simulations of spring and winter wheat water use and yields in wheat-fallow rotations at eastern Washington using different tillage and residue management practices over a period of 6 years showed that the statistical structure of simulated and field data was similar (Pannkuk et al., 1998). Simulated and field data also yielded similar water production functions. The RMSE fluctuated from 7 to 14% of the observed means for grain yield, and from 5 to 9% for evapotranspiration. The Willmott index of agreement fluctuated from 0.92 to 0.97, with all values but one equal to or better

than 0.94. The water balance in CropSyst was evaluated for different cropping systems at a location in Southern Italy (Ventrella and Rinaldi, 1999), showing good overall model performance, except for estimates of soil water content at the end of the summer. Soil cracking was reported as the cause for overestimation of soil water content at upper soil layers and underestimation at lower soil layers.

The nitrogen balance in systems with inorganic and organic fertilization was evaluated on maize systems (Donatelli et al., 1996b), showing a good agreement for both soil water and nitrate estimates over time. Similar results, also for maize systems, were obtained in Central Italy (Silvestri et al., 1999). The application of CropSyst to intensive forage systems in Northern Italy (Confalonieri et al., 2001) was satisfactory in terms of alfalfa biomass estimates, but inadequate with reference to soil nitrogen estimates.

CropSyst was also evaluated in a comparative study with other models to evaluate nitrogen dynamics in Northern Germany (Richter et al., 1999). The results indicated that models more complex than CropSyst regarding the nitrogen module can better simulate soil nitrogen dynamics, although the difference among models in terms of fitting experimental data was small. Marchetti et al. (1997) extracted the denitrification module of CropSyst and compared simulation outputs with measured data and with outputs from other sub-models. The approach used in CropSyst resulted to be the most reliable among those tested.

CropSyst was evaluated for conditions with saline water table in Tunisia (Belhouchette et al., 2001). Simulation of crop growth limited by salinity compared well with experimental data, but the authors suggested that improvements were possible if fluctuations of the water table salt concentration over time could be specified as input to the model. Model evaluation using sprinkler line source experiments with different salinity and irrigation levels for barley grown at Zaragoza, Spain and corn at Davis, California and Fort Collins, Colorado was reported by Ferrer-Alegre and Stöckle (1999).

García de Cortázar et al., 2002 evaluated wheat straw decomposition rates under different temperature and moisture levels in two locations in Central Chile, comparing these measurements with simulations performed with CropSyst. The decomposition rate was evaluated for 3 amounts of wheat straw (3, 6 and 9 Mg ha⁻¹) and 6 temperature treatments (defined by the month when the straw was placed on the field). Comparisons of simulated and measured residues resulted in RMSE fluctuating from 0.24 to 0.29 Mg ha⁻¹ (6–7% of the observed means), with the model providing a realistic simulation of the evolution of residue decomposition.

In summary, evaluations of CropSyst have shown that the model is suitable for the simulation of cropping systems in a variety of conditions, although some limitations have been reported. Properly calibrated (mainly to adjust cultivar specific crop parameters), and after some model verification is conducted (as recommended for all models), CropSyst can be a useful tool for the analysis of cropping systems. Users must exert caution when applying the model for conditions that are not currently simulated (e.g., cracking vertisols and fields impacted by pest and diseases). Examples of documented applications of CropSyst are presented in the next section.

6.3. Model application

Many applications of CropSyst, a deterministic model, have been done in a stochastic fashion by accounting probabilistically for weather variability. In these applications, model outputs are

usually presented as probability distributions, allowing comparison of both the means and the variability resulting from simulated management practice scenarios. Using this methodology, CropSyst was linked to GIS software and applied to evaluate two levels of nitrogen fertilization on seven rotations implemented on a variety of soils in the Po Valley, Italy (Donatelli et al., 1999a; Meinke et al., 2001), allowing the estimation of drainage and nitrogen leaching resulting from different soil–weather–management scenarios. This study was also extended to a region in Central Italy (Donatelli et al., 1999b).

In Catalonia, Spain, CropSyst was used in conjunction with field experiments to develop a decision support system for nitrogen fertilization strategies (Ferrer-Alegre et al., 1999a). In the intensively irrigated Quincy-Pasco area of Central Washington State, a computer simulation study was conducted with the objective of estimating the amount and dynamics of nitrate leaching from a typical irrigated potato–winter wheat–maize rotation in this area (Peralta and Stöckle, 2001). In other studies, the model was applied to evaluate the impact of soil spatial variability on yield and N leaching (Marchetti et al., 1998; Bechini et al., 1999). Long-term simulations were also run using CropSyst to explore the performance of several cropping systems with different input levels (Morari et al., 2000).

CropSyst has been used to study the adaptation of crops to given regions. For example, CropSyst and ArcCS were applied to conduct an assessment of the adaptation of an improved cultivar of millet in Burkina Faso (Badini et al., 1997). The model was also used to evaluate different rotation options in Andorra (Ferrer-Alegre et al., 1999b). In a study in the US Pacific Northwest, CropSyst was used to assess the suitability of selected new crops for dryland farming in this region. The adaptation of yellow mustard, spring canola, spring pea, linola, hard red spring wheat, safflower, millet and maize to the climatic and soil conditions of this region was analyzed in terms of total productivity, yield stability, water use efficiency, and economics (Marcos et al., 1999; Marcos, 2000).

Coupling economic models with CropSyst allowed to perform a risk analysis of the interaction between rainfall and nitrogen fertilization of wheat in conditions of erratic water stress at three Australian locations (Sadras, 2002). The application of CropSyst coupled with an economic model was also illustrated in a case study in Turkey, aimed at evaluating various cropping systems (Eruygur, 2000). A multi-criteria analysis was run using CropSyst to provide technical indicators for an integrated evaluation of cropping systems (Mazzetto et al., 2001). The model is also used by the extension service of the Lombardy region in Italy to produce a seasonal prediction of yield levels in four regions of the Po Valley. A bulletin is regularly updated and published on the web.

The impact of climate change scenarios on cropping systems has been studied using CropSyst and generated weather based on global circulation models at current atmospheric CO₂ concentration and at increased levels. Examples of this type of application have been reported by Tubiello et al. (2000) for Northern, Central, and Southern Italy, and by Bindi et al. (1999) for Southern Spain, Southern France, Northern Italy, and Greece. The response to climate change was also evaluated for sugar beet in various cropping systems implemented at six sites in Central and Northern Italy (Donatelli et al., 2002b), and for sunflower and wheat in Central Italy (Crisci et al., 2001). A study was conducted in the intensively irrigated agricultural area of Central Washington State to evaluate strategies for utilizing early climate forecasts in a region where climate fluctuations affect agriculture and complex water management institutions strongly govern adaptability to climate (Scott et al., 2001).

In summary, CropSyst has been widely applied to estimate the impact of climate, soils, and agricultural management on yield, water and nitrogen balance, drought adaptation, and other cropping systems issues at many world locations. Ongoing developments including CropSyst Watershed, precision agriculture capabilities, and a complete dairy farm production and nutrient management tool as well as plans to develop new farming system decision support tools will further

broaden the scope of future applications of the model.

7. Closing the loop between development and application

Integration of users in the process of model evaluation and improvement has been important in the development of CropSyst. This feedback has helped to debug the code, to check model assumptions and the range of their validity, and to identify many features that have been introduced in the model. Frequent interaction with users has been and will continue to be a priority of the CropSyst development team. Fostering these interactions has required the development of a stable and user-friendly interface and model documentation, the introduction of a free distribution policy, the establishment of an internet page for model downloading and posting of information (with US and Italian sites) and an electronic bulletin board for all registered users, a concerted effort to timely solving problems posed by users (usually electronically), and offering training courses and maintaining visit exchanges with cooperators. All these activities have been instrumental in closing the loop between CropSyst development and application.

On the other hand, model development and applications would also benefit from a better communication and exchange of information among different modeling groups. The CropSyst development team believes that one important step to enhance the progress of cropping systems modeling and applications is to produce reusable, fully documented model components that can be readily utilized by other model developers and advanced users.

References

- Acutis, M., Donatelli, M., 2003. SOILPAR 2.00: software to estimate soil hydrological parameters and functions. *Eur. J. Agron.* 18, 373–377.
- Acutis, M., Donatelli, M., Stöckle, C.O., 1998. Comparing the performance of three weather generators. *Proceedings of the*

- Fifth European Society for Agronomy Congress, Nitra, Slovak Republic, 28 June–2 July, vol. II, pp. 117–118.
- Acutis, M., Donatelli, M., Stöckle, C.O., 1999. Performance of two weather generators as a function of the number of available years of measured climatic data. *Proceedings First International Symposium Modelling Cropping Systems*, Lleida, Spain, 21–23 June, pp. 129–130.
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. *Crop evapotranspiration: Guidelines for computing crop water requirements*. Irr. Drain. Paper 56. UN-FAO, Rome.
- Arkin, G.F., Vanderlip, R.L., Ritchie, J.T., 1976. A dynamic grain sorghum growth model. *Trans. ASAE* 19, 622–626, 630.
- Badini, O., Stöckle, C.O., Franz, E.H., 1997. Application of crop simulation modeling and GIS to agroclimatic assessment in Burkina Faso. *Agric. Ecosyst. Environ.* 64, 233–244.
- Bechini, L., Bocchi S., Maggiore, T., 1999. Spatial interpolation of soil properties for irrigation planning. A case study in Northern Italy. *Proceedings First International Symposium Modelling Cropping Systems*, Lleida, Spain, 21–23 June, pp. 143–144.
- Belhouchette, H., Donatelli, M., Braudeau, E., Wery, J., 2001. Test of the cropping systems model CropSyst in Tunisian conditions. *Proceedings Second International Symposium Modelling Cropping Systems*, 16–18 July, Florence, Italy, pp. 47–48.
- Berti, A., Morari, F., Borin, M., Giardini, L., 2001. Use of CropSyst to simulate a four year rotation with different fertilization levels. *Proceedings Second International Symposium Modelling Cropping Systems*, Florence, Italy, 16–18 July, pp. 105–106.
- Bindi, M., Donatelli, M., Fibbi, L., Stöckle, C.O., 1999. Estimating the effect of climate change on cropping systems at four European sites. *Proceedings First International Symposium Modelling Cropping Systems*, Lleida, Spain, 21–23 June, pp. 147–148.
- Bocchi, S., Confalonieri, R., Bechini, L., 2001. CropSyst for rice in Northern Italy. *Proceedings Second Modelling Cropping Systems International Symposium*, Florence, Italy, 16–18 July 2001, pp. 51–52.
- Boote, K.J., Jones, J.W., Hoogenboom, G., Pickering, N.B., 1998. The CROPGRO model for grain legumes. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 99–128.
- Bouman, B.A.M., van Keulen, H., van Laar, H.H., Rabbinge, R., 1996. The 'School of de Wit' crop growth simulation models: a pedigree and historical overview. *Agric. Syst.* 52, 171–198.
- Bouniols, A., Cabelguenne, M., Jones, C.A., Chalamet, A., Charpentier, J.L., Marty, J.R., 1991. Simulation of soybean nitrogen nutrition for a silty clay soil in southern France. *Field Crop Res.* 26, 19–34.
- Campbell, G.S., 1985. *Soil Physics with Basic*. Elsevier, Amsterdam.
- Castellvi, F., Stöckle, C.O., 2002. Comparing the performance of WGEN and ClimGen in the generation of temperature and solar radiation. *Trans. ASAE* 44, 1683–1687.
- Castellvi, F., Stöckle, C.O., Ibañez, M., 2002. Comparing a locally calibrated versus a generalized temperature generation process. *Trans. ASAE* 44, 1143–1148.
- Chen, S., Zhao, B., Stockle, C.O., Harrison, J., Nelson, R., 2002. Use of models as decision support tools in dairy nutrient management. *ASAE Paper No. 02-4094*, St. Joseph, MI.
- Confalonieri, R., Maggiore, T., Bechini, L., 2001. Application of the simulation model CropSyst to an intensive forage system in Northern Italy. In: *Proceedings Second International Symposium Modelling Cropping Systems*, Florence, Italy, 16–18 July, pp. 59–60.
- Crisci, A., Moonen, C., Ercoli, L., Bindi, M., 2001. Study of the impact of climate change on wheat and sunflower yields using an historical weather data-set and a crop simulation model. *Proceedings Second International Symposium Modelling Cropping Systems*, Florence, Italy, 16–18 July, pp. 119–120.
- de Wit, C.T., Brouwer, R., Penning de Vries, F.W.T., 1970. The simulation of photosynthetic systems. In: Setlik, I. (Ed.), *Prediction and measurement of photosynthetic productivity*. *Proceeding IBP/PP Technical Meeting Trebon 1969*. Pudoc, Wageningen, The Netherlands, pp. 47–50.
- Diaz-Ambrona, C.G.H., O'Leary, G.J., O'Connell, M.G., Connor, D.J., 2001. Application of CropSyst to a new location and crops: advantages and limitations. *Proceedings Second International Symposium Modelling Cropping Systems*, Florence, Italy, 16–18 July, pp. 127–128.
- Donatelli, M., Stöckle, C.O., Ceotto, E., Rinaldi, M., 1996a. CropSyst validation for cropping systems at two locations of Northern and Southern Italy. *Eur. J. Agron.* 6, 35–45.
- Donatelli, M., Spallacci, P., Marchetti, R., Papini, R., 1996b. Evaluation of CropSyst simulations of growth of maize and of water balance and soil nitrate content following organic and mineral fertilization applied to maize. *Proceedings Fourth European Society for Agronomy Congress, Veldhoven-Wageningen, The Netherlands, 7–11 July, vol. I*, pp. 342–343.
- Donatelli, M., Stöckle, C.O., Nelson, R.L., Francaviglia, R., 1999a. Evaluating cropping systems in lowland areas of Italy using the cropping system simulation model CropSyst and the GIS software ARCVIEW. *Proceedings Seventh ICCTA Conference*, Firenze, Italy, 16–17 November 1998, pp. 114–121.
- Donatelli, M., Stöckle, C.O., Nelson, R.L., Gardi, C., Bittelli, M., Campbell, G.S., 1999b. Using the software CropSyst and ARCVIEW in evaluating the effect of management in cropping systems in two areas of the low Po valley, Italy. *Rev. de Cien. Agric.* 22, 87–108.
- Donatelli, M., Stöckle, C.O., Nelson, R.L., Bellocchi, G., 2002a. ET_CSDLL: a DLL for the computation of reference and crop evapotranspiration. *Agron. J.*, (submitted for publication).

- Donatelli, M., Acutis, M., Fila, G., Bellocchi, G., 2002b. A method to quantify time mismatch of model estimates. Seventh Congress of the European Society for Agronomy, Cordoba, Spain, July 15–18, 269–270.
- Donatelli, M., Tubiello, F., Peruch, U., Rosenzweig, C., 2002c. Scenarios of climate change effects on sugar beet in Northern and Central Italy. *Ital. J. Agron.*, in press.
- Donatelli, M., Bellocchi, G., Fontana, F., 2003. RadEst3.00: Software to estimate daily radiation data from commonly available meteorological variables. *Eur. J. Agron.*, 18, 363–367.
- Eruygur, O.H., 2000. Use of bio-physical models in agricultural economics: an application of Cropsyst. MS thesis, Dept. Agr. Economics, Middle East Technical University of Ankara, Turkey, pp. 139.
- Ferrer-Alegre, F., Stöckle, C.O., 1999. A model for assessing crop response to salinity. *Irrig. Sci.* 19, 15–23.
- Ferrer-Alegre, F., Villar, J.M., Carrasco, I., Stöckle, C.O., 1999. Developing management decision tools from yield experiments with the aid of a simulation model: an example with N fertilization in corn. *Proceedings of the First International Symposium Modelling Cropping Systems*, Lleida, Spain, 21–23 June, pp. 175–176.
- Ferrer-Alegre, F., Villar, J.M., Castellví, F., Ballesta, A., Stöckle, C.O., 1999. Contribution of simulation techniques to the evaluation of alternative cropping systems in Andorra. *Proceedings First International Symposium Modelling Cropping Systems*, Lleida, Spain, 21–23 June, pp. 177–178.
- Fila, G., Bellocchi, G., Acutis, M., Donatelli, M., 2003. IRENE: a software to evaluate model performance. *Eur. J. Agron.*, 18, 369–372.
- García de Cortázar, V., Silva, P., Acevedo, E., 2002. Validation of a predictive model of the effect of temperature and humidity on wheat straw decomposition. *Agricultura Técnica (Chile)*, (in press).
- Godwin, D.C., Jones, C.A., 1991. Nitrogen dynamics in soil plant systems. In: Hanks, J., Ritchie, J.T. (Eds.), *Modeling plant and soil systems*, Amer. Soc. of Agronomy, No. 31, pp. 297–302.
- Greenwood, D.J., Lemaire, G., Gosse, G., Cruz, P., Draycott, A., Neeteson, J.J., 1990. Decline in percentage N of C_3 and C_4 crops with increasing plant mass. *Ann. Bot.* 66, 425–436.
- Jackson, R.D., 1982. Canopy temperature and crop water stress. *Adv. Irrig.* 1, 43–85.
- Jara, J., Stöckle, C.O., 1999. Simulation of corn water uptake using models with different levels of process detail. *Agron. J.* 91, 256–265.
- Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agron.*, 18, 267–288.
- Jones, J.W., Tsuji, G.Y., Hoogenboom, G., Hunt, L.A., Thornton, P.K., Wilkens, P.W., Imamura, D.T., Bowen, W.T., Singh, U., 1998. Decision support system for agrotechnology transfer DSSAT v3. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 157–177.
- Jones, J.W., Keating, B.A., Porter, C.H., 2001. Approaches to modular model development. *Agric. Syst.* 70, 421–443.
- Kiniry, J.R., Jones, C.A., O'Toole, J.C., Blanchet, R., Cabelguenne, M., Spanel, D.A., 1989. Radiation-use efficiency in biomass accumulation prior to grain filling for five grain crop species. *Field Crop Res.* 20, 51–64.
- Lindemann, E.R., Stöckle, C.O., Redell, D., 1987. Field testing a computer-assisted on-farm irrigation scheduling program. *ASAE Paper No. 87–2560*, St. Joseph, MI.
- Loomis, R., Connors, D., 1992. *Crop Ecology: Productivity and Management in Agricultural Systems*. Cambridge University Press, Cambridge, UK.
- Marchetti, R., Donatelli, M., Spallacci, P., 1997. Testing denitrification functions of dynamic crop models. *J. Envir. Qual.* 26 (2).
- Marchetti, R., Spallacci P., Ceotto E., Papini R., 1998. Predicting yield variability for corn grown in a silty-clay soil in Northern Italy. In: *Proceedings Fourth International ASA-CSSA-SSSA Conference on Precision Agriculture*, St. Paul, MN, 19–22 July, pp. 467–478.
- Marcos, J., 2000. Simulation-based assessment of alternative crops in the dryland Pacific Northwest. Ph. D. dissertation, Washington State University, Pullman, Washington.
- Marcos, J., Fiez, T., Stöckle, C.O., Huggins, D., 1999. Model-based assessment of alternative crop adaptation to the dryland cropping areas of the Pacific Northwest. *Agronomy Abstracts*, ASA Annual Meeting, Salt Lake City, UT, American Society of Agronomy, Madison, WI.
- Mazzetto, F., Ceccon P., Bonera R., Sacco D., Acutis M., 2001. A model of multicriteria analysis aimed at evaluating different cropping systems. *Proceedings Second Modelling Cropping Systems International Symposium*, Florence, Italy, 16–18 July 2001, pp. 150–151.
- McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holtzworth, D.P., Freebairn, D.M., 1996. APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. *Agric. Syst.* 50, 255–271.
- McKinion, J.M., Baker, D.N., Whisler, F.D., Lambert, J.R., 1988. Application of the GOSSYM/COMAX system to cotton crop management. *ASAE Paper No. 88–7532*, St. Joseph, MI.
- Meinke, H., Baethgen, W.E., Carberry, P.S., Donatelli, M., Hammer, G.L., Selvaraju, R., Stöckle, C.O., 2001. Increasing profits and reducing risks in crop production using participatory systems simulation approaches. *Agric. Syst.* 70, 493–513.
- Monteith, J.L., 1965. *Evaporation and environment*. 19th Symposia of the Society for Experimental Biology, vol. 19. University Press, Cambridge, pp. 205–234.

- Monteith, J.L., 1977. Climate and crop efficiency of crop production in Britain. *Phil. Trans. Res. Soc. Lond. Ser. B* 281, 277–329.
- Morari, F., Berti, A., Borin, M., Giardini, L., 2000. CropSyst model in simulating cropping systems with different input levels. *Proceedings Ninth International Conference on the UN-FAO ESCORENA network*, Gargnano del Garda (BS), Italy, 6–9 September, pp. 257–262.
- Pala, M., Stöckle, C.O., Harris, H.C., 1996. Simulation of durum wheat (*Triticum durum*) growth under differential water and nitrogen regimes in a mediterranean type of environment using CropSyst. *Agric. Syst.* 51, 147–163.
- Pannkuk, C.D., Stöckle, C.O., Papendick, R.I., 1998. Validation of CropSyst for winter and spring wheat under different tillage and residue management practices in a wheat-fallow region. *Agric. Syst.* 57, 121–134.
- Peralta, J.M., Stöckle, C.O., 2001. Nitrate from an irrigated crop rotation at the Pasco-Quincy area (Washington, USA) available for groundwater contamination: a long-term simulation study. *Agric. Ecosyst. Environ.* 88, 23–34.
- Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large scale parameters. *Mon. Weath. Rev.* 100, 81–92.
- Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C., 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). US Dept Agric., Agriculture Research Service. Agriculture Handbook No. 703, pp. 384.
- Richardson, C.W., Wright, D.A., 1984. WGEN: A model for generating daily weather variables. U.S. Department of Agriculture, Agricultural Research Service, ARS-8, pp. 83.
- Richter, G.M., Agostini, F., Donatelli, M., Smith, P., Smith, J., 1999. Modelling the N-dynamics of a wheat-sugar beet rotation at different complexity. *Proceedings First International Symposium Modelling Cropping Systems*, Lleida, Spain, 21–23 June, pp. 239–240.
- Ritchie, J.T., NeSmith, D.S., 1991. Temperature and crop development. In: Hanks J., Ritchie J.T., (Eds.), *Modeling Plant and Soil Systems*, Agronomy Monograph No.31, ASA, CSSA, and SSSA, Madison, WI, pp. 5–29.
- Ritchie, J.T., Singh, U., Godwin, D.C., Bowen, W.T., 1998. Cereal growth, development and yield. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 79–98.
- Rivington, M., Matthews, K.B., Sibbald, A.R., Stöckle, C.O., 2001. Integrating CropSyst with a multiple-objective land use planning tool (LADSS). *Proceedings Second International Symposium Modelling Cropping Systems*, Florence, Italy, 16–18 July, pp. 171–172.
- Ross, P.J., Bristow, K.L., 1990. Simulating water movement in layered and gradational soils using the Kirchhoff transform. *Soil Sci. Soc. Am. J.* 54, 1519–1524.
- Sadras, V.O., 2002. Interaction between rainfall and nitrogen fertilisation of wheat in environments prone to terminal drought: economic and environmental risk analysis. *Field Crops Res.* 77, 201–215.
- Saxton, K.E., Rawls, W.J., Romberger, J.S., Papendick, R.I., 1986. Estimating generalized soil–water characteristics from texture. *Soil Sci. Soc. Amer. J.* 50, 1031–1036.
- Scott, M., L.W. Vail, J.A. Jaksch, Anderson K.K., Stockle, C.O., 2001. Early warning of ENSO events for regional agriculture. Report for the Office of Global Programs, U.S. NOAA, Contract 28340A. Battelle Pacific Northwest Division, Richland, Washington.
- Silvestri, N., Bellocchi, G., Mazzoncini, M., Menini, S., 1999. Evaluation of the CropSyst model for simulating soil water, soil nitrate, green area index and above-ground biomass of maize under different management. *Proceedings First International Symposium Modelling Cropping Systems*, Lleida, Spain, 21–23 June, pp. 253–254.
- Stöckle, C.O., Bellocchi, G., Nelson, R.L., 1998. Evaluation of the weather generator ClimGen for several world locations. *Proceedings Seventh International Congress for Computer Technology in Agriculture*, Florence, Italy, 15–18 November 1998, pp. 34–41.
- Stöckle, C.O., Cabelguenne, M., Debaeke, P., 1997. Comparison of CropSyst performance for water management in Southwestern France using submodels of different levels of complexity. *Eur. J. Agron.* 7, 89–98.
- Stöckle, C.O., Campbell, G.S., 1989. Simulation of crop response to water and nitrogen: an application example using spring wheat. *Trans. ASAE* 32, 66–74.
- Stöckle, C.O., Debaeke, P., 1997. Modelling crop nitrogen requirements: a critical analysis. *Eur. J. Agron.* 7, 161–169.
- Stöckle, C.O., Jara, J., 1998. Modeling transpiration and soil water content from a corn field: 20 min vs. daytime integration step. *Agric. For. Meteorol.* 92, 119–130.
- Stöckle, C.O., Martin, S., Campbell, G.S., 1994. CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. *Agric. Syst.* 46, 335–359.
- Stöckle, C.O., Nelson, R.L., 2000. *Cropsyst User's manual (Version 3.0)*. Biological Systems Engineering Dept., Washington State University, Pullman, WA.
- Stöckle, C.O., Williams, J.R., Rosenberg, N.J., Jones, C.A., 1992. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part I—modification of the EPIC model for climate change analysis. *Agric. Syst.* 38, 225–238.
- Swaney, D.P., Jones, J.W., Boggess, W.G., Wilkerson, C.G., Mishoe, J.W., 1983. Real-time irrigation decision analysis using simulation. *Trans. ASAE* 26, 562–568.
- Tanner, C.B., Sinclair, T.R., 1983. Efficient water use in crop production: research or re-search? In: Taylor, H.M., Jordan, W.R., Sinclair, T.R. (Eds.), *Limitations to efficient water use in crop production*. Amer. Soc. Agron, Madison, WI.
- Tubiello, F., Donatelli, M., Rozenweig, C., Stöckle, C.O., 2000. Effects of climate change and elevated CO₂ on cropping systems: model predictions at two Italian locations. *Eur. J. Agron.* 2–3, 179–189.

- US Department of Agriculture, Soil Conservation Service. 1972. National Engineering Handbook, 4. Hydrology. Washington, DC, pp. 548.
- Van Keulen, H., Seligman, N.G., 1987. Simulation of water use, nitrogen nutrition and growth of a spring wheat crop, Pudoc, Wageningen.
- Ventrella, D., Rinaldi, M., 1999. Comparison between two simulation models to evaluate cropping systems in Southern Italy. Yield response and soil water dynamics. *Agric. Med.* 129, 99–110.
- Wilkerson, G.G., Mishoe, J.W., Jones, J.W., Boggess, W.G., Swaney, D.P., 1983. Within-season decision making for pest control in soybeans. ASAE Paper No. 83–4044, St. Joseph, MI.
- Williams, J.R., Jones, C.A., Dyke, P.T., 1984. A modeling approach to determining the relationship between erosion and soil productivity. *Trans. ASAE* 27, 129–144.
- Willmott, C.J., 1982. Some comments on the evaluation of model performance. *Bull. Amer. Meteorol. Soc.* 63, 1309–1313.

¹ Mendel University of Agriculture and Forestry, Brno, Czech Republic

² Institute of Atmospheric Physics, AS CR, Hradec Králové, Czech Republic

Modelling climate change impacts on maize growth and development in the Czech Republic

Z. Žalud¹ and M. Dubrovský²

With 11 Figures

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Summary

The crop growth model CERES-Maize is used to estimate the direct (through enhanced fertilisation effect of ambient CO₂) and indirect (through changed climate conditions) effects of increased concentration of atmospheric CO₂ on maize yields. The analysis is based on multi-year crop model simulations run with daily weather series obtained alternatively by a direct modification of observed weather series and by a stochastic weather generator. The crop model is run in two settings: stressed yields are simulated in water and nutrient limited conditions, potential yields in water and nutrient unlimited conditions. The climate change scenario was constructed using the output from the ECHAM3/T42 model (temperature), regression relationships between temperature and solar radiation, and an expert judgement (precipitation).

Results: (i) After omitting the two most extreme misfits, the standard error between the observed and modelled yields is 11%. (ii) The direct effect of doubled CO₂: The stressed yields would increase by 36–41% in the present climate and by 61–66% in the 2 × CO₂ climate. The potential yields would increase only by 9–10% as the improved water use efficiency does not apply. (iii) The indirect effect of doubled CO₂: The stressed yields would decrease by 27–29% (14–16%) at present (doubled) ambient CO₂ concentration. The increased temperature shortens the phenological phases and does not allow for the optimal development of the crop. The simultaneous decrease of precipitation and increase of temperature and solar radiation deepen the water stress, thereby reducing the yields. The reduction of the potential yields is significantly smaller as the effect of the increased water stress does not apply. (iv) If both direct and indirect effects of doubled CO₂ are considered, the stressed yields should increase by 17–18%,

and the potential yields by 5–14%. (v) The decrease of the stressed yields due to the indirect effect may be reduced by applying earlier planting dates.

1. Introduction

It is expected that the increasing concentration of greenhouse gases in the atmosphere will affect the climate in the forthcoming decades. The globally averaged surface air temperature is projected to increase by 1.4 to 5.8 °C over the period 1990 to 2100 (IPCC, 2001). Regional temperature changes could, however, differ substantially from the global mean. Further, it is assumed that the global warming will intensify the hydrological cycle, and the frequency of droughts, floods, and hot and cold spells will be increased (Watson et al., 1996). The question stands what the effect of the climate change on various terrestrial ecosystems, e.g. agriculture, forestry, grasslands and water resources, will be.

Increased CO₂ concentration can affect crop growth in two ways.

Firstly, the crop is directly affected by the presence of CO₂ in the ambient air. As atmospheric CO₂ is the primary source of carbon for the plants and its present concentration is suboptimal (Nonhebel, 1996), the increased content of CO₂ in the air stimulates photosynthesis.

Simultaneously, the transpiration intensity is reduced by partially closing the stomata, which leads to the improved water use efficiency (WUE) and thereby to a lower probability of the water stress occurrence. These physiological responses are known as the *CO₂-fertilisation effect* (Dhakhwa et al., 1997) or the *direct effect* of increased CO₂. The experiments made in a controlled environment indicate that the crop growth should increase by about $14 \pm 11\%$ for C₄ plants (e.g., maize) at doubled ambient CO₂ (Kimball et al., 1988; Porter, 1992; Dhakhwa et al., 1997). If the water is a limiting factor, the yields may increase much more due to the additional effect of improved WUE.

The second effect of increased CO₂ relates to the response of a crop to a changed weather regime brought about by the CO₂ increase, and is referred to as the *indirect effect* or the *weather effect*. The most important weather variables that directly determine the crop yield are solar radiation, precipitation and temperature. If no management response (e.g., other cultivar or shift of the planting date) is applied, the maize yields typically decrease with increasing temperature due to a shortening of phenological phases (Maytín et al., 1995; Brown and Rosenberg, 1997). Increasing solar radiation stimulates the leaf assimilation (Wolf and van Diepen, 1995), thereby increasing the yields (Maytín et al., 1995; Brown and Rosenberg, 1997). However, as the increased solar radiation stimulates evapotranspiration, the yields may decrease due to a deepened water stress if the water supply is at its critical level. The effect of precipitation may be either positive if precipitation reduces the existing water stress, or negative, which may be related, e.g., to the intensified nitrogen leaching by the excessive water. The relationships between crop yields and changes in climatic characteristics may differ at individual sites depending on the present climate conditions. The situation is more complicated if the changes in individual climatic characteristics act simultaneously.

Impacts of climate change on crop growth and development may be estimated by two different methods. In experimental methods, the crop is grown under controlled conditions (greenhouse with controlled atmosphere, open top chambers, etc.). An advantage of these methods is that all required characteristics, such as the development

of individual parts of the plant, may be measured directly. On the other hand, it may be too difficult to ensure that the future weather conditions are well represented. Moreover, these experiments are usually very time and money consuming. In light of these problems and due to ever increasing capacity of computer technology and improvements in mathematical modelling of physiological processes, the numerical simulation methods become more and more frequently used in climate change impact studies. The crop models used to simulate the growth and development of the maize include CERES-Maize [Jones and Kiniry (1986); used, e.g., by Iglesias (1995a, 1995b), Alexandrov and Hoogenboom (1999); Bacsí and Hunkár (1994); Dhakhwa et al. (1997); Makadho (1996); Maytín et al. (1995); Mearns et al. (1992, 1996, 1997), Cuculeanu et al. (1999)], WOFOST [Hijmans et al. (1994); used, e.g., by Wolf and van Diepen (1995)], MACROS (Penning de Vries et al., 1989), and EPIC [used, e.g., by Easterling et al. (1993, 1998), Dhakhwa et al. (1997), Brown and Rosenberg (1997)]. The crop models simulate the development of individual parts of the plants, commonly in daily steps. The input to the model incorporates the parameters of the cultivar (genetic coefficients), the field and soil characteristics, the agrotechnological management details (the most important are planting, fertilisation and irrigation), and environmental conditions (concentration of CO₂ and time series of daily weather characteristics). The effect of the climate change is estimated by comparing model crop yields simulated with use of weather series representing the present climate and the changed climate (Fig. 1). The weather series for the changed climate

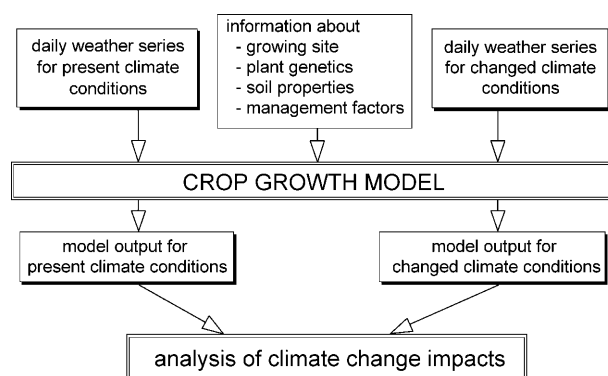


Fig. 1. The scheme of the crop model experiments used in climate change impact studies

conditions are obtained either by a direct modification of observed weather series (Bacsi and Hunkár, 1994; Dhakhwa et al., 1997; Maytín et al., 1995; Mearns et al., 1992; Wolf and van Diepen, 1995; Nonhebel, 1993, 1996) or with a stochastic weather generator whose parameters were derived from the observed weather series and then modified according to the climate change scenario (Cuculeanu et al., 1999; Dubrovský et al., 2000; Riha et al., 1996; Semenov and Porter, 1995; Semenov and Barrow, 1997). The model simulations are performed under two sets of conditions. In unlimiting conditions, the plant is given as much water and nutrients as it needs. In this case, no water stress and nitrogen stress may occur, and the resultant yields are referred to as the *potential yields*. In limiting conditions, water and nutrients supplies are limited and the *stressed yields* are simulated. The climate change impact studies focus on (i) impacts of an increased CO₂ concentration on the crop growth and (ii) possible adaptations through changes of the cultivar and sowing dates. The latter issue is addressed, e.g., by Bacsi and Hunkár (1994), Cuculeanu et al. (1999), Wolf and van Diepen (1995), Easterling et al. (1993).

Maize is one of the most important agricultural crops in the Czech Republic. It is grown both for silage and food. The arable area is about 270 000 ha for the silage and 30 000 ha for the grain maize, the average yields of the grain maize were 4.6 t/ha in 1986–1997. Recently, the MACROS crop growth model was successfully validated and used to estimate potential and water limited yields in various climatic conditions (Žalud and Rožnovský, 1998). The sensitivity of maize yields simulated by both CERES-Maize and MACROS models to selected hydrological parameters was analysed by Štátná and Žalud (1999). Parameterisation and validation of the CERES-Maize crop model was treated in detail by Štátná (1998).

The CERES-Maize crop model is used in this study to assess the effect of the expected climate change (induced by an increase of greenhouse gases concentration) on grain maize yields in the most fertile area of the Czech Republic. The paper follows the previous work by Dubrovský et al. (2000), which was focused on the validation of the weather generator, validation of the variability of the CERES-Maize model yields simulated with the use of synthetic weather series, and

the sensitivity analysis of the model yields to changes in statistical structure of the input weather series. However, since the crop yield prediction was not the main aim of that paper, some input parameters related to the cultivar, soil and agrotechnical management were somewhat simplified. On the contrary, in this paper, these parameters are specified with the greatest accuracy available. The paper consists of the following parts: Methodology, the models (crop growth model and weather generator) and data (input parameters for the crop growth model, daily weather series, and the climate change scenarios) are described in section 2, where the validation of the crop model is also presented. The direct and indirect effects of the projected increase of the CO₂ concentration on the stressed and potential yields are discussed in section 3. The impact on other characteristics of the growth and development are dealt with in section 4. Of the possible adaptation responses to changed climate conditions, the effect of shifted planting date on the crop yields is studied in section 5.

2. Methods and data

2.1 Methodology

The climate change impacts on crop yields were assessed with use of the crop growth model run with weather series representing both the present and changed climates (Fig. 1). In order that the findings obtained by a comparison of model yields for the different climates have a statistical significance, multi-annual crop model simulations were run for each scenario. The descriptive statistics, such as means, standard deviations, and quantile characteristics, were determined and used for the impact assessment. This approach is considered more decisive (in a statistical sense) than the use of single values related to individual years. Since the distribution of the yields may be asymmetric and far from normal, the use of quantiles might be more appropriate because of their robustness. On the other hand, as the sample estimates of the quantiles are loaded by greater error, the means and standard deviations may be more suitable in case the time series is not long enough. Two approaches to the multi-annual crop model simulations are used in this study:

2.1.1 Direct modification approach

The crop model simulations are run with observed pedological, physiological and cultivation data specific for each individual year. Observed weather series is used in the present climate simulations. The weather series for simulations in the changed climate is obtained by a direct modification of observed series according to the climate change scenario (Dubrovský et al., 2000). This method will be referred to as the direct modification (DM) approach.

2.1.2 Weather generator approach

The input to the crop model consists of pedological, physiological and cultivation data taken from a single “representative” year and the 99-year synthetic weather series created by the stochastic weather generator Met&Roll (Dubrovský, 1997). The representative year is defined by the site-typical values of all non-meteorological parameters (including the planting date, soil profile and details on the fertilisation regime) needed to run the model. The parameters of the weather generator derived from the observed series are used to generate weather series representing the present climate. The parameters of the generator are modified in accordance with the climate change scenario to generate series representing the changed climate (Dubrovský et al., 2000). This method will be referred to as the weather generator (WG) approach.

In either approach, the stressed and potential yields were calculated, and both direct and indirect effects of increased CO₂ were assessed. In the adaptation analysis (section 5), only the WG approach was employed.

2.2 Crop model

Crop growth model CERES-Maize version 3.0 (Jones and Kiniry, 1986) is used in this study. The model was developed within the frame of IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) project and was run within the DSSAT [Decision Support System for Agrotechnology Transfer, Hoogenboom et al. (1994)] environment. The model was chosen because of its ability to simulate both the stressed yield, which is limited by the genetic potential

of the crop, temperature, solar radiation and available water and nutrients, and the potential yield, which is limited only by the genetic potential of the crop, temperature and solar radiation. Moreover, the crop models from the CERES series are among the crop growth models, which allow one to modify the ambient concentration of CO₂.

The CERES-Maize model is a mechanistic process-based model, which increments crop growth in daily steps. Modelled processes include (i) phenological development, (ii) extension of leaves, stems and roots, (iii) biomass accumulation and partitioning, (iv) soil water balance and water use by crop, (v) soil nitrogen transformation, uptake by the crop, and partitioning among plant parts (Hunkár, 1994). The input data required for the simulations include: (i) cultivar characteristics (given in terms of genetic coefficients), (ii) field attributes (slope, drains, longitude, latitude), (iii) soil characteristics (texture, bulk density), (iv) planting details (date of seeding, seeding population, row spacing, planting depth), (v) management factors (tillage, irrigation, fertilisation), (vi) series of daily weather characteristics (sum of global solar radiation, maximum and minimum air temperatures and precipitation amount). More details may be obtained, e.g., in Jones and Kiniry (1986), Hunkár (1994), Iglesias (1995a), and Maytín et al. (1995).

2.3 Input data to the CERES-Maize model

The model input data are based on the field experiments made during 1980–1996 at the Žabčice experimental station operated by the Mendel University of Agriculture and Forestry. The station is situated in the southeast of the Czech Republic (49°01'N, 16°37'E, 179 m above sea level), which is one of the warmest and driest regions of the country. The 1961–1990 mean annual temperature is 9.3 °C, and the mean annual precipitation during the same normal period is 480 mm (Rožnovský and Svoboda, 1995). Most of the parameters required as an input to the crop model simulation were measured and archived at this site. The model simulations are run at three ambient CO₂ levels: 1 × CO₂, 1.5 × CO₂ and 2 × CO₂ levels relate to present

CO₂ concentration (330 ppm) and concentrations increased by 50% and 100%, respectively.

2.3.1 Crop variety

The genetic characteristics of the crop variety are expressed in terms of five genetic coefficients, which describe the physiological processes (photosynthesis, respiration, and others) for an individual crop (Maytín et al., 1995): P1 – duration of the juvenile phase [accumulated degree-days (base 8 °C) during the non-reproductive phase of the cultivar]; P2 – sensitivity of photoperiod [coefficient (in hour⁻¹) to represent changes in development rate as a function of day-length]; P5 – duration of the kernel filling period [accumulated degree-days (base 8 °C) in the linear phase of filling]; G2 – maximum number of kernels per plant (obtained at optimum temperature with no water or nutrient stress); G3 – maximum rate of kernel filling (in mg day⁻¹ per kernel, also obtained at optimum temperature with no water or nutrient stress). The cultivar used in this study is Dea (origin PIONEER 3839, licensed from 1982), which is a middle early, two line hybrid with a FAO number of 300. Its advantages include higher resistance against diseases (especially against *Ustilago maydis*) and drought. The average number of cobs per plant is 1.00, located at 96–107 cm above a soil surface, their average length being 16–20 cm. The cobs contain 14 rows of grains, each of them having 24–38 grains. The average weight of a single grain is approximately 0.31 g. The plant develops 12–15 leaves, their mean length and width being 69 cm and 8.6 cm, respectively. The stem creates practically no off-shoots and its height reaches 230–260 cm. The recommended number of plants per hectare ranges from 80 000 to 85 000.

2.3.2 Soil parameters

The soil type of the experimental field is described as Oxyaquic Cryofluvents according to the classification of the US Department of Agriculture (Soil Survey Staff, 1975). The soil parameters were determined by Karpíšek and Prax (1989). The upper 0–28 cm soil layer is classified as Ap, coarse subangular blocky, clay loam texture, dark brown colour and abrupt boundary. The soil layer at 28–35 cm is Ao, medium granular, silty clay

texture, dark brown colour and clear boundary. The 35–61 cm layer is C1, coarse angular, up to 50 cm silty clay, below 50 cm clay loam texture, brown colour and gradual boundary. The 61–80 cm layer is C2, no observable aggregation, up to 70 cm loam, below 70 cm clay loam texture, greyish brown colour and gradual boundary. The last layer below 80 cm is classified as Cg, coarse angular and grey colour.

2.3.3 Weather and climate data

Observational daily series of *TMAX*, *TMIN* and *PREC* were measured at the Žabčice meteorological station, located approximately 1 km from the experimental field. Daily sums of global solar radiation (*SRAD*) were taken from the nearby (40 km apart) station at Kuchařovice. Time-parallel measurements at Žabčice and Kuchařovice during one year (1993) have shown that the mean and the standard deviation of the difference between the daily solar radiation sums measured at the two stations are 0% and 10%, respectively. This is considered to be a sufficient accuracy for using the Kuchařovice radiation data. Annual cycles of selected climatological characteristics of the Žabčice station are shown in Fig. 2; a more detailed table is presented in Dubrovský et al. (2000).

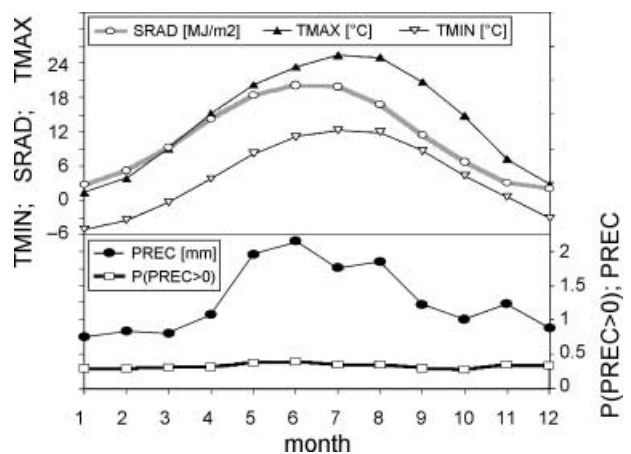


Fig. 2. The mean annual cycle of monthly climatic characteristics measured at Žabčice (except for the solar radiation, which was taken from the neighbouring station, 40 km apart) in 1961–1996. *SRAD*, *TMAX*, *TMIN*, *PREC* are monthly means of daily sum of global solar radiation [MJ m^{-2}], daily maximum and daily minimum temperature [°C], and daily sum of precipitation [mm]; $P(\text{PREC} > 0)$ is the mean probability of wet day occurrence

2.3.4 Other input data

The planting details, management factors and fertilisation regime were set a) individually for each year in the validation experiment (sec. 2.4) and in the experiments made in the DM approach, b) constant for all simulation years in case of the experiments made in the WG approach. In both approaches, all these input data (except for the planting date in experiments made in section 5) were the same for all the climate change and CO₂ scenarios. In the DM approach, the planting date varied between April 24 and May 18, and three to four fertilisation dosages were applied (the total amount of nitrogen varied between 70 and 175 kg/ha) during the vegetation period. In the WG approach, the planting date was May 6, and four fertilisation dosages were applied (total amount of nitrogen was 110 kg/ha). Details on the previous crop, residue, tillage, rotation and chemical application were set according to the historical records. No irrigation was applied.

2.4 Validation of CERES-Maize model

In order that the crop growth model may be used in a climate change impact study, a proper validation must precede.

The grain yields simulated by the crop growth model with use of measured pedological, physiological, cultivation and meteorological data are compared with the observed grain yields in Fig. 3. Observational data from 17 years were available. The figure shows that the model yields fit the observed yields well for most of the years. On average, the model yields overestimate the observed yields by 17% and the standard deviation of the ratio of model to observed yield is 32%. The systematic overestimation could be caused by the occurrence of the non-simulated factors, such as harvest losses, pest and diseases, or by the occurrence of extreme weather events. The greatest departures of the model yields from those observed appear in 1981 and 1991, and are most probably related to the occurrence of extreme floods. After omitting these two years, we find that the model yields overestimate those observed by 12% on average and the standard deviation of the ratio of model to observed yield drops to an acceptable level of 11%. After

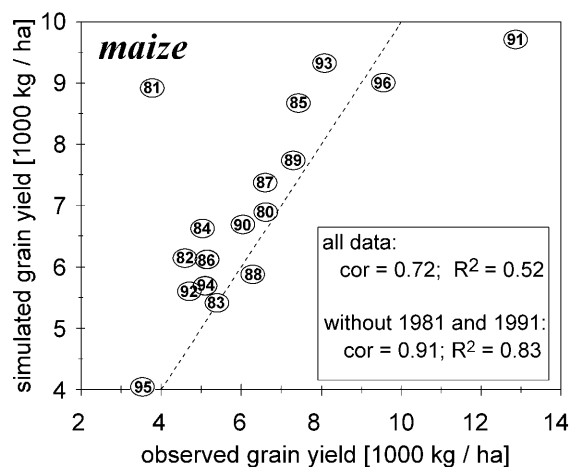


Fig. 3. Validation of the model yields simulated by CERES-Maize. The numbers inside the circles indicate the years. The fit between the observed and modelled yields is expressed in terms of the correlation coefficient (cor) and the coefficient of determination (R²)

omitting years 1981 and 1991, the difference between the model and observation is less than 20% (15%, 10%) in 87% (60%, 40%) of cases. If the model yields are corrected for the systematic error (i.e., the model yields are lowered by 12%) the fraction of the cases with deviations less than 20% (15%, 10%) increases to 100% (73%, 67%). Overall, the fit between the simulated and observed yields is considered satisfactory and corresponds to studies by other authors (Hunkár, 1994; Koestl, 1995; Weiss and Piper, 1992; Dhakhwa et al., 1997; Iglesias, 1995a; Guevara et al., 1999).

2.5 Climate change scenario

Regarding the limited availability and reliability of GCM data, the climate change scenario was constructed in a mixed way (Nemešová et al., 1999). The 2 × CO₂ scenario (Fig. 4) consists of coefficients, which prescribe changes in the means of *SRAD*, *TMAX*, *TMIN* and *PREC*, and changes in standard deviations of *TMAX* and *TMIN*. The coefficients relate to individual months. The changes in the means of daily extreme temperatures are defined as the differences between the means of respective characteristics derived from GCM [model ECHAM, version 3/T42, described in DKRZ (1993)] simulations of 2 × CO₂ and 1 × CO₂ climates. The changes in the standard deviations of *TMAX*

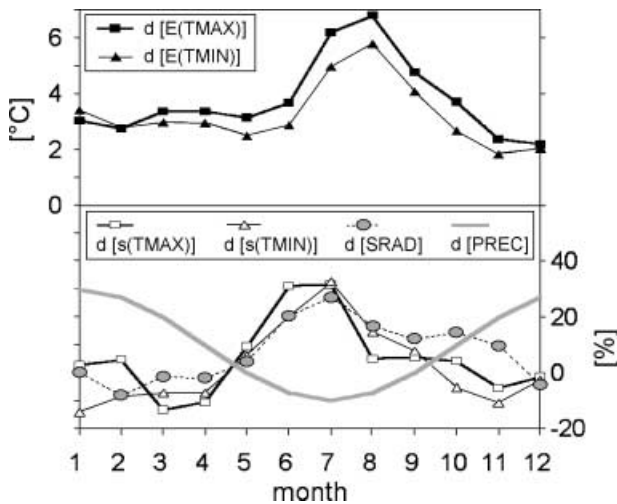


Fig. 4. The climate change scenario for $2 \times \text{CO}_2$ conditions (adopted from Nemešová et al., 1999). $d[E(TMAX)]$ and $d[E(TMIN)]$ are additive changes of monthly means of daily maximum and daily minimum temperature, $d[s(TMAX)]$ and $d[s(TMIN)]$ are percentage increments to the standard deviations of $TMAX$ and $TMIN$, $d[SRAD]$ is a percentage increment to daily sum of global solar radiation, and $d[PREC]$ is a percentage increment to the daily precipitation sum

and $TMIN$ are defined as the ratios of the standard deviations of the respective characteristics derived from the two GCM simulations. The data from the nearest GCM grid point ($48^\circ 50'N$, $16^\circ 52'E$), which nearly coincides with the Žabčice station, were used to define the changes in temperature characteristics. Since the GCM output for $SRAD$ was not available, the changes in global solar radiation were determined with use of statistical relations among monthly means of $SRAD$, $TMAX$ and $TMIN$. Because of a significant misfit between the observed and GCM-simulated precipitation data, the scenario of changes in precipitation sums is based on both findings of the IPCC (IPCC, 1996) and the results of ECHAM validation tests (Nemešová et al., 1998). The $1.5 \times \text{CO}_2$ scenario was derived from the $2 \times \text{CO}_2$ scenario by multiplying the increments displayed in Fig. 4 by 0.5.

2.6 Daily weather series

The daily weather series for the two methods outlined in section 2.1 are produced in two different ways. In the DM approach, the weather series representing changed climate conditions is derived from the observed series by modifying

the four weather variables by increments taken from the climate change scenario. Maximum and minimum temperatures are modified additively, daily sums of precipitation and solar radiation are modified multiplicatively. In this approach, variability of temperature for a given day of the year, frequency of wet day occurrence, and lag-1 correlations and cross-correlations among the four daily weather characteristics remain unchanged. In using the multiplicative modification, daily variabilities of solar radiation and precipitation are implicitly modified by the same coefficient as the mean daily values.

In the WG approach, weather generator Met&Roll (Dubrovský, 1997) was used. Its parameters are derived from the observed weather series in the first step. The parameters include (i) the means and standard deviations of $SRAD$, $TMAX$ and $TMIN$, determined separately for wet and dry days for each day of the year, (ii) lag-0 and lag-1 correlations among the standardised (conditionally on a wet day occurrence) values of $SRAD$, $TMAX$ and $TMIN$ (annual cycle of the correlations is not considered), (iii) the probability of a wet day occurrence and the probability of a wet day following a dry day (monthly), (iv) the parameters of the Gamma distribution for modelling daily precipitation amount (monthly). The set of unmodified parameters is then used to generate series for present climate conditions. To generate series representing changed climate conditions, the parameters of the generator are modified according to the climate change scenario.

Weather generator Met&Roll was validated in previous studies in two ways. Firstly, the stochastic structure of the synthetic series was compared with the structure of the observed series (Dubrovský, 1996, 1997). Validation tests revealed some discrepancies in the statistical structure of synthetic weather series, the most important being: (i) The frequency of occurrence of long dry spells, extreme daily precipitation amounts and the variability of monthly means are underestimated by the generator. (ii) Correlations and lag-1 correlations among weather characteristics exhibit a significant annual cycle not assumed by the model. On the whole, the best fit between the observed and synthetic weather series is experienced in summer months. Secondly, it was tested how the discrepancies

in the stochastic structure affect the variability of the model yield (Dubrovský et al., 2000). In this experiment, the variability of the model yields simulated with the observed series from 17 Czech stations was compared with the variability of the model yields simulated with use of synthetic weather series. No statistically significant difference was revealed, and it was therefore concluded that the weather generator is applicable for the CERES-Maize simulations.

3. Direct and indirect effects of increased CO₂ on crop yields

The time series of the model grain yields simulated in the DM approach at various combinations of ambient CO₂ levels and weather regimes are displayed in Fig. 5 (stressed yields) and Fig. 6

(potential yields). The summary statistics for the 17-year runs made in the DM approach and for the 99-year runs in the WG approach are given in Table 1 and graphically displayed in Figs. 7 and 8. The variability of the grain yields simulated in the WG approach is expressed in terms of quantiles (Fig. 8), which give better insight into the variability but cannot be used with the DM approach (Fig. 7) because of the shortness of the simulation series. The results displayed in the figures and in Table 1 show the following:

3.1 Indirect effect

The indirect effect of increased CO₂ on stressed crop yields in individual years may be seen in Fig. 5a,b. Regarding the method of obtaining the weather data for the changed CO₂ level, it

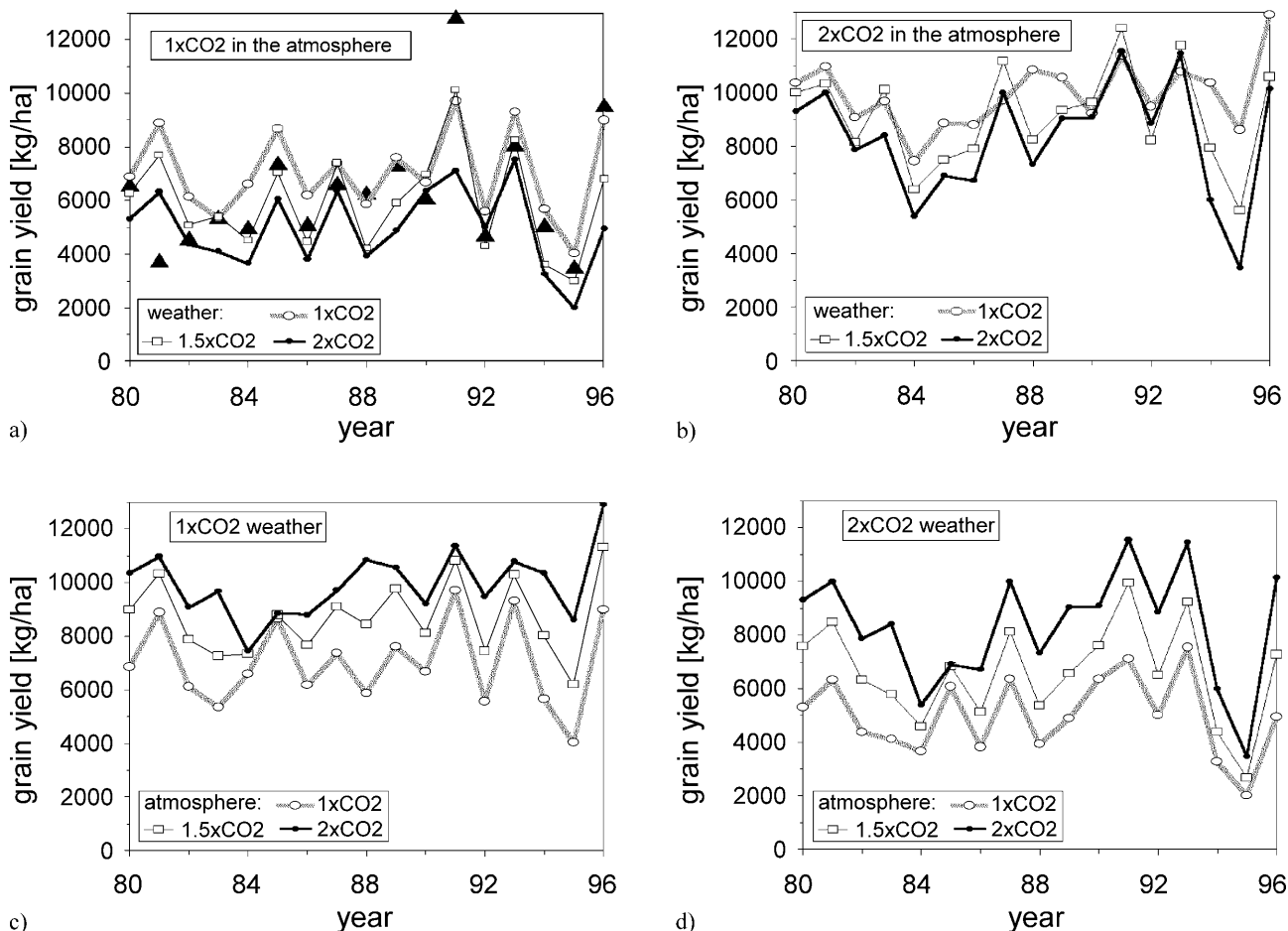


Fig. 5. Time series of stressed grain yields simulated at various levels of direct and indirect CO₂ effects. The weather series for 1.5 × CO₂ and 2 × CO₂ climates were obtained by direct modification of observed weather series (Žabčice, 1980–1996). **a)** present level of ambient CO₂ and weather regimes related to three CO₂ levels; **b)** as (a) but for doubled ambient CO₂; **c)** present weather regime and three levels of ambient CO₂; **d)** same as (c) but for 2 × CO₂ weather regime. The solid triangles in (a) mark the observed yields

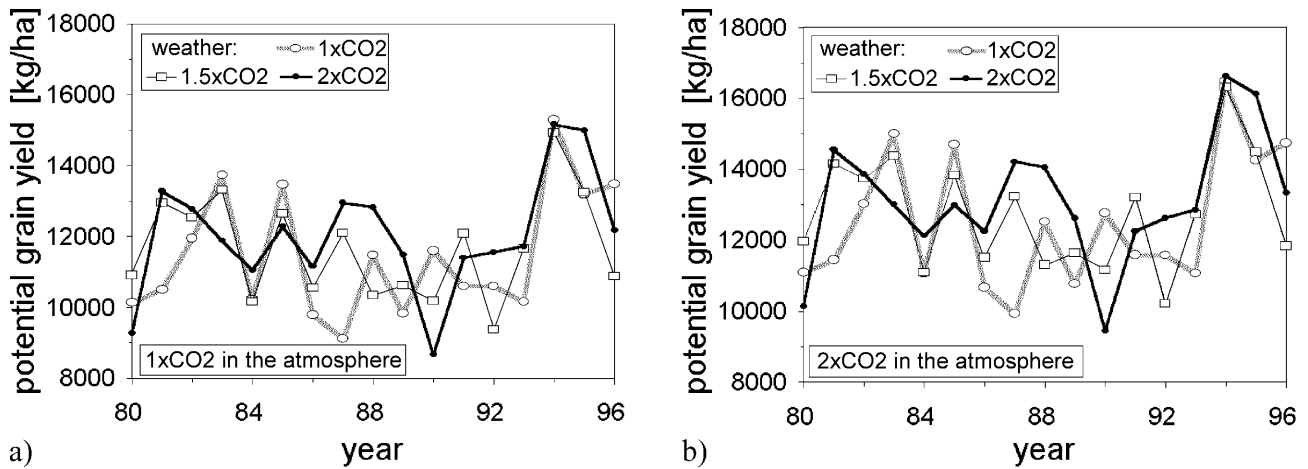


Fig. 6. As Fig. 5a,b but for the potential yields (note the changed scale of the ordinate)

Table 1. Summary statistics of the stressed and potential model yields obtained in DM and WG approaches. The “CO₂ for the indirect effect” indicates the concentration of CO₂ (with respect to the baseline concentration) used to drive the climate change scenario (sec. 2.5), the “CO₂ for the direct effect” indicates the concentration of ambient CO₂. The magnitudes of the direct/indirect/both effects are given in terms of the ratios of the means of the respective yields and the yields obtained with the zero direct/indirect/both effects. Z(avg) is the index of production potential (Eq. 1)

CO ₂ for the indirect effect	1 ×	1 ×	1 ×	1.5 ×	1.5 ×	1.5 ×	2 ×	2 ×	2 ×
CO ₂ for the direct effect	1 ×	1.5 ×	2 ×	1 ×	1.5 ×	2 ×	1 ×	1.5 ×	2 ×
a) stressed yields, DM approach:									
avg [kg/ha]	7037	8706	9955	5948	7702	9143	5010	6616	8332
std [kg/ha]	1567	1380	1244	1814	1972	1809	1438	1804	2100
std/avg [%]	22	16	12	31	26	20	29	27	25
direct effect	1.00	1.24	1.41	1.00	1.29	1.54	1.00	1.32	1.66
indirect effect	1.00	1.00	1.00	0.85	0.88	0.92	0.71	0.76	0.84
both effects	1.00				1.09				1.18
Z(avg)	0.61	0.73	0.80	0.51	0.63	0.72	0.41	0.53	0.63
b) potential yields, DM approach:									
avg [kg/ha]	11482	11962	12515	11677	12167	12761	12044	12555	13133
std [kg/ha]	1704	1743	1836	1427	1485	1553	1608	1678	1743
std/avg [%]	15	15	15	12	12	12	13	13	13
direct effect	1.00	1.04	1.09	1.00	1.04	1.09	1.00	1.04	1.09
indirect effect	1.00	1.00	1.00	1.02	1.02	1.02	1.05	1.05	1.05
both effects	1.00				1.06				1.14
c) stressed yields, WG approach:									
avg [kg/ha]	7777	9494	10581	6665	8374	9718	5666	7439	9127
std [kg/ha]	1950	2025	1676	1814	1675	1459	1687	1795	1629
std/avg [%]	25	21	16	27	20	15	30	24	18
direct effect	1.00	1.22	1.36	1.00	1.26	1.46	1.00	1.31	1.61
indirect effect	1.00	1.00	1.00	0.86	0.88	0.92	0.73	0.78	0.86
both effects	1.00				1.08				1.17
Z(avg)	0.68	0.79	0.84	0.59	0.72	0.79	0.52	0.65	0.76
d) potential yields, WG approach:									
avg [kg/ha]	11486	11960	12546	11227	11703	12272	10999	11470	12049
std [kg/ha]	1927	2015	2120	1716	1789	1878	1673	1743	1836
std/avg [%]	17	17	17	15	15	15	15	15	15
direct effect	1.00	1.04	1.09	1.00	1.04	1.09	1.00	1.04	1.10
indirect effect	1.00	1.00	1.00	0.98	0.98	0.98	0.96	0.96	0.96
both effects	1.00				1.02				1.05

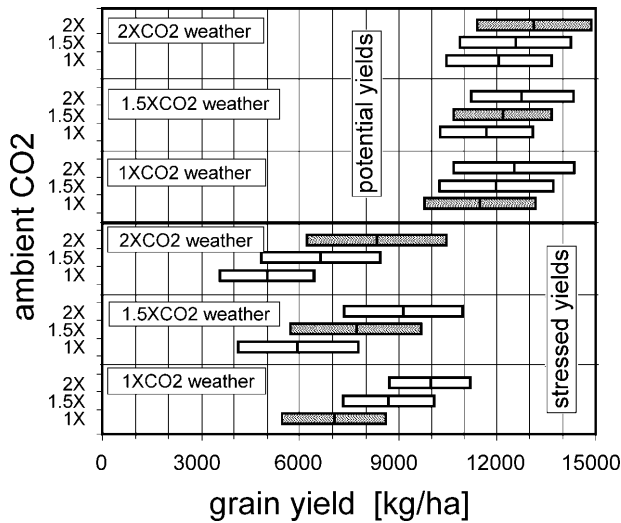


Fig. 7. Summary statistics (average \pm standard deviation) of the stressed (bottom) and potential (top) model yields in the 17-year crop growth simulation run with weather series obtained by the direct modification of the observed weather series. The labels to the left of the vertical give the concentration of ambient CO_2 (with respect to the present level), the interior labels ($1 \times \text{CO}_2$ weather, $1.5 \times \text{CO}_2$ weather, $2 \times \text{CO}_2$ weather) indicate the climate change scenario used to create the weather series. The shaded bars indicate that both direct and indirect effects are driven by the same CO_2 concentration

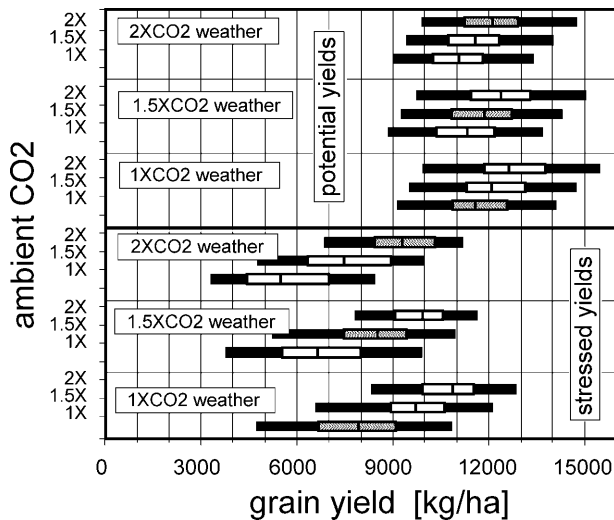


Fig. 8. Similar as the previous figure but the summary statistics of the grain yields were derived from the 99-year crop growth simulation run in the WG approach and are expressed in terms of quantiles. The bars represent 5th, 25th (lower quartile), 50th (median), 75th (upper quartile), and 95th member from the set of values arranged in an ascending order

is assured in the DM approach that the values of the weather characteristics for a given year in the $1.5 \times \text{CO}_2$ climate are always between the

values related to the $1 \times \text{CO}_2$ and $2 \times \text{CO}_2$ climates. However, although the changes in weather characteristics related to increased CO_2 tend to reduce the stressed yields (Fig. 7, Fig. 8), the model yields do not follow this trend in some years (see, e.g., yields in 1987 and 1991 displayed in Fig. 5b). The analogous analysis applied to the time series of the potential yields (Fig. 6) shows that the relationship between the model potential yields and weather is even more complex. On average, the stressed yields decrease due to the indirect effect of doubled CO_2 by 14% ($2 \times \text{CO}_2$ in the atmosphere, WG approach) to 29% ($1 \times \text{CO}_2$ in the atmosphere, DM approach). This decrease is assumed to be due to the rise of temperature sums and a resultant shortening of individual phenological phases not allowing for an optimal development of the crop. Moreover, the simultaneous decrease of summer precipitation and increase of potential evapotranspiration (due to increased temperature and solar radiation) imply an elevated water stress (Fig. 9c) that also contributes to a reduction of the yields. Due to the lack of the effect of increased water stress, the magnitude of the indirect effect on potential yields is significantly lower: slightly negative in the WG approach (Fig. 8) and even slightly positive in the DM approach (Fig. 7).

3.2 Direct effect

An increased concentration of ambient CO_2 implies higher yields (Fig. 5c,d; Fig. 7; Fig. 8). As given in the introduction, this increase is contributed to by the intensified photosynthesis and (in the case of limited yield only) improved WUE. As the magnitude of the latter mechanism depends on water available, the increase of the yields in the years with sufficient precipitation during the vegetation period (1984, 1985, 1987, 1991) is less pronounced compared to the “dry” years (1983, 1994, 1995). Since the water availability affects only stressed yields, the magnitude of the direct effect on the potential yields (9–10% increase in the $2 \times \text{CO}_2$ atmosphere) is only due to the intensified photosynthesis, and accordingly lower than for the stressed yields. Comparing the magnitudes of the direct effect on the stressed and potential yields (Table 1), we can see that the effect of better

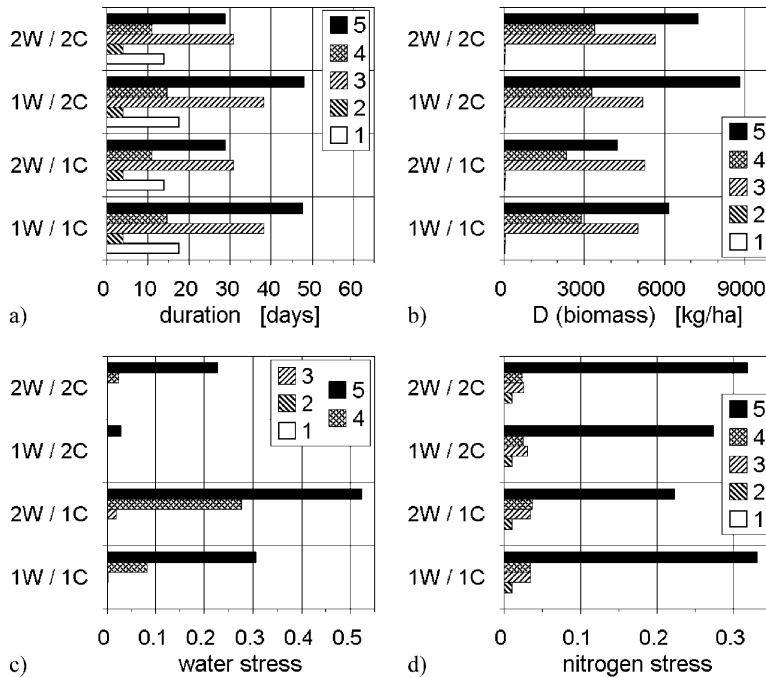


Fig. 9. The means of the crop growth characteristics related to the five phenological phases (indicated by numbers 1–5 in the legend box). The characteristics were calculated from the 99-year crop model simulations performed in the WG approach at two levels of ambient CO_2 ($1 \times \text{CO}_2$ and $2 \times \text{CO}_2$ levels are labelled by 1C and 2C on the ordinate) and present and $2 \times \text{CO}_2$ weather conditions (labelled by 1W and 2W). The four panels relate to **a**) duration of the phenological phase, **b**) an increment to the biomass, **c**) index of the water stress (value within $\langle 0,1 \rangle$ interval), and **d**) index of the nitrogen stress (value within $\langle 0,1 \rangle$ interval)

WUE is much greater than the effect of intensified photosynthesis. Contrary to the indirect effect, the changes of the yields are approximately proportional to the change in ambient CO_2 concentration (Fig. 5c,d).

3.3 Combined effects of CO_2 change

It may be noted that the direct and indirect effects of increased CO_2 on stressed yields are not additive. The mean stressed yields simulated in the DM approach (Table 1, Fig. 7) decrease due to the indirect effect of doubled CO_2 by 29% (from 7037 to 5010 kg/ha) in the present ambient CO_2 concentration, but only by 16% (from 9955 to 8332 kg/ha) in the $2 \times \text{CO}_2$ atmosphere. The mean stressed yields increase due to the direct effect of doubled CO_2 by 41% (from 7037 to 9955 kg/ha) in $1 \times \text{CO}_2$ weather, but by 66% (from 5010 to 8332 kg/ha) in $2 \times \text{CO}_2$ weather conditions. Similar trends are obtained in the WG approach (Fig. 8). These results may indicate that the reduction of the yields due to the water stress (as a result of the indirect effect) will be lower in the $2 \times \text{CO}_2$ atmosphere, or, from a different point of view, the positive effect on the yields of the better WUE due to increased CO_2 will be greater in $2 \times \text{CO}_2$ weather conditions. The magnitude of the direct effect of increased

CO_2 is greater than the magnitude of the indirect effect, so that the superposition of both effects implies positive change in maize yields in increased CO_2 conditions. The mean model stressed yields increase by 17–18% in $2 \times \text{CO}_2$ conditions and the trends are almost identical in both DM and WG approaches. The potential yields increase by 5–14% in $2 \times \text{CO}_2$ conditions, the trends obtained in WG approach are lower compared to the trends obtained in DM approach.

3.4 Effect of the CO_2 change on the variability of the model yields

The variability of the model stressed yields (expressed in terms of the coefficient of variation, which is defined as a ratio of the standard deviation to the average) decreases due to the direct effect of increased CO_2 but increases due to the indirect effect of increased CO_2 . These changes are assumed to be related to the water stress, the intensity of which is negatively (positively) correlated with the intensity of the direct (indirect) effect. The increasing intensity of the water stress reduces the mean yields but enhances the variability of the yields. If both direct and indirect effects are combined, variability tends to increase (from 22% in $1 \times \text{CO}_2$

conditions to 25% in $2 \times \text{CO}_2$ conditions) if simulated in the DM approach but tends to decrease (from 25% to 18%) if simulated in the WG approach.

3.5 Comparison of results obtained in DM and WG approaches

The means of the stressed yields obtained in the WG approach are by 10% greater on average than the yields obtained in the DM approach. This corresponds to the choice of the representative year whose parameters were based on year 1989 which exhibited about 10% greater yields compared to the average yield. Importantly, the ratio of the WG mean to DM mean exhibits no significant relationship with CO_2 change, which implies that the trends in the mean yields due to the direct and indirect effects are similar in both approaches (paragraphs a and c of Table 1). The results of the F-test suggest that the differences between the variabilities (expressed in terms of the coefficient of variation) of the stressed yields obtained in the two approaches are statistically significant but the explanation is not apparent to the authors. It may be just noted that the number of the yields used to calculate a single statistic in the DM approach is much lower compared to the number of values available in the WG approach (17 vs. 99), so that the statistics obtained in the WG approach are loaded by a lower sampling error and thus should be given greater weight in assessing the trends. In addition, the variability of DM yields may be affected by the interannual variability of non-meteorological parameters, which are held constant in the WG approach. This should result in greater variability of DM yields, which may be observed in the $1.5 \times \text{CO}_2$ and $2 \times \text{CO}_2$ climates. As for the potential yields, the magnitude of the direct effect is about the same in both the WG and DM approaches; the indirect effect is slightly negative in the WG approach but slightly positive in the DM approach.

3.6 Stressed vs. potential yields

The effects (both direct and indirect) of varying CO_2 on potential yields are much less pronounced than those in water and nutrient limited conditions (stressed yields). For example, the direct effect of

doubled CO_2 on potential yields is 9–10% (compare with 36–66% in stressed conditions) and the indirect effect is +5% in the DM approach (compare with –16 to –29% in stressed conditions) and –4% in the WG approach (compare with –14 to –27% in stressed conditions). In contrast with the stressed conditions, the direct and indirect effects on potential yields are mutually additive: the magnitude of the direct effect is the same for all weather regimes, and the magnitude of the indirect effect is the same for all ambient CO_2 levels. This is explained by the water stress, which causes nonlinearities in trends of the stressed yields but is absent in simulating the potential yields. For further interpretation, the index of production potential, Z , is introduced. The value of the index is defined as a ratio of stressed (Y_S), and potential (Y_P) yields under given weather conditions (w) and ambient CO_2 concentration (c):

$$Z(w, c) = \frac{Y_S(w, c)}{Y_P(w, c)} \times 100\% \quad (1)$$

This index may serve as a measure of impacts of limiting factors on the grain yields. In case of the field experiment the value of Z is always greater than 0% and lower than 100%. The zero value of Z would mean that the stress totally inhibits the growth, $Z=100\%$ would mean that no stress affects the yields. It can be seen from Table 1 that Z increases with increasing intensity of the direct effect but decreases with increasing intensity of the indirect effect. This behaviour relates to the water stress, which decreases due to the direct effect of increased CO_2 but increases due to the indirect effect. If both the effects are combined, the value of Z slightly increases with increasing CO_2 .

4. Effect of CO_2 change on other growth and development characteristics

The studies of climate change impact on crops are mostly concerned with yields. However, biomass growth, occurrence of the water and nitrogen stresses during individual growth phases, duration of the phases, and maximum leaf area index (LAI_{max}), are also worth mentioning in the impact assessments. The mean values of selected characteristics related to the five growth

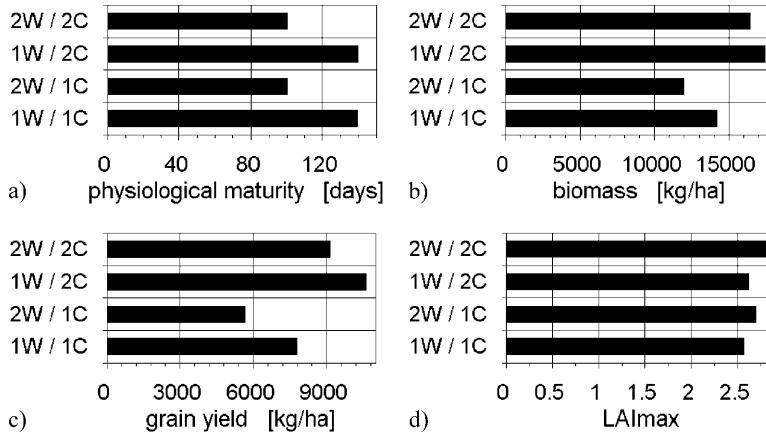


Fig. 10. As in Fig. 9 but for the characteristics related to the whole growing period. The four panels display **a)** the time of achievement of the physiological maturity (days after planting), **b)** the total biomass at the harvest maturity, **c)** the grain yield, and **d)** the maximum value of the leaf area index

phases (considered by the CERES-Maize model) and the whole growing period, two climate scenarios and two ambient CO_2 levels are shown in Figs. 9 and 10. The five phases are: (i) from emergence to the end of juvenile phase, (ii) from the end of juvenile phase to the floral initiation, (iii) from the floral initiation to the end of leaf growth, (iv) from the end of leaf growth to the beginning of grain filling, and (v) the grain filling phase. The figures indicate:

4.1 Direct effect

(i) The duration of individual phenological phases (Fig. 9a) and LAImax (Fig. 10d) are nearly independent of the concentration of CO_2 in the atmosphere. (ii) More biomass (increases by 23% and 37% in present and $2 \times \text{CO}_2$ weather conditions, respectively; Fig. 10b) and grain yield (increases by 36% and 61% in present and $2 \times \text{CO}_2$ weather conditions, respectively; Fig. 10c) are expected if the ambient CO_2 concentration is doubled. The increase is mostly related to the improved WUE⁴, which nearly eliminates the water stress in the 4th and 5th growth phases (Fig. 9c). The changes in biomass growth are expected only in these two phases (Fig. 9b).

4.2 Indirect effect

(i) Increasing temperature sums will result in shortening the crop phenological development (Fig. 9a). All phenological phases (except for the second one, which lasts 4 days on average and will not be affected) will be shortened. The 5th phase is reduced most significantly, by 40%. The physiological maturity (Fig. 10a) will be

achieved by 39 days sooner: it drops from 139 to 100 days. (ii) The biomass will be reduced by 15% (6%) and the grain yields by 27% (14%) in the present (doubled) ambient CO_2 concentrations (Fig. 10b,c). The reduction of the biomass is mainly due to a shortening of the fifth phenological phase and significant increase of the water stress in this phase (as a result of increased temperatures, increased intensity of solar radiation and decreased precipitation).

5. Adaptation to climate change by shifting the planting date

Up to now, it was assumed that all input parameters except for the weather series and ambient CO_2 concentration are constant. However, the yields may apparently be modified by various management responses, such as adjustments in fertilisation and irrigation regimes, shifting the planting date, or using other cultivar. Only the shift of the planting date (PD) is considered in the present study.

The 99-year crop model simulations were run in the WG approach for two levels of ambient CO_2 (present and doubled concentrations) and two climates (present and $2 \times \text{CO}_2$ climates), at water and nutrient limited conditions. The value of PD was varied within the interval ($D_0 - 60$ days, $D_0 + 30$ days), where $D_0 = 126$ (May 6) is the planting date of the “representative year”. The results displayed in Fig. 11 show:

(i) The model grain yields simulated in the present climate and ambient CO_2 concentration (Fig. 11a) are rather insensitive to small changes in PD. Specifically, the median of

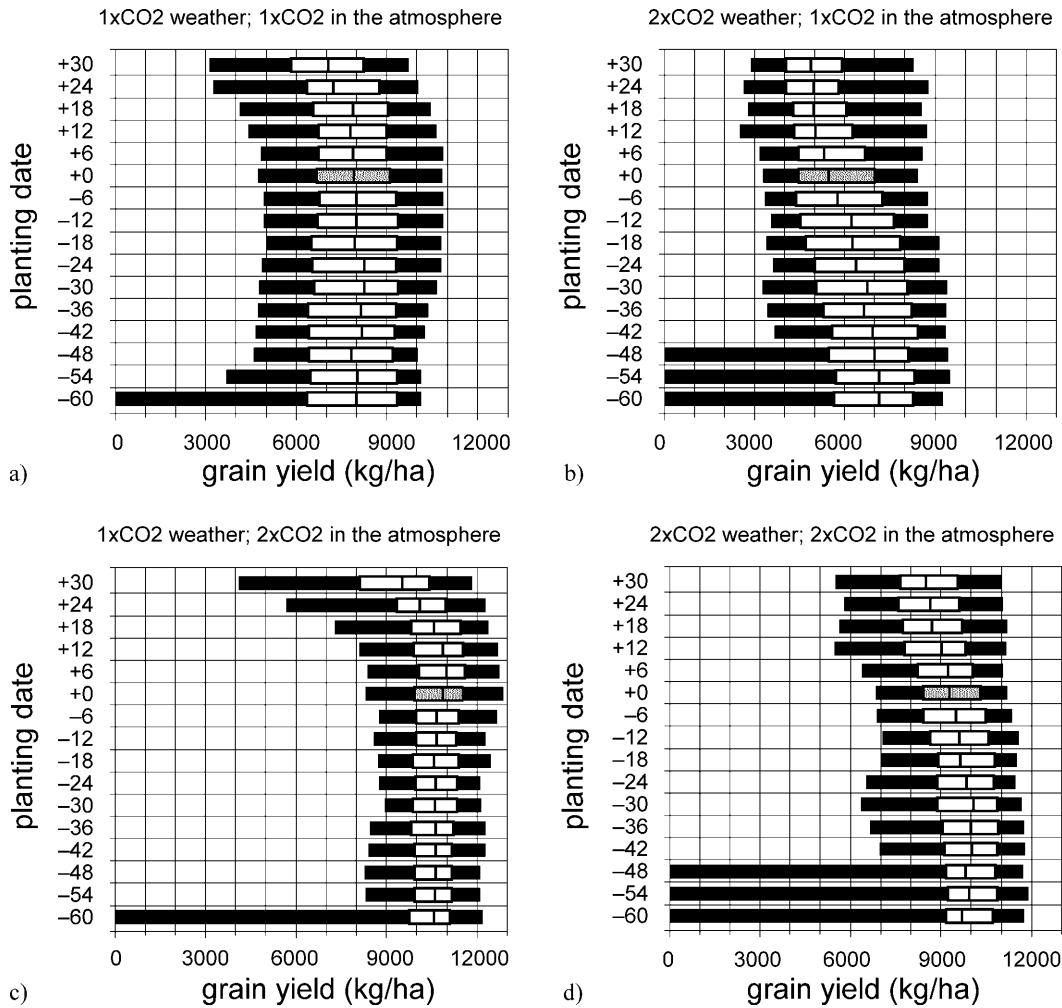


Fig. 11. Sensitivity of the grain yields to the planting date, which is given in terms of the deviation (in days) from the representative year's planting date (May 6, the 126th day of the year). The bars represent quantiles (5th, 25th, median, 75th, 95th) of the model yields obtained in the 99-year simulations made in the WG approach at two levels of ambient CO₂ and two weather regimes. The shaded bars relate to the representative year's planting date

the yields remains nearly constant if PD varies within ($D_0 - 60$ days, $D_0 + 18$ days). In case of the earlier PD, the probability that the yield is damaged by a spring frost increases: one zero yield occurs in the 99-year series if $PD = D_0$, but three (six) zero yields occur if $PD = D_0 - 36$ ($D_0 - 60$). On the other hand, if the planting date is delayed beyond D_0 , the grain yields tend to decrease due to the occurrence of the autumn low temperatures, which precociously terminate the grain filling phase. In the case of the planting date delayed by 1 month, the average grain yield decreases by 11%.

- (ii) The decreases of the yields resulting from the changes in daily weather conditions in the $2 \times \text{CO}_2$ climate, especially from the

increased temperature, might be mitigated by applying earlier planting terms (Fig. 11b,d). However, the mitigation is only partial, as the high temperatures occurring at the later phases of the crop development cannot be avoided by earlier planting. In the case of the one month earlier planting date, the mean duration of the growing period is prolonged from 100 days to 117 days (compare to 140 days in $1 \times \text{CO}_2$ climate) and the mean yields are increased by 775 kg/ha at present ambient CO₂ (Fig. 11b; note that the graphs display quantile characteristics but the magnitudes of the indirect effect are calculated from the means), and by 402 kg/ha at doubled ambient CO₂ (Fig. 11d). This means that the negative indirect effect of doubled

CO₂ manifested by a 27% decrease of the stressed yields simulated in the WG approach at present ambient CO₂ (Table 1) is reduced to 17%, and the 14% decrease at doubled CO₂ is reduced to 10%. Surprisingly in the first sight, the frequency of a frost damage is greater in the 2 × CO₂ climate, which exhibits warmer temperatures compared to the present climate. This paradox may be explained partly by a faster development of the plants in 2 × CO₂ climate, which implies that the individual phenological phases start sooner, and partly by a randomness involved in generating the synthetic weather series. The randomness affects the sample frequency of occurrence of spring frosts, but the differences in the frequencies of occurrence of zero yields between the present and 2 × CO₂ climates cannot be considered statistically significant.

6. Conclusion

The impacts of increased concentration of atmospheric CO₂ on grain maize yields were analysed. The analysis was based on the multi-year CERES-Maize crop model simulations run with daily weather series obtained alternatively by a direct modification of observed weather series and a stochastic weather generator. Two effects of increased CO₂ were distinguished. The direct effect, which is related to the functioning of CO₂ in the ambient air, is manifested by an increased rate of photosynthesis and an improved water use efficiency. The indirect effect is related to weather conditions, which will change due to the increase of greenhouse gases concentration. To show the role of the two CO₂ effects, the scenarios linking their different levels (present level, CO₂ increased by 50%, CO₂ increased by 100%) were employed in this paper. The core experiments were those, in which the CO₂ concentration for both direct and indirect effects of increased CO₂ was the same. As the model yields are affected by water and nitrogen stresses, which depend on weather conditions in a rather complex manner, and, moreover, may be mitigated by adjustments in the irrigation and fertilisation regime, the yields were simulated in two model settings. The stressed yields were

modelled with water and nutrient routines switched on, and the potential yields were modelled with the water and nutrient routines switched off. In the latter settings, the crop is given as much water and nutrients as it needs.

The main results obtained in this study may be summarised in the following points:

- (i) The validation tests show a very good fit between the observed and modelled yields of maize. After omitting the two most extreme misfits (probably originating from extreme floods), the accuracy expressed in terms of the standard error is 11%, which is comparable with other studies.
- (ii) The magnitude of the indirect effect related to changed weather conditions is negative. The stressed yields decrease by 27–29% in the present concentration of ambient CO₂, and by 14–16% in the 2 × CO₂ atmosphere. The increased temperature will shorten the phenological phases and will not allow for an optimal development of the crop. The simultaneous decrease of precipitation and increase of temperature and solar radiation sums will further reduce the yields through deepening the water stress. Since the magnitude of the indirect effect is closely related to the site-specific climatic conditions and the climate change scenario employed, the comparison with other studies has only limited information value. Nevertheless, it may be noted that Bacsí and Hunkár (1994) report changes in maize yields from –14 to +7% using three GCM-based climate change scenarios and the DM approach. Similarly, Iglesias (1995b) used five GCM-based climate change scenarios and five locations in Spain to simulate maize yields under increased CO₂. Although the direct effect of increased CO₂ was included, the maize yields decreased (by 2 to 27%) for all scenarios and locations. The decreases were attributed mainly to shortened crop growth phases due to the increased temperatures.
- (iii) The magnitude of the direct effect of increased CO₂ on stressed yields is a result of a superposition of two mechanisms: intensified photosynthesis and better WUE. The stressed yields increase by 36–41% (the two numbers relate to the WG and

DM approaches) due to the direct effect in the present climate and by 61–66% in the $2 \times \text{CO}_2$ climate. The values obtained in the $2 \times \text{CO}_2$ climate are higher because the water stress is higher and the positive effect on the yields of improved WUE is more pronounced. The obtained values may be compared to results by other authors. For example, Dhakhwa et al. (1997) found in their crop simulation experiments that the direct effects of elevated CO_2 concentration varied for different plant components; the yield increased by 18% (CERES-Maize model) and by 14% (EPIC model) in doubled ambient CO_2 . Wolf and van Diepen (1995) report 0% (at Brindisi in Italy) to 46% (at Orleans, France) increase in maize yields due to the increase of CO_2 from 353 to 550 ppm. Brown and Rosenberg (1997) used EPIC to simulate maize yields in three locations under various climate sensitivity scenarios and found the yields to increase by 6–19% as the CO_2 increased from 350 to 550 ppm. These numbers, however, relate to stressed yields and are therefore affected by changes in water stress, which may differ for individual sites and climate scenarios used.

- (iv) The positive direct effect of doubled CO_2 dominates over the negative effect of changed weather conditions. In result, the stressed yields would increase in $2 \times \text{CO}_2$ conditions by about 17–18% if both the direct and indirect effects were considered.
- (v) The decrease of the mean yields due to the indirect effect of doubled CO_2 may be reduced by one third if the maize is planted 1 month sooner (compared to the planting date of the representative year). Application of the earlier planting date would result thus in an additional 4% increase of the yields in $2 \times \text{CO}_2$ conditions.
- (vi) The impacts of doubled CO_2 on potential yields are less pronounced than the impacts on the stressed yields. The lower magnitude of the indirect effect (the yields change by -4 to $+5\%$) is related probably to the water stress: The stress increases in the $2 \times \text{CO}_2$ climate, thereby reducing the yields simulated under water and nutrient limited conditions, but does not affect the potential yields. The lower

magnitude of the direct effect of doubled CO_2 (9–10% increase of the yields) is related to a missing additional effect of improved water use efficiency, which increases the stressed yields but does not apply in water and nutrient unlimited conditions. Superposition of both direct and indirect effects of doubled CO_2 results in the 5–14% increase of the potential yields. The increase of the potential yields found in the present study contradicts Wolf and van Diepen (1995) who used the WOFOST crop model and report no direct effect of increased CO_2 on the potential yields. The disagreement may be explained by the use of different methods to incorporate the direct effect of CO_2 in the two crop models.

- (vii) The results obtained in the two approaches (DM and WG) are similar. Although the values of the mean yields differ, the percentage changes mostly exhibit the same behaviour. The differences between the results obtained in the two approaches may be attributed to the differences between the input data used: (a) The usage of the representative year in the WG approach may cause a systematic deviation of the mean yields. In addition, it implies that the non-meteorological input parameters do not vary from year to year in contrast with the DM approach and reality. On the other hand, it may be noted that the non-meteorological input data (e.g., planting date and fertilisation regime), which are varied in dependence on the weather regime in reality, need not be optimal if the weather series is modified but other settings of the crop simulation experiment are left unchanged (although different for individual years). (b) The changes in variability of daily extreme temperatures and solar radiation included in the climate change scenario were taken into account in the WG approach but not in the DM approach. This may contribute to some discrepancies regarding the effect of the variability of weather characteristics on crop yields (Dubrovský et al., 2000). (c) The number of values used to calculate a single statistic for a given scenario is limited by the length of the observational series in the DM approach. In the present study, this length is 17 years which is much

lower compared to 99 years used in the WG approach. In result, the statistics obtained in the WG approach are loaded by a lower sampling error. In summary, both approaches appear to be valuable tools in assessing climate change impacts on crop yields and have their important advantages. The superiority of the DM approach is the intensive usage of all (both weather and non-weather) observed data. This (a) allows one to better account for the interannual variability of all input parameters, and (b) eliminates the necessity to approximate the statistical structure of the weather series by the model, which cannot reproduce all statistical properties of the weather series. On the other hand, the employment of the generator allows (a) running longer crop simulation experiments, thereby achieving higher accuracy of model summary statistics, and (b) making more detailed sensitivity analyses with respect to changes in a broad spectrum of climate characteristics (Dubrovský et al., 2000). Moreover, since the parameters of the generator may be interpolated in space relatively easily (Guenni, 1994), the impact analysis may be performed even if the sufficiently long observed weather series is not available for the location.

To conclude, it may be stated that the results are in good agreement with the rules governing the growth and development of the crop. Specifically, the increases or decreases of the stressed and potential yields may be logically explained by effects of a changed weather regime and changed ambient CO₂ concentration on the duration of growing period, water stress occurrence and photosynthesis rate.

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References

Alexandrov V, Hoogenboom G (1999) Evaluation of the CERES Model for Maize and Winter Wheat in South-eastern Europe. In: Proc International Symposium Modelling Cropping Systems, 21–23 June 1999, Lleida, Spain, pp 131–132

- Bacsi Z, Hunkár M (1994) Assessment of the impacts of climate change on the yields of winter wheat and maize, using crop models. *Időjárás* 98: 119–134
- Brown RA, Rosenberg NJ (1997) Sensitivity of crop yield and water use to change in a range of climatic factors and CO₂ concentrations: a simulation study applying EPIC to the central USA. *Agric Forest Meteorol* 83: 171–203
- Cuculeanu V, Marica A, Simota C (1999) Climate change impact on agricultural crops and adaptation options in Romania. *Climate Research* 12: 153–160
- Dhakhwa GB, Campbell CL, LeDuc SK, Cooter EJ (1997) Maize growth: assessing the effect of global warming and CO₂ fertilization with crop models. *Agric Forest Meteorol* 87: 253–272
- DKRZ (1993) The ECHAM3 Atmospheric General Circulation Model. Report No.6. Deutsches Klimarechenzentrum, Hamburg, 184 pp
- Dubrovský M (1996) Validace stochastického generátoru Met&Roll. *Meteorologické Zprávy* 49: 129–138 (in Czech, with English abstract)
- Dubrovský M (1997) Creating daily weather series with use of the weather generator. *Environmetrics* 8: 409–424
- Dubrovský M, Žalud Z, Štátná M (2000) Sensitivity of CERES-Maize yields to statistical structure of daily weather series. *Climatic Change* 46: 447–472
- Easterling WE, Crosson PR, Rosenberg NJ, McKenney MS, Katz LA, Lemon KM (1993) Agricultural impacts of and responses to climate change in the Missouri-Iowa-Nebraska-Kansas (MINK) region. *Climatic Change* 24: 23–61
- Easterling WE, Weiss A, Hays CJ, Mearns LO (1998) Spatial scales of climate information for simulating wheat and maize productivity: the case of the US Great Plains. *Agric Forest Meteorol* 90: 51–63
- Guenni L (1994) Spatial interpolation of the parameters of stochastic weather models. In: Paoli G (ed) *Climate change, uncertainty and decision making*. Berlin: Institute for Risk Research, University of Waterloo, Ontario and IGBP-BAHC, pp 61–79
- Guevara ER, Meira S, Maturano M, Coca G (1999) Maize simulation for different environments of Argentina. In: Proc International Symposium Modelling Cropping Systems, 21–23 June 1999, Lleida, Spain, pp 131–132
- Hijmans RJ, Guiking-Lens IM, van Diepen CA (1994) WOFOST 6.0. (User's guide for the WOFOST 6.0 crop growth simulation model). Wageningen, 145 pp
- Hoogenboom G, Jones JW, Wilkens PW, Batchelor WD, Bowen WT, Hunt LA, Pickering NB, Singh U, Godwin DC, Bear B, Boote KJ, Ritchie JT, White JW (1994) Crop models, DSSAT Version 3.0. International Benchmark sites Network for Agrotechnology Transfer. Honolulu: University of Hawaii, 692 pp
- Hunkár M (1994) Validation of crop simulation model CERES-Maize. *Időjárás*, 98: 37–46
- Iglesias A (1995a) Modelling the effects of climate change and climatic variability on crops at the site scale – effects on maize. In: Harrison PA, Butterfield RE, Downing TE (eds) *Climate Change and Agriculture in Europe – Assessment of Impacts and Adaptations*. Research report No.9, Environmental Change Unit, University of Oxford, UK, pp 223–231

- Iglesias A (1995b) Modelling the effects of climate change on crops at the regional scale – effects on wheat and maize in Spain. In: Harrison PA, Butterfield RE, Downing TE (eds) *Climate Change and Agriculture in Europe – Assessment of Impacts and Adaptations*. Research report No.9, Environmental Change Unit, University of Oxford, UK, pp 310–319
- IPCC (1996) *Climate Change 1995: The Science of Climate Change*. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change [Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (eds)]. Cambridge and New York: Cambridge University Press, 572 pp
- IPCC (2001) *Climate Change 2001: Synthesis Report*. Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 450 pp (in press)
- Jones CA, Kiniry JR (eds) (1986) *CERES-Maize: A simulation model of maize growth and development*. TX: Texas A&M University Press, College Station, 194 pp
- Karpíšek M, Prax A (1989) Dlouhodobé antropogenní vlivy na změny fyzikálních a chemických charakteristik i úrodnost půd v hospodářském obvodu školního statku Žabčice. M.Sc. thesis, Mendel University of Agriculture and Forestry, Brno, Czech Republic, 96 pp (in Czech)
- Kimball BA, Idso SB, Mauney JR (1988) Effects of atmospheric CO₂ enrichment on root:shoot ratio of carrot, radish, cotton and soybean. *Agriculture Ecosystems and Environment* 21: 293–299
- Koestl M (1995) Test dreier unterschiedlicher Maiswachstumsmodelle bezüglich einer möglichen zukünftigen Anwendbarkeit in Österreich. M.Sc. thesis, BOKU University, 91 pp (in German, with English abstract)
- Makadho JM (1996) Potential effects of climate change on corn production in Zimbabwe. *Climate Research* 6: 147–151
- Maytín CE, Acevedo MF, Jaimez R, Andressen R, Harwell MA, Robock A, Azkcar A (1995) Potential effects of global climatic change on the phenology and yield of maize in Venezuela. *Climatic Change* 29: 189–211
- Mearns LO, Rosenzweig C, Goldberg R (1992) Effect of Changes in Interannual Climatic Variability on CERES-Wheat Yields: Sensitivity and 2 × CO₂ General Circulation Model Studies. *Agric Forest Meteorol* 62: 159–189
- Mearns LO, Rosenzweig C, Goldberg R (1996) The Effect of Changes in Daily and Interannual Climatic Variability on CERES-Wheat: A Sensitivity Study. *Clim Change* 32: 257–292
- Mearns LO, Rosenzweig C, Goldberg R (1997) Mean and variance change in climate scenarios: methods, agricultural applications, and measures of uncertainty. *Climatic Change* 35: 367–396
- Nemešová I, Kalvová J, Klimperová N, Buchtele J (1998) Comparison of GCM-simulated and observed climates for assessing hydrological impacts of climate change. *J Hydrol Hydromech* 46: 237–263
- Nemešová I, Kalvová J, Dubrovský M (1999) Climate change projections based on GCM-simulated daily data. *Studia Geophysica et Geodaetica*, 43: 201–222
- Nonhebel S (1993) Effects of changes in temperature and CO₂ concentration on simulated spring wheat yields in the Netherlands. *Climatic Change* 24: 311–329
- Nonhebel S (1996) Effects of temperature rise and increase in CO₂ concentration on simulated wheat yields in Europe. *Climatic Change* 34: 73–90
- Penning de Vries FW-T, Jansen DM, ten Berge HFM, Bakema A (1989) Simulation of ecophysiological processes of growth in several annual crops. *Simulation Monographs* 29, Pudoc Wageningen, The Netherlands, 267 pp
- Porter H (1992) Interspecific variation in the growth response of plants to an elevated ambient CO₂ concentration. *Vegetation* 104–105: 77–97
- Riha SJ, Wilks DS, Simoens P (1996) Impact of Temperature and Precipitation Variability on Crop Model Predictions. *Climatic Change* 32: 293–311
- Rožnovský J, Svoboda J (1995) *Agroklimatická charakteristika oblasti Žabčic*. Mendel University of Agriculture and Forestry, Folia, Brno, Czech Republic, 49 pp (in Czech, with English abstract)
- Semenov MA, Barrow EM (1997) Use of a stochastic weather generator in the development of climate change scenarios. *Climate Change* 35: 397–414
- Semenov MA, Porter JR (1995) Climatic variability and the modelling of crop yields. *Agric Forest Meteorol* 73: 265–283
- Soil Survey Staff (1975) *Soil Taxonomy*. U.S. Department of Agriculture Handbook No. 436., U.S. Government Printing Office, Washington, DC, 754 pp
- Štašná M (1998) Parameterization, validation and utilization of the crop growth CERES-Maize model. Ph.D. thesis, Mendel University of Agriculture and Forestry, Brno, Czech Republic, 135 pp
- Štašná M, Žalud Z (1999) Sensitivity analysis of soil hydrologic parameters for two crop simulation models. *Soil and Tillage Research* 50: 305–318
- Watson RT, Zinyowera MC, Moss RH (1996) *Climate Change 1995: Impacts, Adaptation and Mitigation of Climate Change*. Cambridge Univ Press, 878 pp
- Weiss A, Piper EL (1992) Modifying the response of CERES-Maize to defoliation during vegetative growth. *Agric Syst* 40: 379–392
- Wolf J, van Diepen CA (1995) Effects of climate change on grain maize yield potential in the European Community. *Climatic Change* 29: 299–331
- Žalud Z, Rožnovský J (1998) Parametrizace a verifikace modelu MACROS. *Rostlinná výroba* 11: 509–515 (in Czech, with English abstract)

Authors' addresses: Martin Dubrovský (e-mail: dub@ufa.cas.cz), Institute of Atmospheric Physics, Husova 456, 50008 Hradec Králové, Czech Republic; Zdeněk Žalud, Mendel University of Agriculture and Forestry, Brno, Czech Republic.



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MODELING AGRICULTURAL PRODUCTION RISK AND THE ADAPTATION TO CLIMATE CHANGE

ROBERT FINGER¹, STÉPHANIE SCHMID²

¹Institute for Environmental Decisions, ETH Zurich, Switzerland

²Agroscope Reckenholz-Tänikon Research Station ART, Zürich, Switzerland

rofinger@ethz.ch



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*Robert Finger, Stéphanie Schmid**

Abstract

A model that integrates biophysical simulations in an economic model is used to analyze the impact of climate change on crop production. The biophysical model simulates future plant-management-climate relationships and the economic model simulates farmers' adaptation actions to climate change using a nonlinear programming approach. Beyond the development of average yields, special attention is devoted to the impact of climate change on crop yield variability.

This study analyzes corn and winter wheat production on the Swiss Plateau with respect to climate change scenarios that cover the period of 2030-2050. In our model, adaptation options such as changes in seeding dates, changes in production intensity and the adoption of irrigation farming are considered. Different scenarios of climate change, output prices and farmers' risk aversion are applied in order to show the sensitivity of adaptation strategies and crop yields, respectively, on these factors.

Our results show that adaptation actions, yields and yield variation highly depend on both climate change and output prices. The sensitivity of adaptation options and yields, respectively, to prices and risk aversion for winter wheat is much lower than for corn because of different growing periods. In general, our results show that both corn and winter wheat yields increase in the next decades. In contrast to other studies, we find the coefficient of variation of corn and winter wheat yields to decrease. We therefore conclude that simple adaptation measures are sufficient to take advantage of climate change in Swiss crop farming.

Keywords

climate change, robust estimation, yield variation, corn, winter wheat, market liberalization

1 Introduction

In the next decades Swiss farmers will face changing climatic conditions, which are characterized by elevated carbon dioxide concentrations, reduced summer rainfalls and elevated temperatures for the Swiss Plateau region (OCCC, 2005). Furthermore, Swiss agriculture will face changing market conditions due to market liberalization. Both input and output prices are expected to decrease in the next decades. The goal of this paper is to assess

*Robert Finger (Institute for Environmental Decisions, ETH Zürich), Dr. Stéphanie Schmid (Agroscope Reckenholz-Tänikon Research Station ART, Zürich). This work was supported by the Swiss National Science Foundation in the framework of the National Centre of Competence in Research on Climate (NCCR Climate). We would like to thank Werner Hediger for helpful comments.

impacts of climate and price changes on Swiss corn (*Zea mays L.*) and winter wheat (*Triticum L.*) production.

Previous studies that analyzed the effects of climate change (CC) on crop production and crop variability were either based on (crop) simulation or regression models. Crop simulation models simulate and compare crop productivity for different climatic conditions (e.g. TORRIANI ET AL., 2007a). Regression models use historical climate and agricultural data to outline potential effects of climate change on crop productivity (e.g. ISIK AND DEVADOSS, 2006). Both approaches are not sufficient to analyze all aspects of impacts of CC on crop production (ANTLE AND CAPALBO, 2001). If the analysis is restricted to crop physiology, such as in crop simulations, farmer's adaptation actions are not taken into account. But, sufficient inference requires consideration of farmers' reactions to changes in climate and economic conditions. This contrasts the extrapolation of historical farm-level and aggregated data that takes into account farmers' historical reactions to changes in climatic and economic conditions. However, historical data is not able to capture future plant-climate interactions in a sufficient manner, in particular if the crop-weather relationship is restricted to a few variables such as temperature and rainfall. Moreover, such models cannot sufficiently integrate expected CO₂ fertilization effects on plants due to low variation in historical CO₂ concentrations (ANTLE AND CAPALBO, 2001). In order to overcome these drawbacks, we use a combination of both approaches, simulation of future crop productivity and regression models.

Existing studies show that CC will have particular influence on yield variation (MEARNS ET AL., 1996, TUBIELLO ET AL., 2000, SOUTHWORTH ET AL., 2002, FUHRER, 2003, CIAIS ET AL., 2005, and, TORRIANI ET AL., 2007a). The analysis of yield variation was restricted on climatic variables such as shifts in annual means and intra-annual distributions of climatic variables. These studies do not take adaptation actions of the farmers into account. In contrast, our approach considers farmers' adaptation actions to CC and is thus more sufficient to model the impact of CC on yield variation. An empirical example for corn and winter wheat production on the Swiss Plateau is used to assess the impact of CC on both crop yields and yield variability.

Our model covers no short term adaptation actions (i.e. tactical decisions) of farmers, but adaptation choices with a longer time horizon, i.e. strategic and structural decisions (cp. RISBEY ET AL., 1999). We consider strategic and structural decisions that consist of changes in production intensity, changes in seeding dates and the adoption of irrigation farming. Even though crop yields are influenced by various factors, our analysis is restricted on the crucial inputs nitrogen fertilizer and irrigation water. Thus, the analysis is of particular environmental and economic interest because application of both inputs can lead to the degradation of environmental systems (IEEP, 2000, and, KHANNA ET AL., 2000). Nitrogen fertilizer is furthermore a major source of climate relevant agricultural emissions (HUNGATE ET AL., 2003).

Our model is based on an integrated assessment approach that integrates a biophysical in an economic model. In contrast to other integrated models (e.g. ANTLE AND CAPALBO, 2001), farmers' behavior is simulated using nonlinear programming. The model is divided into three major parts: data simulation, estimation of model parameters and economic simulation. Data simulation describes the yield simulation process which includes the experimental design that enhances yield variability with respect to nitrogen fertilizer and irrigation. Furthermore, current and simulated future daily weather data are crucial inputs for the simulation process. The data simulation results in individual datasets for each climatic scenario and crop that contain yield and input data. These datasets are used to estimate production and yield variation functions, respectively. Subsequently, based on these functions, farmers' adaptation choices under different climate, price and risk aversion scenarios are simulated using nonlinear programming. Final assessment is based on a comparison of optimal input levels

and consequential yield levels, yield variation, coefficients of variation and utility of quasi-rents for these scenarios of climate change, future prices and risk aversion.

In Section 2, 3 and 4, the data simulation, the economic model and the estimation processes are described, respectively. Estimation and economic simulation results are presented in Section 5 and 6, respectively. A final discussion of the impact of climate change on Swiss corn and winter wheat production is given in the concluding Section 7.

2 Crop yield simulation and data

Our analysis is based on yield data generated by the deterministic crop yield simulation model CropSyst (e.g. STÖCKLE ET AL., 2003). This is a process-based, multi-crop, multi-year cropping system simulation model. The model simulates above- and belowground processes of a single land block fragment representing a biophysically homogenous area. The model processes are simulated on a daily time step. They comprise the soil water budget, soil-plant nitrogen budget, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, and soil erosion by water. These processes are simulated in response to weather, soil characteristics, crop characteristics, and management options. The model is therefore highly suitable to analyze the impact of environment and management on crop productivity, and has already been tested for a wide range of environmental conditions (e.g. DONATELLI ET AL., 1997, and, STÖCKLE ET AL., 2003). TORRIANI ET AL. (2007a) provide a model calibration, tests of yield simulation and a documentation of critical crop parameters of corn and winter wheat for the Swiss Plateau that are used in our yield simulation. In general, the comparability of simulated and observed yields is restricted because the simulations do not account for yield reducing events such as hail, disease and insect infestation.

CropSyst requires daily values of maximum and minimum temperature, solar radiation, and maximum and minimum relative humidity. In CropSyst, phenology is determined by thermal time, i.e., a specific development stage is reached when the required daily accumulation of average air temperature above a base temperature and below a cutoff temperature is reached. Daily climate input as required by CropSyst is obtained from the monitoring network of the Swiss Federal Office of Meteorology and Climate (MeteoSwiss). We use data from six meteorological stations distributed over the Swiss Plateau ranging from 06°57' to 08°54' longitude (FINGER AND SCHMID, 2007). To simulate current climate conditions, we use climate data of the years 1981 to 2003. Compared to an approach with one single location, the use of observations from six different weather stations broadens the data base. For the atmospheric CO₂ concentration input we use recordings from the years 1981 to 2003. They range from 339 ppm to 379 ppm (SCHRÖTER ET AL., 2005).

Two climate change scenarios are applied to generate crop production functions for the coming decades. Climate scenarios with projections for the years 2030 and 2050 were taken from OcCC (2005). OcCC climate projections are based on simulations with two CO₂ emission scenarios, four global climate models, and eight regional climate models. These simulations with totally 16 scenario-model combinations on a grid of 50x50 km over the whole European continent were performed within the scope of the PRUDENCE project (CHRISTENSEN ET AL., 2001). The OcCC climate projections used in this study represent the median of the simulations with the 16 scenario-model combinations for the years 2030 and 2050. The scenarios are abbreviated in the following as 2030 and 2050. The baseline for these climate anomalies is the year 1990. They include seasonal changes of temperature and precipitation for northern Switzerland (Table 1).

Table 1: Seasonal anomalies of temperature and precipitation

	2030				2050			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Temperature	+ 1	+ 0.9	+ 1.4	+ 1.1	+ 1.8	+ 1.8	+ 2.7	+ 2.1
Precipitation	1.04	1.00	0.91	0.97	1.08	0.99	0.83	0.94

*) Anomalies of temperature in °C (absolute value) and of precipitation in relative values with respect to the climate of the year 1990. DJF: December-February; MAM: March-May; JJA: June-August; SON: September-November.

Source: OCCC (2005)

Based on today's weather data and the anomalies of temperature and precipitation (Table 1), a set of climate data are generated for each of the climate change scenarios using the stochastic weather generator LARS-WG (SEMENOV AND BARROW, 1998). To achieve monthly anomalies as required by LARS-WG, the seasonal anomalies are linearly interpolated. For the 2030 scenario, the CO₂ concentrations (IPCC, 2000) range from 437 ppm to 475 ppm. For the 2050 scenario, CO₂ concentrations in the range of 495 ppm to 561 ppm are assumed. Within the simulation years, the atmospheric CO₂ concentration is varied randomly within the defined range.

For each location and scenario, the same soil type is assumed. It follows TORRIANI ET AL. (2007a) where this soil is used to calibrate the CropSyst model for Switzerland. The soil texture is characterized with 38% clay, 36% silt, and 26% sand. Based on the texture, CropSyst assesses the hydraulic properties of the soil. Soil depth amounts to 1.5 m and the soil organic matter content is at 2.6% weight in the top soil layer (5 cm) and 2.0% in lower soil layers.

The applied management scenarios are uniform on the simulated crop area and include nitrogen (N) fertilization and irrigation. The amount of N applied per year ranged between 0 and 320 kg ha⁻¹ for corn and between 0 and 360 kg ha⁻¹ for winter wheat. Currently applied amounts of N fertilizer (WALTHER ET AL., 2001) are expanded in the simulation in order to cover potential future N fertilization strategies. For corn (winter wheat), there are three fertilizer applications per year if $N \leq 160$ kg ha⁻¹ ($N \leq 180$ kg ha⁻¹) and four fertilizer applications per year if $N > 160$ kg ha⁻¹ ($N > 180$ kg ha⁻¹), respectively, as shown in Table 2. For higher N amounts, however, an additional application date is introduced between the second and third date. In the simulations, fertilizer application dates are defined relative to the seeding date and derived from DUBOIS ET AL. (1998) and WALTHER ET AL. (2001).

Table 2: Distribution of annual fertilizer amounts

	Distribution of annual fertilizer [kgN ha ⁻¹] to the dates of application	
Corn	up to 160 kg:	1 : 1 : 0 : 2
	up to 320 kg:	1 : 1 : 1 : 2
Winter Wheat	up to 180 kg:	6 : 7 : 0 : 5
	up to 360 kg:	6 : 7 : 5 : 5

To simulate irrigation, we chose the automatic irrigation option of CropSyst. With this option, irrigation is triggered as soon as soil moisture is lower than a specific user-defined value. The degree of soil moisture is expressed as a value between 0 (permanent wilting point) and 1 (field capacity). When soil moisture falls below the previously defined value, water is added to the soil until field capacity is reached. However, there is an upper limit of irrigation water of 20 mm per irrigation event. Irrigation starts one day after seed and ends on the day of

harvest. The simulated experimental framework is equal for each climate scenario. This allows for comparability of results.

For simulations under current climate we use seeding dates provided by DUBOIS ET AL. (1999) and TORRIANI ET AL. (2007a). The temperature increase under the climate change scenarios leads to a shift of the annual temperature pattern and thus to a shift of the period of optimal crop development (TORRIANI ET AL., 2007a). Therefore, seeding dates are placed according to the temperature offset of the climate change scenario (Table 3). Even though seeding dates are placed earlier, CC leads to shorter maturity periods. Thus, shifts in average dates of maturity, which are equal to dates of harvest, are larger than for seeding dates (Table 3).

Table 3: Seeding and average harvesting dates for the applied climate scenarios.

	Climate Scenario	Current climate	2030	2050
Corn	Seeding date	10 th May (130)	7 th May (127)	4 th May (124)
	Average Day of Maturity (Harvest)	17 th September (263)	4 th September (250)	28 th August (240)
Winter Wheat	Seeding date	10 th October (283)	13 th October (286)	16 th October (289)
	Average Day of Maturity (Harvest)	05 th August (217)	27 th July (208)	18 th July (199)

*) Numbers in brackets are days of year.

Source: CropSyst Simulations.

For each location and year one simulation is conducted without application of fertilizer and irrigation. Furthermore, to broaden variability, the amount of fertilizer and the degree of soil moisture that triggers irrigation was varied randomly within the defined range. The datasets contain, depending on the crop and climate scenario, between 527 and 541 observations. A dry matter content of 85% and 90% is assumed for corn and winter wheat yields, respectively.

3 The economic model

Our analysis is based on utility-maximization with expected utility $E(U)$ defined as follows:

$$E(U(\pi)) = \int_0^{\infty} U(\pi) f(\pi) d\pi \quad (1)$$

Where E is the expectation operator and $U(\pi)$ is the utility of quasi-rents π (revenue minus variable costs). The latter is treated as a random variable with density function $f(\pi)$. The stochastic character of quasi-rents can be the result of both stochastic yields and stochastic prices. Input and output prices are assumed to be deterministic in our analysis. Only crop yields are stochastic, with yield variation σ_y . Production and yield variation functions are assumed to be known. Yield variation is therefore treated as risk and not as uncertainty. Risk preferences are incorporated with a preference parameter towards variation of quasi-rents (σ_π). The utility function, which is linear in quasi-rents, is defined as follows (following HAZELL AND NORTON, 1986):

$$U(\pi) = E(\pi) - \gamma \sigma_\pi \quad (2)$$

Where γ is the coefficient of risk aversion (defined as $-(\partial U / \partial \sigma_\pi) / (\partial U / \partial \pi)$) which indicates risk-averse, risk-neutral and risk-taking behavior if $\gamma > 0$, $\gamma = 0$, and $\gamma < 0$, respectively.

An indicator function, I , is used to model farmers' adoption of irrigation farming: $I = 1$ for adoption of an irrigation system and $I = 0$ for crop farming without irrigation. Farmers are

assumed to implement an irrigation system if expected utility minus adoption costs is higher than expected utility of crop farming without application of irrigation. That is, $I=1$ iff $E(U(\pi_{I=1})) - K > E(U(\pi_{I=0}))$, where K are the variable costs of adoption, e.g. the rental costs of the irrigation system. Expected quasi-rent $E(\pi)$ is defined as

$$E(\pi) = pE(y(X)) - ZX - IK \quad (3)$$

Where $y(X)$ denotes the functional relationship, i.e. production function, between output scalar (y) and the vector of inputs (X), p the output price scalar and Z an input price vector. The input vector consist of two inputs: nitrogen (N) and irrigation water (W). The decision on adoption of irrigation farming leads to two types of production functions in this model: one with and one without irrigation, respectively. This distinction is omitted in this section to ensure lucidity. The standard deviation of quasi-rent is defined as:

$$\sigma_\pi = |E((\pi - E(\pi)))| \quad (4)$$

Under assumption of deterministic prices and by rearrangement of (4), the standard deviation of quasi-rent simplifies to $\sigma_\pi = p \sigma_y$. Expected yields (i.e. solutions on the production function) are used to derive yield variation, $\sigma_y(X)$. The latter is defined as the absolute difference between observed yields (i.e. simulated observations) and expected yields (eqn. 5).

$$\sigma_y(X) = |y(X) - E(y(X))| \quad (5)$$

Therefore, the difference between observed and predicted yields for observation i is the absolute residual of the regression analysis, e_i , i.e. $\sigma_{yi}(X_i) = |e_i| = |y_i(X_i) - \hat{y}_i(X_i)|$. Yield variation is determined by weather and soil conditions and input use, $\sigma_y(X) = f(I \cdot W, N)$.

In this model, the intercept captures weather and soil effects on yield variability. Irrigation water is part of yield variation functions only for irrigation farming, i.e. $I = 1$. Substitution of eqn. (3) and (5) in (2) leads to the following final optimization problem:

$$\max_{X, y} E(U(\pi)) = pE(y(X)) - ZX - \gamma p \sigma_y(X) - IK \quad (6)$$

Expected utility (eqn. 6) is maximized subject to the production function constraint $y(X)$. The first order condition for utility maximization is presented in section 6.

4 Estimation methodology and functional forms

The production function, $y = f(X)$, is fitted to a square root functional form (eqn. 7), following FINGER AND HEDIGER (2007).

$$Y = \alpha_0 + \alpha_1 \cdot N^{1/2} + I \cdot \alpha_2 \cdot W^{1/2} + \alpha_3 \cdot N + I \cdot \alpha_4 \cdot W + I \cdot \alpha_5 \cdot (N \cdot W)^{1/2} \quad (7)$$

Y denotes corn yield in kilogram, N the amount of nitrogen applied (kg ha^{-1}), and W irrigation water applied in mm. The α_i 's are parameters that must satisfy the subsequent conditions in order to ensure decreasing marginal productivity of each input factor: $\alpha_1, \alpha_2 > 0$ and $\alpha_3, \alpha_4 < 0$. If $\alpha_5 > 0$, the two input factors are complementary. They are competitive if $\alpha_5 < 0$, while $\alpha_5 = 0$ indicates independence of the two input factors.

The estimation of model parameters is a two step procedure that is described in the following. First step is the estimation of production function coefficients (eqn. 7) using robust regression. These estimates are used to calculate robust regression residuals for the entire

dataset. Subsequently, robust regression residuals are used to estimate yield variation functions in a second step of estimation (eqn. 5).

4.1 Robust Regression and the Production Function

In this study, robust regression is used to estimate the coefficients of production functions (eqn. 7). This estimation technique was found to increase the accuracy of estimation and to expose the true underlying input-output relationship (FINGER AND HEDIGER, 2007).

The main idea of robust regression is to give little weight to outlying observations in order to isolate the true underlying relationship. Outliers are characterized by exceptional yield levels and exceptional input-output relationships, respectively, i.e. they deviate from the relationship described by the majority of the data. The further away an observation is from the true relationship, the smaller is the corresponding weight of contribution to the robust regression analysis. The identification of the true relationship and of outliers, respectively, is a non-trivial challenge, in particular, if the situation exceeds the simple regression case. We use the Reweighted Least Squares (RLS) regression for the robust estimation. RLS is a weighted least squares regression, which is based on an analysis of Least Trimmed Squares regression residuals that gives zero weights to observations identified as outliers (see ROUSSEEUW AND LEROY, 1987 for details). An observation is identified as outlier if the standardized residual exceeds the cutoff value of 2.5 (HUBERT ET AL., 2004).

Extreme yield events, e.g. caused by extreme climatic events such as droughts, negatively affect risk-averse decision makers. Such extreme yield events increase yield variation and lead thus to decreasing levels of utility. The modeling of extreme yield events is inefficient if Ordinary Least Squares (OLS) regression is used for the estimation of coefficients and related residuals. One outlier can be sufficient to move the coefficient estimates arbitrarily far away from the actual underlying values (ROUSSEEUW AND LEROY, 1987, and, HUBERT ET AL., 2004). Thus, analyses based on regression residuals derived by OLS estimation are inefficient and can produce misleading results. In contrast, robust regression and robust regression diagnostics enable efficient estimation in the presence of outliers.

In order to correct for heteroscedasticity, feasible generalized least squares (FGLS) regression is applied. Thus, weights are generated with respect to both, outliers and heteroscedasticity in the final estimation of production functions. The estimation is conducted with the ROBUSTREG and MODEL procedure, respectively, of the SAS statistical package (SAS INSTITUTE, 2004).

4.2 Yield Variation Function

Observations which are identified as outliers are not taken into account for the final estimation of production function coefficients. However, these observations are of particular interest for the estimation of yield variation because they increase yield variation. Therefore, residuals are calculated for the entire dataset, including the observations identified as outliers. The inclusion of outliers in the further analysis is possible if and only if no typing, copying or measuring errors but exceptional climatic events are source of the here identified outliers as proved for the here analyzed datasets by FINGER AND HEDIGER (2007). Residuals are the difference between observed (here: CropSyst simulations) and predicted observations (input-output combinations on the production function), $|e_i| = |Y_i(X_i) - \hat{Y}_i(X_i)|$. Yield variance is, among other factors such as weather and soil, determined by input use. This relationship is modeled using a square root function (eqn. 8) for corn. Irrigation water (W) is only an element of yield variation functions for irrigation farming ($I = 1$).

$$\sigma_y(X) = \beta_0 + I \cdot \beta_1 \cdot W^{0.5} + \beta_2 \cdot N^{0.5} \quad (8)$$

Where β_0 is the yield variation solely determined by weather and soil conditions. β_1 and β_2 quantify the influence of irrigation and nitrogen application on yield variation, i.e. $\beta_i = \partial\sigma_y(X)/\partial X_i^{0.5}$. An input is risk decreasing if $\beta_i < 0$ and risk increasing if $\beta_i > 0$, respectively. For winter wheat, a quadratic specification was found to be most adequate (eqn. 9).

$$\sigma_y(X) = \beta_0 + I \cdot \beta_1 \cdot W + \beta_2 \cdot N^2 + \beta_3 \cdot N \quad (9)$$

Interpretation of coefficients β_0 and β_1 remains as for eqn. 8. However, the influence of nitrogen on yield variation was found to have a quadratic shape for winter wheat, first decreasing, then increasing yield variation (coefficients β_2 and β_3 in eqn. 9).

The yield variation function is estimated using the MODEL procedure of the SAS statistical package and FGLS regression in order to correct for heteroscedasticity. In contrast to other studies, which focus on heteroscedasticity correction (JUST AND POPE, 1979) and take simultaneous equation biases into account (ISIK AND KHANNA, 2003), our estimation approach focuses on efficient estimation in presence of extreme events. Taking into account that such events are more likely to occur along with changing climate (e.g. FUHRER ET AL., 2006), this property is of particular interest.

5 Estimation Results

This section is devoted to the presentation and interpretation of regression analysis results which are input for the economic model. Simulation results of the economic model that are used for final assessment are presented in Section 6.

Coefficient estimates of the corn and winter wheat production functions (eqn. 7) for the assumed climate scenarios are presented in Table 4 and 5, respectively. It shows that coefficient estimates have the correct (i.e. the expected) sign. The intercept, i.e. the base yield where neither nitrogen nor irrigation is applied, shows an increase from the baseline scenario to the 2050 scenario for both crops. This is because of more favourable climatic conditions for crop growth. In particular an increased CO₂ concentration leads to higher yield levels (FUHRER, 2003). Higher yield levels are furthermore the result of applied shifts in seeding days as this is a powerful adaptation option to avoid negative effects of climate change (cp. SOUTHWORTH ET AL., 2002, and, TORRIANI ET AL., 2007a). However, we are aware that current parameterizations of the CO₂ effects as implemented in many crop models such as CropSyst have recently been questioned by LONG ET AL. (2006).

The analysis of base yields, where neither irrigation nor nitrogen fertilization takes place, is purely hypothetical. Both winter wheat and corn farm management without any input use is inexistent in Switzerland. Therefore, conclusions of the impact of climate change on yield levels can be drawn if and only if optimal input levels and according optimal yield levels are calculated in the subsequent section.

Table 4 shows furthermore a constant increase of the interaction parameter $(NW)^{1/2}$ from the baseline to the 2050 scenario for corn. Independency of nitrogen fertilizer and irrigation water in the baseline and 2030 scenario shifts to significant complementary interaction in the 2050 scenario. The interaction is important, as nitrogen is taken up in a water solution (LIU ET AL., 2006). In the first two scenarios, nitrogen uptake is sufficiently ensured by rainfall. In the latter scenario, which is characterized by lower amounts of rainfall (Table 1), optimal nitrogen uptake is only ensured if irrigation takes place. Moreover, nitrogen leaching is reduced if rainfall is substituted by irrigation that never exceeds field capacity as in our CropSyst simulations (not shown). Therefore, climate change is expected to increase the application of nitrogen fertilizer in presence of irrigation but to decrease nitrogen application if no irrigation is available.

Table 4: Coefficient Estimates: Production Function for Corn.

Coefficient	Climate scenario		
	Baseline	2030	2050
Intercept	6601.924 (162.13)**	6972.651 (180.68)**	7053.137 (165.17)**
$N^{1/2}$	313.0936 (16.34)**	347.6081 (19.79)**	309.8714 (16.36)**
$W^{1/2}$	67.1385 (4.17)**	59.65229 (4.69)**	71.58906 (5.50)**
N	-10.544 (8.15)**	-10.9985 (9.38)**	-9.59084 (7.60)**
W	-2.49922 (2.17)*	-0.93264 (1.09)	-1.0195 (1.19)
$(NW)^{1/2}$	0.364377 (0.45)	1.04329 (1.55)	3.522244 (4.92)**
Coefficient of det. (adj.)	0.7330	0.8403	0.8371

*) Note: Statistics in parentheses are t statistics

(**) – indicates significance at the 1% level

(*) – indicates significance at the 5% level

Table 5: Coefficient Estimates: Production Function for Winter Wheat.

Coefficient	Climate scenario		
	Baseline	2030	2050
Intercept	4582.359 (67.37)**	4894.397 (80.81)**	5142.069 (81.35)**
$N^{1/2}$	161.2262 (9.34)**	178.4068 (11.93)**	151.3398 (9.64)**
$W^{1/2}$	25.48017 (1.18)	70.16545 (3.73)**	68.29841 (3.38)**
N	-5.23933 (5.43)**	-5.96726 (7.16)**	-5.18194 (5.90)**
W	-0.85541 (0.56)	-2.93945 (2.19)*	-3.47498 (2.36)*
$(NW)^{1/2}$	0.508462 (0.59)	-0.35761 (0.48)	0.535636 (0.67)
Coefficient of det. (adj.)	0.3877	0.4663	0.3715

However, Table 5 shows that this is not the case for winter wheat. The interaction parameter $(NW)^{1/2}$ is not affected by CC and remains insignificantly low. The different seasonal shifts in rainfall and temperature patterns (Table 1) and different timing of maturity stages (Table 3) lead to this difference between corn and winter wheat. TORRIANI ET AL. (2007a) already pointed out that irrigation will become more important for spring than for winter crops at the Swiss Plateau.

5.1 Input use and yield variation

In Table 6 and 7, final coefficient estimates for the yield variation functions for corn and winter wheat (eqn. 8 and 9) are presented. For both crops, the coefficient β_0 , i.e. yield variation solely determined by weather and soil conditions, decreases from the baseline to the 2030 scenario and increases in the 2050 scenario. If neither irrigation nor nitrogen fertilizer application takes place, yield variation increases from the 2030 to the 2050 scenario.

Table 6: Coefficient Estimates: Yield Variation Function for Corn (Eqn.8).

Coefficient	Climate scenario		
	Baseline	2030	2050
β_0 (Intercept)	409.0276 (14.78)**	381.7547 (18.33)**	468.5082 (19.52)**
β_1 ($N^{0.5}$)	38.98357 (10.78)**	39.2059 (11.82)**	39.81619 (11.26)**
β_2 ($W^{0.5}$)	-8.1252 (2.41)*	-12.7453 (5.32)**	-20.2869 (8.19)**
Coefficient of det. (adj.)	0.1901	0.2441	0.2718

Table 7: Coefficient Estimates: Yield Variation Function for Winter Wheat (Eqn.9).

Coefficient	Climate scenario		
	Baseline	2030	2050
β_0 (Intercept)	789.2329 (23.11)**	680.4995 (22.21)**	728.5457 (23.60)**
β_1 (W)	-0.49937 (1.63)	-0.40804 (1.50)	-0.45408 (1.62)
β_2 (N ²)	0.004154 (2.37)*	0.006181 (3.97)**	0.008927 (5.75)**
β_3 (N)	-2.19199 (3.85)**	-2.50537 (4.97)**	-3.37643 (6.69)**
Coefficient of det. (adj.)	0.0659	0.0548	0.0829

For corn, irrigation causes a decrease ($\beta_2 < 0$) and nitrogen fertilizer causes an increase ($\beta_1 > 0$) in yield variation (Table 6). The property of irrigation to lower corn yield variation ($|\beta_2|$), continuously increases along our climate change scenarios. Higher temperatures and decreased rainfalls make irrigation to a more risk decreasing activity in future. The coefficient β_1 , the property of nitrogen fertilizer to increase yield variation, is nearly constant under different climate conditions (Table 6). There is no impact of climate change on the relationship of yield variation and nitrogen for corn production.

For winter wheat, nitrogen first causes a decrease, than an increase in yield variation (Table 7). Irrigation causes a decrease of the latter. In contrast to results for corn, the relationship between input use and yield variation is not affected of CC for both inputs nitrogen and irrigation (Table 7). However, conclusions on the impact of climate change on the yield variation can be drawn if and only if utility maximizing input levels and according yield variations are calculated in the subsequent section.

6 Optimal Input Use, Yield, Expected Utility, Yield variation and Adoption Rates

Prediction of influence of climate change upon yield, input use and farmers' utility requires modeling of farmers' behavior, i.e. maximization of expected utility (eqn. 6). The derived optimal input levels provide the highest expected utility per hectare. The input price vector W is restricted on variable costs. Therefore, total variable costs ZX consist of variable nitrogen costs (nitrogen applied times nitrogen price) and the variable irrigation costs (irrigation water applied times price of irrigation water). Other costs are assumed constant and thus irrelevant for the profit maximizing input combination. The optimization problem of eqn. (6) leads to the following first order condition:

$$\partial f(x_i^*) / \partial x_i - z_i / p - \gamma \cdot \beta_i = 0 \quad (10)$$

Where z_i denotes the price and x_i^* the optimal level of input i . A risk premium is included in the tangency condition if $\gamma \neq 0$. The risk premium is the product of the coefficient of risk aversion and the influence-coefficient of input i on yield variation, i.e. $\gamma\beta_i$. This is the difference between expected marginal productivity and the ratio of input and output prices at the optimal level of input use. Therefore, the optimal level of factor use for an input that increases (decreases) yield variation is smaller (larger) for a risk-averse than for a risk-neutral agent. Eqn.10 is solved for both irrigation and non-irrigation farming independently.

6.1 Prices and Risk Aversion

Due to market liberalization, Swiss agriculture will face diminishing output-input price ratios in crop production down to levels of, for instance, the European Union (EU). The differences between current Swiss and EU prices are much smaller for inputs such as nitrogen fertilizer than for outputs such as corn and wheat. Price forecasts for the periods of interest in our

analysis, i.e. 2030 to 2050, are impossible. In order to show the sensitivity of adoption processes to both climate and economic variables, we assume three price scenarios for 2030 and 2050: current EU prices (P_{EU}), $1.5 \times P_{EU}$ and $2 \times P_{EU}$. Price assumptions are presented in Table 8 and are documented more detailed in FINGER AND SCHMID (2007).

Table 8: Price Scenarios (in CHF)

Price Scenario	Corn kg ⁻¹	Wheat kg ⁻¹	Nitrogen kg ⁻¹	Irrigation (mm per ha)
Current	0.396	0.57	1.33	0.6
P_{EU}	0.185	0.182	0.91	0.6
$1.5 \times P_{EU}$	0.2775	0.273	0.91	0.6
$2 \times P_{EU}$	0.37	0.364	0.91	0.6

Specifying a parameter towards farmers' risk attitude is crucial for the analysis. Various studies estimated farmers' risk parameter γ with widely differing results (HAZELL AND NORTON, 1986). However, no such case study exists for Swiss farmers. Therefore, we restrict numerical analysis on two cases of constant (i.e. independent from the level of utility) risk aversion: $\gamma = 0.5$ and $\gamma = 1$, respectively.

6.2 Results

There are 3×2 scenarios for each crop (price and risk aversion scenarios). For reasons of lucidity, not all results are presented in detail. For one scenario ($\gamma = 0.5$, P_{EU}) optimal input levels, expected utility, optimal yield levels and optimal yield variation are presented in Table 9 and 10. In these tables, results are presented for both irrigation and non-irrigation farming. Furthermore, differences in input levels, utility, yields and yield variation between irrigation and non-irrigation farming are presented. All results are within the range of the data.

Table 9 shows that the assumed combinations of price and climate change scenarios have only small effects on optimal use of nitrogen fertilizer for corn. In contrast, the optimal amount of applied irrigation water more than doubles from the baseline and the 2030 scenario to the 2050 scenario. Future levels of utility are lower for both climate scenarios mainly due to the decline in output prices. Yield levels increase by up to twenty percent from the baseline to the 2050 scenario for irrigation farming ($I = 1$). In contrast, optimal levels of corn yields decline from the 2030 to the 2050 scenario for non-irrigation farming. Corn yield variation decreases from the baseline to the 2050 scenario for irrigation farming but increases for non-irrigation farming.

For winter wheat (Table 10), optimal amounts of nitrogen and irrigation water are smaller for the future scenarios compared with the baseline scenario mainly because of the reduced output/input price ratio. Both climate change and irrigation farming have only small impacts on yield variation of winter wheat. Therefore, differences between irrigation and non-irrigation farming are much smaller for winter wheat than for corn. In particular the increase of expected yield levels due to irrigation is in maximum 307 kg ha^{-1} for winter wheat (2050 scenario, Table 10) but 1596 kg ha^{-1} for corn (2050 scenario, Table 9).

Table 9: Corn: Optimal input levels, expected utility, yields and yield variation.

Irrigation Indicator Climate Scenario	Nitrogen (kg ha ⁻¹)	Irrigation Water (mm)	Expected Utility per ha	Optimal Yield (kg ha ⁻¹)	Optimal Yield Variation
I=1					
Baseline	114.10	87.48	3286.2	9189	749.4
2030	112.48	85.20	1632.79	9995	679.9
2050	137.93	208.49	1685.66	10788	643.2
I=0					
Baseline	111.5	0	3147.22	8732	820.7
2030	106.16	0	1567.24	9387	785.7
2050	99.84	0	1529.5	9192	866.4
Difference I=1 and I=0					
Baseline	2.6	87.48	138.98	457	-71.3
2030	6.32	85.2	65.55	608	-105.8
2050	38.09	208.49	156.16	1596	-223.2

*) Scenario: $\gamma = 0.5$, P_{EU} . For irrigation ($I = 1$) and non-irrigation farming ($I = 0$).

Table 10: Winter Wheat: Optimal input levels, expected utility, yields, yield variation.

Irrigation Indicator Climate Scenario	Nitrogen (kg ha ⁻¹)	Irrigation Water (mm)	Expected Utility per ha	Optimal Yield (kg ha ⁻¹)	Optimal Yield Variation
I=1					
Baseline	138.59	90.01	3019.59	5976	520.3
2030	75.03	30.87	1007.01	6274	514.7
2050	71.33	30.92	1023.44	6348	519.1
I=0					
Baseline	131.72	0	2934.92	5743	572.6
2030	76.58	0	973.16	5999	524.9
2050	68.93	0	986.67	6041	538.2
Difference I=1 and I=0					
Baseline	6.87	90.01	84.67	233	-52.3
2030	-1.55	30.87	33.85	275	-10.2
2050	2.4	30.92	36.77	307	-19.1

*) Scenario: $\gamma = 0.5$, P_{EU} . For irrigation ($I = 1$) and non-irrigation farming ($I = 0$).

Adoption of irrigation farming is triggered by utility differences between irrigation and non-irrigation farming in our model. For both crops, utility differences $E(U(\pi_{I=1})) - E(U(\pi_{I=0}))$ decrease from the baseline to the 2030 scenario due to the decline of output prices (Table 9 and 10). In contrast to winter wheat, this difference increases for corn in the 2050 scenario. Even though the output price is lower, CC leads to a higher profitability of irrigation in corn farming.

Results of the other scenarios can be summarized as follows. Higher output prices lead, in general, to higher input use, higher yield levels, lower yield variation and higher levels of utility. Furthermore, this leads to larger utility differences between irrigation and non-irrigation farming for both crops. That is, an increase of output prices increases the profitability of irrigation farming. The increase of the coefficient of risk aversion from 0.5 to 1.0 leads to lower amounts of nitrogen for corn, but higher optimal nitrogen use for winter wheat. This leads furthermore to an increase of the optimal amount of irrigation water and the profitability of irrigation farming. Yield variation decreases for both crops if risk aversion increases. The effect of changes in risk aversion on yield levels is ambiguous.

6.3 Adoption of Irrigation Farming

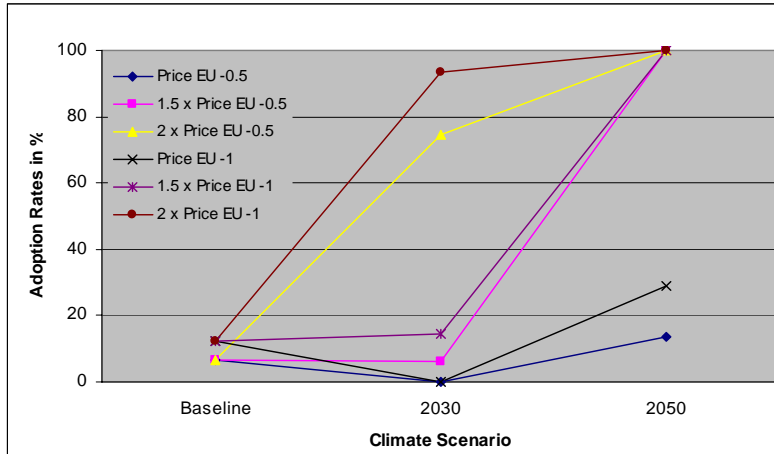
Farmers' are assumed to adopt irrigation farming, $I=1$, if and only if $E(U(\pi_{I=1})) - K > E(U(\pi_{I=0}))$, where K denotes the variable adoption costs for e.g. renting of equipment. Adoption costs are modeled stochastically to reflect heterogeneous adoption costs for farmers due to, for example, differences in farm size, access to irrigation water and infrastructure endowments (KULSHRESHTHA AND BROWN, 1993). 100000 draws are made from a normal distribution $N(200,40)$. This results in simulated costs that range between 20 and 385 with an interquartile range between 173 and 226. Even though this distribution of costs is not representative, it avoids corner solutions compared with a single value for adoption costs. Thus, this approach is more suitable to highlight the sensitivity of the model. Comparability between the scenarios is ensured by applying equal distribution of costs for each scenario.

Every simulated observation adopts irrigation farming if the utility difference between irrigation and non-irrigation farming (see Table 9 and 10) is larger than the simulated costs:

The simulated adoption rates never exceed one percent for winter wheat. Irrespective of the price and risk aversion scenarios, the assumed CC scenarios lead not to adoption of irrigation farming in winter wheat production because of shifts in maturity stages (Table 3) and only small reductions of relevant spring rainfall in the applied climate change scenarios (Table 1). This is consistent with the results of TORRIANI ET AL. (2007a) that show only marginal benefits of irrigation in winter wheat farming.

In contrast, the baseline adoption rate for corn is 6.5 % ($\gamma = 0.5$) and 12.3% ($\gamma = 1$), respectively. As shown in Figure 1, the future adoption rates are mainly determined by future prices and future risk aversion of farmers. In general, higher prices and higher risk aversion lead to higher adoption rates. As a consequence, all farmers switch to irrigation (corn) farming in 2050 for the 1.5 x P_{EU} and 2 x P_{EU} scenarios. Assuming P_{EU} , however, the highest adoption rate is 29% for the 2050 scenario with $\gamma = 1$. That is, even in 2050 the adoption of irrigation farming will be relatively small if Swiss farmers' face current EU prices.

Figure 1: Adoption Rates of Irrigation Farming for Corn.



*) Note: Price EU -1 denotes the P_{EU} , $\gamma = 1$ scenario.

To obtain final results, the adoption rates are combined with the results for input use, yield level, yield variation and utility. For instance, the final result for optimal yields (Y^*) is calculated as follows: $Y^* = adoption\ rate \cdot Y^*(I = 1) + (1 - adoption\ rate) \cdot Y^*(I = 0)$. In order

to derive utility for farmers that adopt irrigation farming, the average costs of the adopters in the simulated sample are subtracted from the expected utility (e.g. in Table 9).

Final model results for yield levels, yield variation, coefficients of variation, nitrogen use and utility of quasi-rents are shown in Figure 2 and 3. It shows that both yield levels and utility of quasi-rents are less affected by levels of risk aversion than by output prices. That is, differences between risk aversion scenarios for a single price scenario are smaller than vice versa. In contrast, nitrogen use and yield variation are clearly affected by both risk aversion and output prices.

Figure 2 shows increasing yields and decreasing yield variation for future corn and winter wheat production. Even though corn yield variation increases for two scenarios ($\gamma = 0.5$, P_{EU} in 2050; and; $\gamma = 0.5$, $1.5 \times P_{EU}$ in 2030, Figure 2), the coefficients of variation, i.e. the ratio of yield variation and yield level, for all scenarios are unambiguously decreasing (Figure 2). Figure 2 further shows that an increase of both risk aversion and output prices leads to a decrease of the coefficient of variation for corn and winter wheat, respectively.

The optimal amount of applied nitrogen for winter wheat decreases mainly due to output price reductions (Figure 3). Increasing output prices lead, however, to increasing optimal amounts of applied nitrogen. In contrast, the latter increases up to 250 kg ha^{-1} for corn in the 2050, $\gamma = 0.5$, $2 \times P_{EU}$ scenario. High adoption rates of irrigation farming (Figure 1) and the positive interaction between nitrogen use and irrigation in the 2050 scenario (Table 4) lead to this strong increase of nitrogen use. Utility of quasi-rents for winter wheat depends on output prices but not climate change as shown in Figure 3. Neither adoption of irrigation farming nor changes in production intensity are profitable (i.e. used) adaptation strategies to CC in winter wheat farming. In contrast, for high corn prices the adaptation possibility of adoption of irrigation farming enables even increasing utility levels for climate change scenarios (Figure 3).

Figure 2: Final Model Estimates for Yield, Yield Variation and Coefficient of Variation for Corn and Winter Wheat.

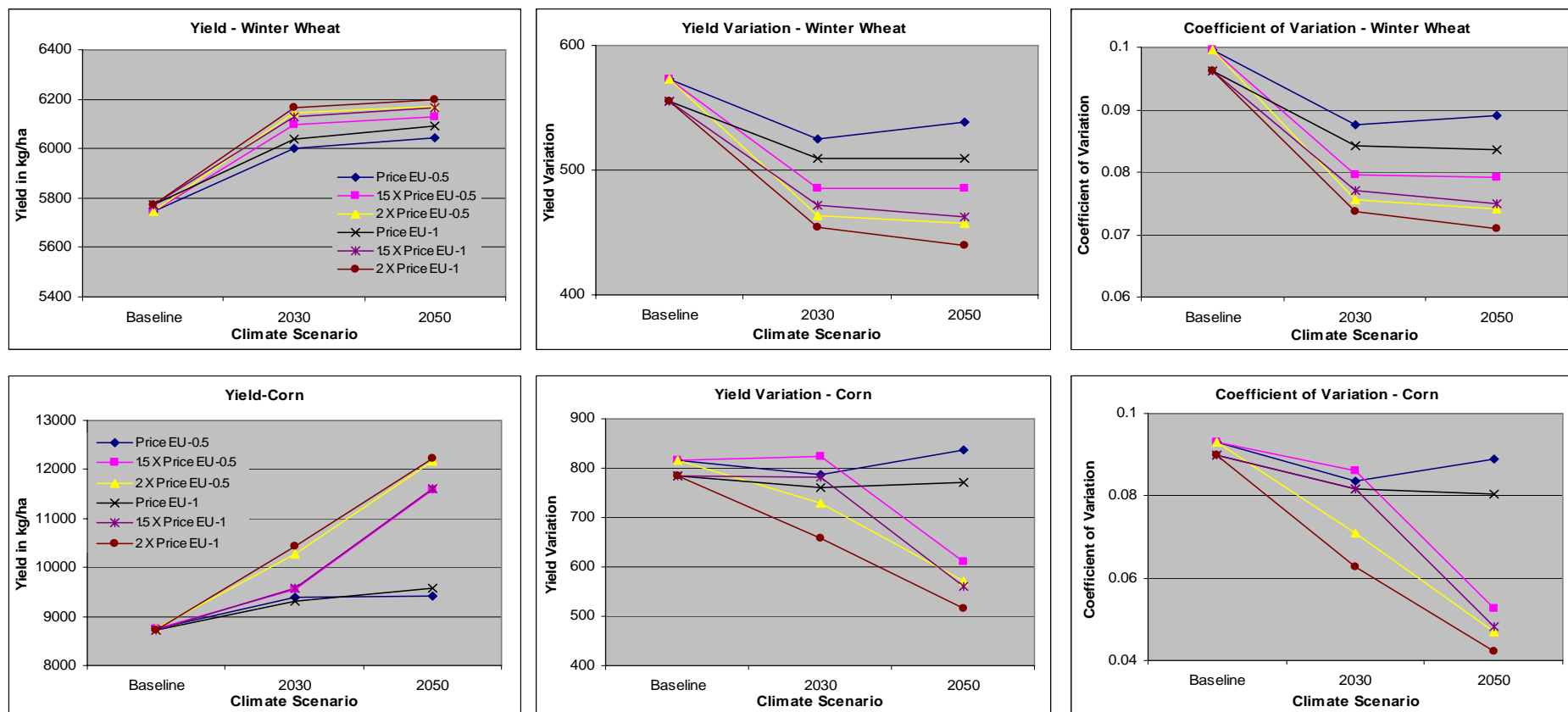
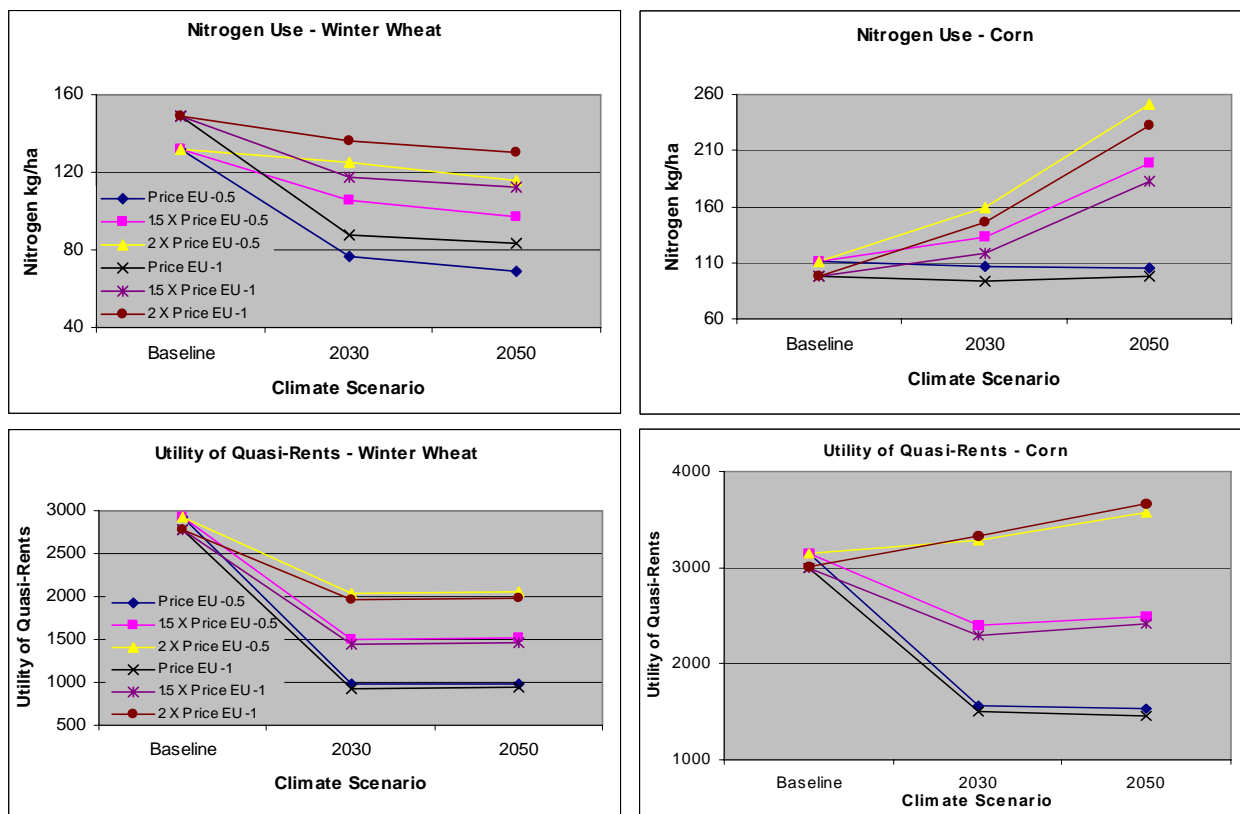


Figure 3: Final Model Estimates for Nitrogen Use and Utility of Quasi-Rents for Corn and Winter Wheat.



7 Discussion and Conclusions

Approaches of earlier studies that analyzed the impact of climate change on crop production were not able to incorporate both future climate-plant interactions and adaptation measures simultaneously. To overcome this drawback, we use a modeling approach that combines predicted climate-plant relationships (crop simulation modeling) and an economic model that focuses on strategic adaptation.

We found beneficial effects of climate change if adaptation measures such as changes in seeding dates, changes in production intensity and implementation of irrigation systems are taken into account. For the time horizon considered in this analysis (2030-2050) we found corn and winter wheat yields to increase above current levels. FLÜCKIGER AND RIEDER (1997) projected decreasing corn and increasing winter wheat yields in Switzerland using a regression modeling approach. For winter wheat this is consistent with our analysis because the adaptation options considered in our study do not significantly change the impact of climate change on winter wheat production. The difference for corn yield projections is due to adaptation measures that are taken into account in our analysis but are not considered in FLÜCKIGER AND RIEDER (1997).

Yield variation of corn is projected to increase but decrease for winter wheat in the analysis of TORRIANI ET AL. (2007a). The latter result is consistent with our findings. The increase of corn yield variation contrasts our results because in particular changes in production intensity are not taken into account in TORRIANI ET AL. (2007a). However, it has to be taken into consideration that the applied climate change scenarios in FLÜCKIGER AND RIEDER (1997), TORRIANI ET AL. (2007a) and our analysis are different.

Altogether, higher and less variable yields projected from our analysis lead to a decrease of the coefficient of variation for future corn and winter wheat production at the Swiss Plateau. We chose numerical examples of constant risk aversion. However, several studies (see SERRA ET AL., 2006) point out decreasing instead of constant risk aversion of farmers. That is, risk aversion of farmers increases with decreasing utility. All but one of the scenarios assumed in our study leads to lower utility levels in future. Thus, farmers are expected to be more risk averse in future than currently. An increase of risk aversion causes lower coefficients of variation. Therefore, even higher reductions in the coefficients of variation for corn and winter wheat are expected than indicated by our study.

In order to validate the here presented results, further soil types and further CC scenarios should be considered. Further climate change scenarios should emphasize the altitude of future extreme climatic events such as droughts. The here applied estimation procedure for model parameters, using robust regression, is in particular suitable for the incorporation of such extreme climatic events.

In conclusion, our approach of modeling impacts of climate change on crop production and production risk is valuable for further research, because it enables the simultaneous analysis of climate change, price and risk aversion scenarios. It can be extended with further adaptation measures. Our case study shows that simple adaptation measures such as changes in seeding dates, changes in production intensity and adoption of irrigation farming are sufficient to generate positive effects of climate change for corn and winter wheat production at the Swiss Plateau. Taken into account that further adaptation measures such as breeding and financial instruments such as weather derivatives were found to be valuable adaptation strategies for Swiss crop production (TORRIANI ET AL. (2007a,b), the latter will take advantage of climate change.

References

- ANTLE, J.M. AND CAPALBO, S.M. (2001): Econometric-Process Models for Integrated Assessment of Agricultural Production Systems. *American Journal of Agricultural Economics* 83: 389-401.
- CHRISTENSEN, J. H., CARTER, T. AND GIORGI, F. (2002): PRUDENCE employs new methods to assess European climate change. *Eos Trans. AGU* 83: 147.
- CIAIS, P., REICHSTEIN, M., VIOVY, N., GRANIER, A., OGEE, J., ALLARD, V., AUBINET, M., BUCHMANN, N., BERNHOFER, C., CARRARA, A., CHEVALLIER, F., DE NOBLET, N., FRIEND, A. D., FRIEDLINGSTEIN, P., GRUNWALD, T., HEINESCH, B., KERONEN, P., KNOHL, A., KRINNER, G., LOUSTAU, D., MANCA, G., MATTEUCCI, G., MIGLIETTA, F., OURCIVAL, J.M., PAPALE, D., PILEGAARD, K., RAMBAL, S., SEUFERT, G., SOUSSANA, J.F., SANZ, M.J., SCHULZE, E.D., VERSALA, T. AND VALENTINI, R. (2005): Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature* 437: 529 - 533.
- DONATELLI, M., STÖCKLE, C. O., CEOTTO, E. AND RINALDI, M. (1997): CropSyst validation for cropping systems at two locations of northern and southern Italy. *European Journal of Agronomy* 6: 35-45.
- DUBOIS, D., ZIHLMANN, U. AND FRIED, P. M. (1999): Burgrain: Erträge und Wirtschaftlichkeit dreier Anbausysteme. *Agrarforschung* 6: 169-172.
- DUBOIS, D., SCHERRER, C., GUNST, L., JOSSI, W. AND STAUFFER, W. (1998): Effect of different farming systems on the weed seed bank in the long-term trials Chaiblen and DOK. *Journal of Plant Diseases and Protection, Special Issue XVI*: 67-74.
- FINGER, R. AND HEDIGER, W. (2007): The application of robust regression to a production function comparison – the example of Swiss corn. Paper accepted for presentation at the 7th International ESEE conference ‘Integrating Natural and Social Sciences for Sustainability’, Leipzig, Germany, June 5-8, 2007.
- FINGER, R. AND SCHMID, S. (2007): The Impact of Climate Change on Mean and Variability of Swiss Corn Production. Paper presented at the “Workshop for Resource and Environmental Economics” ETH Zürich, 26 - 27.02. 2007. In http://www.cer.ethz.ch/resec/research/workshops/Nachwuchsworkshop/Finger_Paper.pdf (31.05.2007).
- FLÜCKIGER, S. AND RIEDER, P. (1997): Klimaänderung und Landwirtschaft. VDF Hochschulverlag, Zürich.
- FUHRER, J. (2003): Agroecosystem responses to combinations of elevated CO₂, ozone and global climate change. *Agriculture, Ecosystems and Environment* 97: 1-20.
- FUHRER, J., BENISTON, M., FISCHLIN, A., FREI, C., GOYETTE, S., JASPER, K. AND PFISTER, C. (2006): Climate risks and their impact on agriculture and forests in Switzerland. *Climatic Change* 79: 79-102.
- HAZELL, P. B. AND NORTON, R. (1986): Mathematical Programming for Economic Analysis in Agriculture. Macmillan Publishing Company, New York.
- HUBERT, M., ROUSSEUW, P. J. AND VAN AELST, S., 2004. Robustness. In: Sundt, B. and Teugels, J. (Eds.): *Encyclopedia of Actuarial Sciences*, New York Wiley & Sons: 1515-1529.
- HUNGATE, B.A., DUKES, J.S., SHAW, M.R., LUO, Y. AND FIELD, C.B. (2003): Nitrogen and Climate Change. *Science* 302: 1512-1513.
- IEEP (2000): The Environmental Impacts of Irrigation in the European Union. Institute for European Environmental Policy (IEEP), London.

- IPCC (2000): Special Report on Emission Scenarios. A special report of Working Group III for the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
- ISIK, M. AND KHANNA, M. (2003): Stochastic Technology, Risk Preferences, and Adoption of Site-Specific Technologies. *American Journal of Agricultural Economics* 85: 305-317.
- ISIK, M. AND DEVADOSS, S. (2006): An analysis of the impact of climate change on crop yields and yield variability. *Applied Economics* 38: 835-844.
- JUST, R. E. AND POPE, R. (1979): Production Function Estimation and Related Risk Considerations. *American Journal of Agricultural Economics* 61: 276-284.
- KHANNA, M., ISIK, M. AND WINTER-NELSON, A. (2000): Investment in site-specific crop management under uncertainty: implications for nitrogen pollution control and environmental policy. In: *Agricultural Economics* 24: 9-21.
- KULSHRESHTHA, S. N. AND BROWN, W. J. (1993): Role of farmers' attitudes in adoption of irrigation in Saskatchewan. *Irrigation and Drainage Systems* 7: 85-98.
- LIU, Y., SWINTON, S. M. AND MILLER, N. R. (2006): Is site-specific yield response consistent over time? Does it pay? *American Journal of Agricultural Economics* 88: 471-483.
- LONG, S. P., AINSWORTH, E. A., LEAKEY, A. D. B., NÖSBERGER, J. AND ORT, D. R. (2006): Food for Thought: Lower-Than- Expected Crop Yield Stimulation with Rising CO₂ Concentrations. *Science* 312: 1918-1921.
- MEARNS, L. O., ROSENZWEIG, C. AND GOLDBERG, R. (1996): The effect of changes in daily and interannual climatic variability on CERES-Wheat: A sensitivity study. *Climatic Change* 32: 257-292.
- OCCC (2005): Die Klimazukunft der Schweiz - Eine probabilistische Projektion. Organe consultatif sur les changements climatiques, OcCC (Swiss Advisory Body on Climate Change), Berne.
- RISBEY, J., KANDLIKAR, M., DOWLATABADI, H. AND GRAETZ, D. (1999): Scale, Context, and Decision Making in Agricultural Adaptation to Climate Variability and Change. *Mitigation and Adaptation Strategies for Global Change* 4: 137-165.
- ROUSSEEUW, P. J. AND LEROY, A. M. (1987): Robust regression and outlier detection. Wiley & Sons, New York.
- SAS INSTITUTE, 2004. SAS/STAT 9.1 User's Guide. SAS Institute Inc., Cary, NC.
- SCHRÖTER, D., CRAMER, W., LEEMANS, R., PRENTICE, C. I., ARAÚJO, M. B., ARNELL, N. W., BONDEAU, A., BUGMANN, H., CARTER, T. R., GRACIA, C. A., DE LA VEGA-LEINERT, A. C., ERHARD, M., EWERT, F., M., G., HOUSE, J. I., KANKAANPÄÄ, S., KLEIN, R. J. T., LAVOREL, S., LINDNER, M., METZGER, M. J., MEYER, J., MITCHELL, T. D., REGINSTER, I., ROUNSEVELL, M., SABATÉ, S., SITCH, S., SMITH, B., SMITH, J., SMITH, P., SYKES, M. T., THONICKE, K., THUILLER, W., TUCKER, G., ZAEHLE, S. AND ZIERL, B. (2005): Ecosystem service supply and vulnerability to global change in Europe. *Science* 310: 1333-1337.
- SEMOV, M. A., BROOKS, R. J., BARROW, E. M. AND RICHARDSON, C. W. (1998): Comparison of the WGEN and LASR-WG stochastic weather generators for diverse climates. *Climate Research* 10: 95-107.
- SERRA, T., ZILBERMAN, D., GOODWIN, B.K. AND FEATHERSTONE, A. (2006): Effects of decoupling on the mean and variability of output. *European Review of Agricultural Economics* 33: 269-288.
- SOUTHWORTH, J., PFEIFER, R.A., HABECK, M., RANDOLPH, J.C., DOERING, O.C. AND GANDADHAR, R.D. (2002): Sensitivity of winter wheat yields in the Midwestern United

- States to future changes in climate, climate variability, and CO₂ fertilization. *Climate Research* 22: 73-86.
- STÖCKLE, C. O., DONATELLI, M. AND NELSON, R. (2003): CropSyst, a cropping systems simulation model. *European Journal of Agronomy* 18: 289-307.
- TORRIANI, D., CALANCA, P., SCHMID, S., BENISTON, M. AND FUHRER, J. (2007a): Potential effects of changes in mean climate and climate variability on the yield of winter and spring crops in Switzerland. *Climate Research*: in press.
- TORRIANI, D., CALANCA, P., BENISTON, M. AND FUHRER, J. (2007b): Alternative Hedging Strategies in Maize Production to Cope with Climate Variability and Change. Paper accepted for presentation at the 101st EAAE Seminar 'Management of Climate Risks in Agriculture', Berlin, Germany, July 5-6, 2007.
- TUBIELLO, F. N., DONATELLI, M., ROSENZWEIG, C. AND STÖCKLE, C. O. (2000): Effects of climate change and elevated CO₂ on cropping systems: model predictions at two Italian locations. *European Journal of Agronomy* 13: 179-189.
- WALTHER, U., RYSER, J.P. AND FLISCH R. (eds.) (2001): Grundlagen für die Düngung im Acker- und Futterbau (GRUDAF). *Agrarforschung* 8: 1-80.

Modelling Nutrient Management in Tropical Cropping Systems

Editors: **R.J. Delve and M.E. Probert**



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Preface

In tropical regions, organic materials are often more important than fertilisers in maintaining soil fertility, yet fertiliser recommendations and most crop models are unable to take account of the level and quality of organic inputs that farmers use.

Computer simulation models, such as the Agricultural Production Systems Simulator (APSIM) developed by CSIRO and the Queensland Department of Primary Industries, have proven their value in many cropping environments. These proceedings report the results of an ACIAR-supported project to test and improve the capability of APSIM to predict the decomposition of various organic inputs, the dynamics of nitrogen and phosphorus in soil, and crop yields. They document the achievements of the project and show the benefits of linking laboratory, field and modelling studies.

Another activity of the project was to train and support national collaborators in East and southern Africa in the use of APSIM for integrated, nutrient-management practices.

The project was implemented through the Soil, Water and Nutrient Management Consortium (SWNM) of the Consultative Group on International Agricultural Research (CGIAR). Project partners came from a number of institutions with an interest in simulation modelling and nitrogen and phosphorus dynamics.

As a result of this project, the APSIM computer model has been enhanced in several areas and tested against long-term data sets. The information gained will be widely used by researchers and extension services in the tropics.



Peter Core
Director
ACIAR

1

Introduction

R.J. Delve* and M.E. Probert†

These proceedings derive from the end-of-project meeting of the ACIAR-funded project 'Integrated nutrient management in tropical cropping systems: improved capabilities in modelling and recommendations' (Project no. LWR2/1999/003). The meeting was held in Nairobi, Kenya in January 2003. The project was managed by the Tropical Soil Biology and Fertility Institute for the Soil, Water, and Nutrient Management consortium of the Consultative Group on International Agricultural Research (CGIAR), in collaboration with CSIRO Sustainable Ecosystems/Agricultural Production Systems Research Unit (APSRU).

Smallholder farmers in the tropics rely to a large extent on organic inputs and biological processes for managing soil fertility. Biologically based farming systems range from annual cropping and fallow rotations involving biologically fixed nitrogen, to intensive continuous cropping with additions of manures and/or composts, that may be augmented with inorganic fertilisers. There has been considerable advance in the past decade in understanding the role of organic materials in soil-nutrient availability and maintenance of soil organic matter. Models that can simulate nutrient release patterns according to the resource quality, soil conditions, and climate would provide a means of making initial recommendations for testing with farmers according to their resource availability and soil management practices. Currently, crop and ecosystem models do not include appropriate routines

for simulating nitrogen dynamics following incorporation of organic inputs of the diverse nature found in tropical cropping systems.

Another major gap in soil fertility recommendations for the tropics is that of phosphorus management. Crop production on many of the soils in the tropics is limited primarily by phosphorus. Our understanding of soil phosphorus dynamics and indicators of phosphorus availability lags far behind that for nitrogen. Part of the problem in modelling phosphorus is in its complex biogeochemical cycle. To date, no crop or ecosystems model has adequately captured phosphorus dynamics for estimating crop (or ecosystem) production. Considerable data have been gathered on phosphorus dynamics and soil phosphorus fractions in relation to plant productivity from a variety of soil types and management conditions in the tropics. As well as being crucial for improving understanding of P in the soil-plant system and P management, the data can be used for developing phosphorus routines of crop and ecosystem production models.

The APSIM modelling framework (Keating et al. 2003; web site <www.apsim.info>) was selected for this project because it is one of the most appropriate models for use in tropical soil and crop management. This model provides not only the short time-step essential for simulating effects of management on nutrient availability and crop growth, but also incorporates longer-term effects of changes in soil organic matter content on N mineralisation and hence on crop growth. Selection of APSIM was also based on efforts by APSRU towards developing modules to describe the release of nutrients (N and P) from added organic inputs (APSIM 'Manure'), the dynamics of phosphorus in soil (APSIM 'SoilP'), and routines within the 'Maize' crop module to limit

* Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture, PO Box 6247, Kampala, Uganda <r.delve@cgiar.org>.

† CSIRO Sustainable Ecosystems, 306 Carmody Road, St Lucia, Queensland 4067, Australia <merv.probert@csiro.au>.

growth due to inadequate supply of P in addition to nitrogen and water constraints. These modules provided a framework necessary for simulating the effects of diverse organic inputs on cropping systems found in tropical regions. Once a model has been tested and verified for a particular purpose, in this case the combined use of organic and inorganic nutrient sources, it can be a valuable tool in focusing research and ultimately for making recommendations for crop and soil management.

Project partners came from a range of institutions with an interest in simulation modelling and N and P dynamics. These partners were:

Kenya

- International Centre for Research in Agro-Forestry (ICRAF)
- International Livestock Research Institute (ILRI)
- Kenya Agricultural Research Institute (KARI)
- Tropical Soil Biology and Fertility (TSBF) Institute

Zimbabwe

- International Maize and Wheat Improvement Center (CIMMYT)
- International Crop Research Institute for the Semi-arid Tropics (ICRISAT)
- TSBF – Southern Africa Soil Fertility Network

Colombia

- International Center for Tropical Agriculture (CIAT)
- Colombian Corporation of Farming Investigation (CORPOICA)

Southeast Asia

- International Board for Soil Research and Management (IBSRAM), with national partners

Project Planning and Operations

The purpose of the project was to develop a modelling capability that can be applied to farming systems where both organic and inorganic sources of nutrients are used. In tropical regions, organic materials are often more important for maintenance of soil fertility than fertilisers, yet current fertiliser recommendations and most crop models are unable to take account of the organic inputs and the different qualities of these organic inputs that farmers use. This project tested and, where necessary, improved the APSIM Manure and SoilP modules so that they can

be applied to the management of soil fertility, especially in low-input systems in the tropics.

A project implementation workshop in 1999 brought together 25 participants with experience in the management of organic inputs and phosphorus dynamics in soil. At the workshop, decisions were made on the nature of the data sets needed to test the model and where new data were to be collected so that they are compatible with inputs required by APSIM.

During the project, meetings were held in Nairobi to familiarise collaborators with APSIM, train them in APSIM use, and to compile data sets for testing and evaluating the Manure and SoilP modules. Any code changes required within APSIM were done in Australia by APSRU, and modified versions of the modules were tested in subsequent workshops. Outside of these formal workshops, modelling support was provided in East and southern Africa, as well as in Asia, to continue developing the data sets, modelling work and support to APSIM users.

Project Objectives

The project objectives were:

- to collate and synthesise data from existing trials compatible with the requirements of APSIM for testing and modification of the manure and phosphorus modules
- to strengthen the capability of APSIM to predict nutrient availability and subsequent crop growth following the addition of organic and inorganic nitrogen and phosphorus nutrient sources
- to train and support national collaborators in East and southern Africa in the use of APSIM for integrated nutrient management practices.

Project Outcomes

These proceedings document the achievements of the project and show the benefits from linking laboratory, field and modelling studies. Resource-poor farmers face difficult decisions over the use of scarce nutrient sources in production systems. Efforts are required to expand our knowledge of the biophysical aspects of alternative uses of organic nutrient sources and also the socioeconomic driving forces behind farmers' decision-making (Chapter 2.1). Often the decisions on the use of organic resources are taken without an assessment or appreciation of the impact

of alternative uses on plant production and on soil and water resources. While existing simulation models are able to simulate responses of crops to, for example, inorganic fertiliser additions, there are still gaps in our ability to simulate short and long-term effects of additions of different organic N and organic and inorganic P resources (Chapter 2.2). A deeper understanding from the farmers' perspective of the comparative values and usefulness of manures and other locally available resources is required in order to increase the production and efficiency of their production systems and to be able to target improved management options using participatory approaches (Chapter 2.3).

Consideration of the influence of organic resource quality on nutrient management and nutrient release dynamics, introduced in Chapter 2.1, is expanded in Section 3. These chapters cover different analytical techniques for measuring resource quality, and relate the resource quality factors to the mineralisation of nitrogen. It is the understanding that comes from such studies that needs to be represented in the models, with the indicators that can be measured being used to parameterise the models.

Simulation models were not able to mimic the complex pattern of N release that has been reported for some animal manures, notably materials that exhibit initial immobilisation of N even when the C:N of the material suggests it should mineralise N. The APSIM SoilN module was tested against existing data sets and modified so that the three pools that constitute added organic matter could be specified in terms of both the fraction of carbon in each pool and also their C:N ratios; previously it has been assumed that all pools have the same C:N ratio (Chapter 4.1). The revised Manure module is better able to simulate the general patterns on N mineralisation that have been reported for different quality manures (Chapters 4.1 and 4.2). Attempting to simulate P mineralisation from organic sources in a manner analogous to that done for N results in the P concentration required for net mineralisation being much higher than found experimentally. It is suggested that this arises because much of the P is water soluble. It is expected that specifying the C:P ratio of each pool will overcome this anomaly.

The APSIM Maize module was enhanced so that uptake of P was determined by the availability of P in the soil, the P in the plant was partitioned between the plant components, and crop growth was influenced by the P status of the plant (Chapter 4.3). This

'P-aware' maize module was a major breakthrough in our thinking of how to explicitly reflect P dynamics, and especially P limitations in crop simulations. Further fieldwork has been initiated using funds from other donors to produce the data required to parameterise other crop modules, specifically cowpea and millet (in West Africa, funded by IFDC), pigeonpea, groundnut and sorghum (in India, funded by the UK Department for International Development) and canola (in Australia funded by CSIRO and the Grains Research and Development Corporation).

In this project the SoilP, Manure and Maize modules have been tested against three long-term data sets from western Kenya (Chapter 4.4), central Kenya (Chapter 4.5) and India (Chapter 4.6).

Conclusions

The APSIM model now includes a capability to simulate the N and P dynamics from different quality manures and their effects on crop growth. There is only one other modelling group that is working on soil P routines and limiting simulated plant growth as a consequence of a P constraint (Daroub et al. 2003).

This project has contributed to the improvement and validation of the APSIM Manure and SoilP modules. The organic resource quality parameters and methods for measuring them that have been identified through this project provide more relevant and streamlined data collection protocols for model parameterisation. Ultimately, the project outputs will contribute to improving the capacity to make recommendations to farmers on better management of nitrogen and phosphorus nutrient sources for crop production.

The improved management of soil fertility needs to be evaluated from economic, social, and environmental perspectives. From the economic sense, combinations of organic and inorganic nutrient sources need to be identified that increase and maintain crop production. This evaluation should include differences in both the short and longer-term benefits. From the social and economic sense, organic resources identified can substitute for mineral fertilisers in areas where fertilisers are not available or affordable. From an environmental aspect, management practices could be identified that would result in smaller losses of nutrients and would rebuild or maintain the soil resource base.

The modified model and protocols resulting from this research are applicable to researchers and extension services in the tropics. At the national levels, the teams trained in the use of the model could provide guidelines and recommendations for both researchers and extension services on the types of organic inputs, and their appropriate combinations with mineral fertilisers, that should provide the best short and long-term effects. Such recommendations could be used for designing long-term experiments for verifying model predictions or directly for achieving impact on-farm.

References

- Daroub, S.H., Gerakis, A., Ritchie, J.T., Friesen, D.K. and Ryan, J. 2003. Development of a soil–plant phosphorus model for calcareous and weathered tropical soils. *Agricultural Systems*, 76, 1157–1181.
- Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy*, 18, 267–288.

2

Invited Papers

2.1

The Multiple Roles of Organic Resources in Implementing Integrated Soil Fertility Management Strategies

Bernard Vanlauwe and Nteranya Sanginga*

Abstract

The Tropical Soil Biology and Fertility (TSBF) Institute, its African Network (AfNet), and various other organisations, have adopted ‘integrated soil fertility management’ (ISFM) as the paradigm for tropical soil fertility management research and development. The development of ISFM is the result of a series of paradigm shifts generated through experience in the field and changes in the overall socioeconomic and political environment faced by the various stakeholders, including farmers and researchers. The first part of the paper illustrates these shifts and outlines how the science of organic matter management has developed in the framework of the various paradigms. The second part focuses on the technical backbone of ISFM strategies, by illustrating the roles of organic resources, mineral fertiliser and soil organic matter in providing soil-related goods and services. Special attention is given to the potential occurrence of positive interactions between these three factors, leading to added benefits in terms of greater crop yield, improved soil fertility status, and/or reduced losses of C and nutrients to the environment. The third section aims at confronting the principles and mechanisms for soil fertility management, highlighted in the second section, with reality, and focuses on the impact of other realms of capital on soil management opportunities and the potential of decision aids to translate all knowledge and information in a format accessible to the various stakeholders.

During the past four decades, the paradigms underlying soil fertility management research and development efforts have undergone substantial evolution to respond to changes in the overall social, economic, and political environment the various stakeholders are facing and the experiences gained by researchers.

During the 1960s and 1970s, an ‘external input’ paradigm was driving the research and development agenda. The appropriate use of external inputs, e.g. fertilisers, lime, or irrigation water, was believed to be sufficient to alleviate any constraint to crop production. Following this paradigm together with the use of improved cereal germplasm, the green revolu-

tion boosted agricultural production in Asia and Latin America in ways not seen before. However, for a variety of reasons, application of the green revolution strategy in sub-Saharan Africa (SSA) resulted in only minor achievements (IITA 1992). This, together with environmental degradation resulting from massive applications of fertilisers and pesticides in Asia and Latin-America between the mid-1980s and early-1990s (Theng 1991), and the abolition of the fertiliser subsidies in SSA (Smaling 1993), imposed by structural adjustment programs, led to a renewed interest in organic resources in the early 1980s following an ‘organic input’ paradigm. The balance shifted from mineral inputs only to low mineral input sustainable agriculture (LEISA) in which organic resources were believed to enable sustainable agricultural production. After a number of years of

* Soil Biology and Fertility Institute of CIAT, PO Box 30677, Nairobi, Kenya <b.vanlauwe@cgiar.org> and <n.sanginga@cgiar.org>.

investment in research activities evaluating the potential of LEISA technologies, such as alley cropping or live-mulch systems, several constraints were identified both at the technical (e.g. lack of sufficient organic resources; lack of sufficient short-term yield increases) and the socioeconomic level (e.g. labour-intensive technologies).

In this context, Sanchez (1994) formulated the 'second paradigm' for tropical soil fertility research: 'Rely more on biological processes by adapting germplasm to adverse soil conditions, enhancing soil biological activity and optimising nutrient cycling to minimise external inputs and maximise the efficiency of their use'. This paradigm did recognise the need for both mineral and organic inputs to sustain crop production, and emphasised the need for all inputs to be used efficiently. This advice was driven by (i) the lack of a sufficient amount of either mineral or organic inputs, (ii) the recognition that both inputs fulfil a set of different functions, and (iii) the potential for creating added benefits when applying organic resources in combination with fertilisers. The second paradigm also highlighted the need for improved germplasm; in earlier studies more emphasis was put on the nutrient supply side without worrying too much about the demand for these nutrients. Optimal synchrony or use efficiency requires both supply and demand to function optimally.

From the mid-1980s to the mid-1990s, the shift in paradigm towards the combined use of organic and mineral inputs was accompanied by a shift in approaches towards involvement of the various stakeholders in the research and development process, mainly driven by the 'participatory' movement (Swift et al. 1994). One of the important lessons learnt was that the farmers' decision-making process was not merely driven by the soil and climate but by a whole set of factors cutting across the biophysical, socioeconomic, and political domain. The 'sustainable livelihoods approach' (DFID 2000) recognises the existence of five realms of capital (natural, manufactured, financial, human and social) that constitute the livelihoods of farmers. It was also recognised that natural capital, such as soil, water, atmosphere, or biota does not only create services which generate goods with a market value (e.g. crops and livestock) but also services which generate amenities essential for the maintenance of life (e.g. clean air and water). Due to the wide array of services provided by natural capital, different stakeholders may have conflicting interests in natural capital. The 'integrated natural

resource management' (INRM) research approach aims at developing interventions that take all the above into account (Izac 2000). The 'integrated soil fertility management' (ISFM) paradigm, which forms an integral part of the INRM research approach with a focus on appropriate management of the soil resource, is currently adopted in the soil fertility research and development community. Although technically ISFM follows the second paradigm (Sanchez 1994), it goes further in explicitly recognising the important role of the social, cultural, and economic processes regulating soil fertility management strategies. ISFM is also broader than 'integrated nutrient management' (INM) as it recognises the need for an appropriate physical and chemical environment for plants to grow optimally, besides a sufficient and timely supply of available nutrients.

The Science of Organic Matter Management Following Shifts in Soil Fertility Management Paradigms

The conceptualisation of the role of organic resources in tropical soil fertility management has evolved alongside the changes in the guiding paradigms. In the context of the external input paradigm, organic resources were given little attention and were certainly not felt essential for sustainable crop production (Table 1). Confirming this paradigm, Sanchez (1976) stated that, when mechanisation is feasible and fertilisers are available at reasonable cost, there is no reason to consider the maintenance of soil organic matter (SOM) as a major management goal.

Although organic inputs had not been new to tropical agriculture, the first seminal synthesis on organic matter management and decomposition was not written until 1979 (Swift et al. 1979). Between 1984 and 1986, a set of hypotheses was formulated based on two broad themes, 'synchrony' and 'SOM' (Swift, 1984, 1985, 1986) building on the concepts and principles formulated in 1979. Under the first theme, the O(rganisms)–P(hysical environment)–Q(uality) framework for organic matter (OM) decomposition and nutrient release (Swift et al. 1979), formulated earlier, was elaborated and translated into hypotheses driving management options to improve nutrient acquisition and crop growth. Under the second theme, the role of OM in the formation of functional SOM fractions was stressed. It is also interesting to note that, during this period,

organic resources were seen mainly as sources of nutrients, and more specifically N (Table 1). During the 1990s, the formulation of the research hypotheses relating to residue quality and N-release led to a vast amount of projects aiming at validation of these hypotheses, both within TSBF and other research groups dealing with tropical soil fertility. This information has been instrumental in permitting proper evaluation of the sustainability and efficiency of systems based on the organic input paradigm.

Table 1. The changing role of organic resources in tropical soil fertility management.

Period	Soil fertility management paradigm	Role of organic resources
1960s	External input paradigm	Organic matter plays a minor role
1980s	Biological management of soil fertility; LISA	Organic matter is a source of nutrients
1996	Second paradigm – combined application of organic resources and mineral fertiliser	Organic matter fulfils other important roles besides supplying nutrients
Now	Integrated soil fertility management	Organic matter management has social, economic, and political dimensions

A significant part of the work dealing with organic resource management aimed at fine-tuning procedures for organic resource quality determination. Short-term N availability from organic resources was

initially related mainly to their C:N ratio. Efforts to fine-tune organic resource quality assessments were derived from feed-quality assessments, traditionally used in the field of animal science. Examples are the determination of the fibre components of organic resources in terms of hemicellulose, cellulose, and lignin following various modification of the Van Soest fractionation scheme (Van Soest 1963; Van Soest and Wine 1968). Soluble polyphenols (King and Heath 1967) also became standard indicators of organic resource quality, as these appeared to strongly affect the short-term release of mineral N, mainly from leguminous organic resources that commonly have a rather high N content (e.g. Palm and Sanchez 1991). Further work indicated that soluble polyphenols are also very diverse (Harborne 1997) and react differently with proteins in organic resources. The protein-binding capacity, also originating from animal science, was found to be more sensitive in predicting mineral N release than the total soluble polyphenol content (Handayanto et al. 1997). Recently, spectroscopic approaches are being validated for their potential to determine organic resource quality (Shepherd et al. 2004).

Two major events further accentuated the relevance of decomposition processes to tropical soil fertility management. Firstly, a workshop held in 1995, on the theme ‘Plant litter quality and decomposition’, resulted in a book summarising the state of the art in the topic (Cadisch and Giller 1997). Secondly, TSBF, in collaboration with its national partners and Wye College, developed the ‘organic resource database’ (ORD) and related decision-support system (DSS) for OM management (Fig. 1; Palm et al. 2001). ORD contains information on organic resource quality

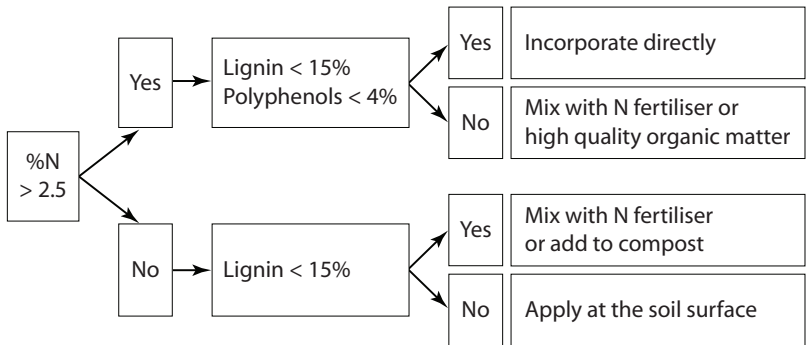


Figure 1. The decision-support system for organic matter management. Source: Palm et al. (2001).

parameters including macronutrient, lignin and polyphenol contents of fresh leaves, litter, stems and/or roots from almost 300 species found in tropical agro-ecosystems. Careful analysis of the information contained in the ORD led to the development of the DSS, which makes practical recommendations for appropriate use of organic materials, based on their N, polyphenol, and lignin contents resulting in four categories of materials (Fig. 1). Recently, a farmer-friendly version of the DSS has been developed by Giller (2000).

The DSS recognises the need for certain organic resources to be applied together with mineral inputs, consistent with the second paradigm. Organic resources are seen as inputs complementary to mineral fertilisers, and their potential role has consequently been broadened from a short-term source of N to a wide array of benefits both in the short and long term (Table 1; Vanlauwe et al. 2002a). The potential for positive interactions is treated in more detail below.

Finally, the ISFM paradigm has also led to increased emphasis on the social, economic, and policy dimensions of organic input management (TSBF 2002).

The Technical Backbone of ISFM: Optimal Management of Organic Resources, Mineral Inputs, and the Soil Organic Matter Pool

Optimal management of the soil resource for provision of goods and services requires the optimal management of organic resources, mineral inputs, and the SOM pool (Fig. 2). Each of these resources contributes to the provision of goods and services individually, but, more interestingly, these various resources can be hypothesised to interact and generate added benefits in terms of extra crop yield, an improved soil fertility status, and/or reduced losses of nutrients.

Impact of individual factors on the provision of goods and services

Numerous studies have looked at crop responses to applied fertiliser in SSA and have reported substantial increases in crop yield. Results from the FAO Fertilizer Program have shown an average increase in maize grain production of 750 kg ha⁻¹ in response to medium NPK applications (FAO 1989). Value-to-cost

ratios (VCR) varied between 1.1 and 8.9, and were usually above the required minimum ratio of 2. National fertiliser recommendations exist for most countries, but actual application rates are nearly always much lower, and in many cases zero, due to socioeconomic constraints rather than technical ones. For a variety of reasons, fertilisers are expensive in SSA; for example, prices were \$7.5 per 50 kg bag of urea in Germany versus \$13–17 per 50 kg bag in Nigeria in 1999 (S. Schulz, pers. comm., 2000). This is further aggravated by the lack of credit schemes to purchase these inputs, as there is often a large interval between fertiliser purchase and revenue collection from selling harvested products. Mineral inputs have relatively little potential to enhance the SOM status, which is central to the provision of many soil-based ecosystem services (Vanlauwe et al. 2001a). In the case of N fertiliser, they may even contaminate (ground)water resources when not used efficiently. The production of N fertiliser itself requires a substantial amount of energy, usually derived from fossil fuels, and contributes to the CO₂ load of the atmosphere.

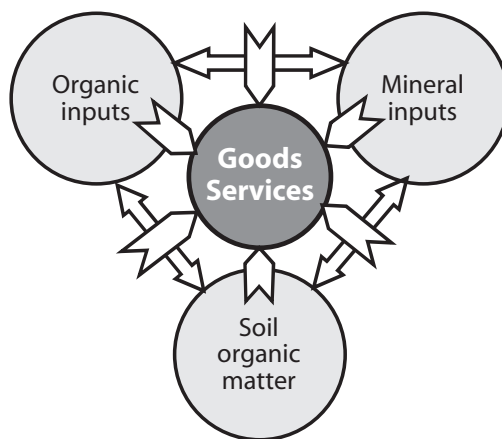


Figure 2. The goods and environmental services generated by the soil are the result of the management of organic resources, mineral inputs, and the soil organic matter pool, and the interactions between these various factors.

In cropping systems with sole inputs of organic resources, short-term data reveal a wide range of increases in maize grain yield compared with the control systems without inputs (Fig. 3). Although yields on fields with a low soil fertility status (e.g.

with control yields below 1000 kg ha⁻¹), can easily be increased up to 140% after incorporation of a source of OM in the cropping system, this would lead to absolute yields hardly exceeding 1500 kg ha⁻¹ (Fig. 3). With higher soil fertility status, the maximum increases observed were proportionally lower, falling to virtually nil at control grain yields of about 3000 kg ha⁻¹. Thus, in most cropping systems, absolute yield increases in the OM-based treatments are far below 1000 kg ha⁻¹, while significant investments in labour and land are needed to produce and manage the OM. This is partly related to the low N use efficiency of OM (Vanlauwe and Sanginga 1995; Cadisch and Giller 1997). Other problems are low and/or imbalanced nutrient content, unfavourable quality, or high labour demand for transporting bulky materials (Palm et al. 1997).

Although most of the organic resources show limited increases in crop growth, they do increase the soil organic C status (Vanlauwe et al. 2001a) and have a potentially positive impact on the environmental service functions of the soil resource. Soil

organic matter is not only a major regulator of various processes underlying the supply of nutrients and the creation of a favourable environment for plant growth, but also regulates various processes governing the creation of soil-based environmental services such as buffering the atmospheric CO₂ loads or favouring water infiltration in the soil through a better soil structure (Fig. 4).

Potential interactions between the various factors on the provision of goods and services

The second paradigm initiated a substantial effort to evaluate the impact of combined applications of organic resources and mineral inputs, as positive interactions between both inputs could potentially result in added benefits (Fig. 5). Two hypotheses that could form the basis for the occurrence of such benefits were formulated by Vanlauwe et al. (2001a): The “direct hypothesis” postulated that: ‘Temporary immobilisation of applied fertiliser N may improve the synchrony between the supply of and demand for

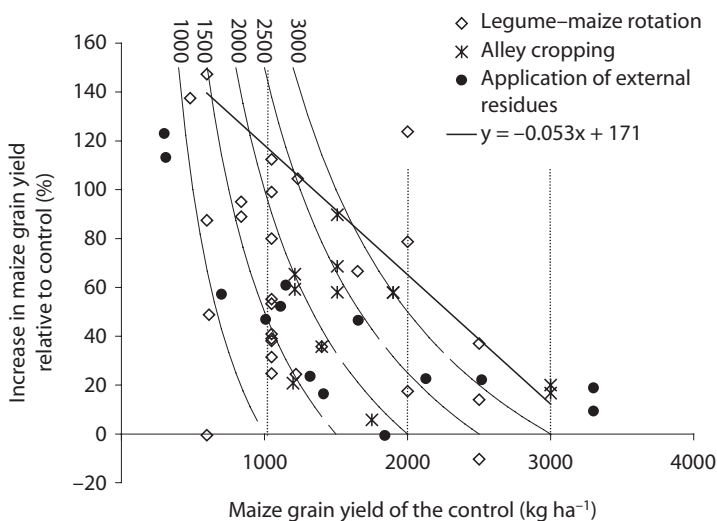


Figure 3. Increase in maize grain yield relative to the control in cropping systems based on organic matter management (legume-maize rotation, alley cropping, systems with application of external organic matter) without inputs of fertiliser N as influenced by the initial soil fertility status, expressed as yield in the control plots. The linear regression line shows the estimated maximal increases in grain yield. The curved lines show the absolute yields in the treatments receiving organic matter (in kg ha⁻¹). Source: Vanlauwe et al. (2001a).

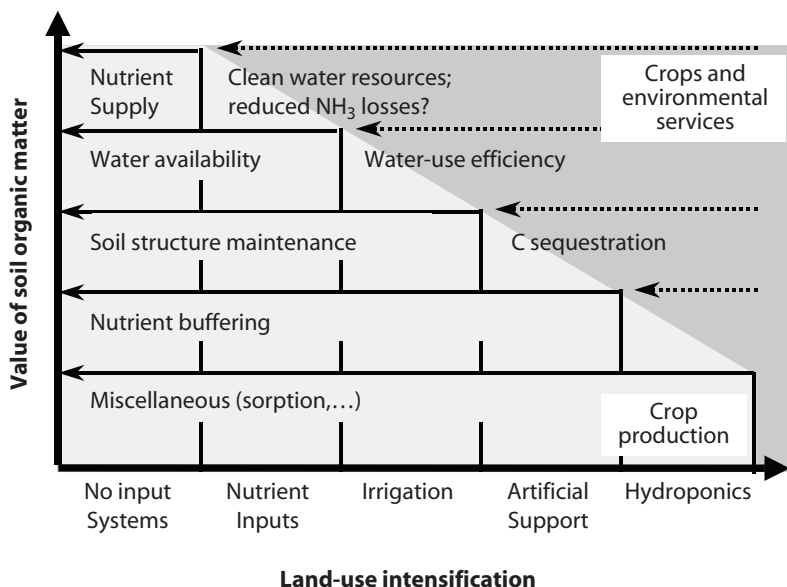


Figure 4. From the crop production point of view, the relevance of soil organic matter (SOM) in regulating soil fertility decreases (plain horizontal arrows) as natural capital is being replaced by manufactured or financial capital with increasing land-use intensification. From an integrated soil fertility management point of view, that also considers environmental service functions besides crop production functions, one could argue that the relevance of SOM does not decrease (dashed horizontal arrows).

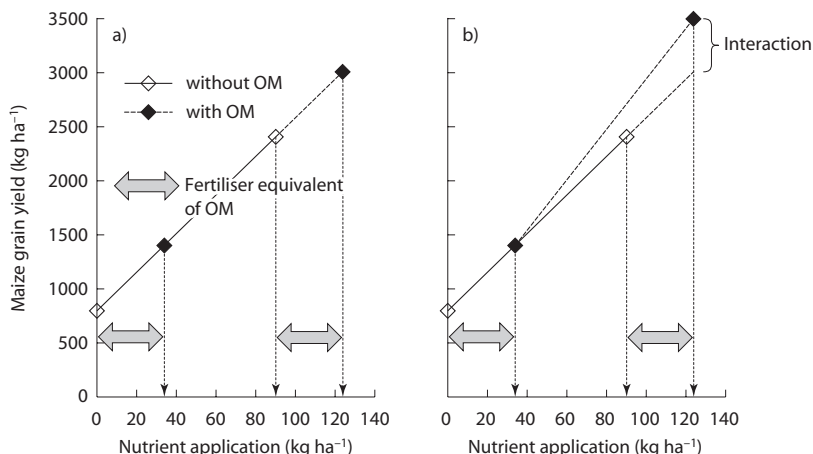


Figure 5. Theoretical response of maize grain yield to the application of a certain nutrient as fertiliser in the presence or absence of organic matter. The interaction effect is indicated on the graph. It is assumed that the applied nutrient rates belong to the linear range of the response curve. Source: Vanlauwe et al. (2001a).

N and reduce losses to the environment'. The 'indirect hypothesis' was formulated for N supplied as fertiliser and proposed that: 'Any organic matter-related improvement in soil conditions affecting plant growth (except N) may lead to better plant growth and consequently enhanced efficiency of the applied N'. The indirect hypothesis recognises that organic resources can have multiple benefits besides the short-term supply of available N. Such benefits could be an improved soil P status by reducing the soil P sorption capacity, improved soil moisture conditions, less pest and disease pressure in legume–cereal rotations, or other mechanisms. Both hypotheses predict an enhancement in N-use efficiency: processes following the direct hypothesis through improvement of the N supply and processes following the indirect hypothesis through an increase in the demand for N. Obviously, mechanisms supporting both hypotheses may occur simultaneously.

Testing the direct hypothesis with ^{15}N labelled fertiliser, Vanlauwe et al. (2002b) concluded that direct interactions between OM and fertiliser-N exist not just in the laboratory but also under field conditions. The importance of residue quality and ways in which organic inputs are incorporated into soil to the magnitude of these interactions was also demonstrated. In a multi-locational trial with external inputs of organic matter, Vanlauwe et al. (2001b) observed added benefits from the combined treatments at two of the four sites, which experienced serious moisture stress during the early phases of grain filling. The positive interaction in these two sites was attributed to the reduced moisture stress in the 'mixed' treatments compared to the sole urea treatments because of the presence of organic materials (surface and subsurface placed) and constitutes evidence for the occurrence of mechanisms supporting the indirect hypothesis. Although more examples supporting the indirect hypothesis can be found in literature, it is clear that a wide range of mechanisms could lead to an improved use efficiency of applied external inputs. These mechanisms may also be site-specific, e.g. an improvement in soil moisture conditions is of little relevance in the humid forest zone. Unravelling these, where feasible, as a function of easily quantifiable soil characteristics, is a major challenge and needs to be done in order to optimise the efficiency of external inputs. On the other hand, when applying organic resources and mineral fertiliser simultaneously, one hardly ever observes negative interactions, indicating that even without clearly

understanding the mechanisms underlying positive interactions, applying organic resources in combination with mineral inputs stands as an appropriate fertility management principle.

Because SOM affects a series of factors supporting plant growth, and because of the observed within-farm variability in soil fertility and SOM status, interest has recently developed in relating the use efficiency of mineral N inputs to the SOM status. A set of hypotheses follows the general principles behind the indirect hypothesis outlined above and results in positive relationships between SOM content and fertiliser use efficiency. On the other hand, SOM also releases available N that may be better synchronised with the demand for N by the plant than is fertiliser N, and consequently a larger SOM pool may result in lower fertiliser N use efficiencies. A preliminary investigation, carried out in a long-term alley cropping trial, showed a negative correlation between the proportion of maize N derived from the applied fertiliser and the topsoil organic C content and supports the latter hypothesis (B. Vanlauwe et al., unpublished data). Other reports show higher use efficiency of N fertiliser (H. Breman, pers. comm.) and P fertiliser (A. Bationo, pers. comm.) for homestead fields with a higher SOM content.

Finally, application of organic resources is the easiest way to increase SOM. Although it is only possible in the medium to long term to induce substantial changes in soil organic C content in experimental trials using realistic organic matter application rates, the sometimes large differences in SOM found between fields within one farm prove that farmers are already managing the SOM status. While residue quality has been shown to significantly affect the short-term decomposition/mineralisation dynamics (Palm et al. 2001), it is unclear whether quality is still an important modifier of the long-term decomposition dynamics. Several hypotheses have been formulated, most of them postulating that slowly decomposing, low-quality organic inputs with relatively high lignin and polyphenol content will have a more pronounced effect on the SOM pool than rapidly decomposing, high-quality organic inputs (Fig. 1). The 'C stabilisation potential' could be an equivalent index to the N fertiliser equivalency index used to describe the short-term N release dynamics. The few trials that have shown significant increases in SOM have used farmyard manure as organic input, which may be related to the presence of resistant C in

the manure, as the available C is digested while passing through the digestive track of the animal.

From Theory to Practice: Implementation of ISFM Practices at the Farm Level

Having focused on the principles and technical issues underlying the ISFM research agenda, these need to be put into the wider context this paper began with. This section looks at ISFM options from the farmer perspective and considers ways to disseminate these options to the various stakeholders.

Production of organic matter in existing cropping systems: the bottleneck in implementing ISFM practices

Although there is a wide range of potential niches to produce organic resources within existing cropping systems (Table 2), introducing an organic matter production phase in a cropping system creates prob-

lems with adaptability and adoptability of such technologies, especially if this fallow production phase does not yield any commercial product, such as grain or fodder. Although a significant amount of organic matter can potentially be produced in cropping systems with in situ organic matter production, adoption of such cropping systems by the farmer community is low and often driven by other than soil-fertility regeneration arguments. Dual-purpose grain legumes, on the other hand, have a large proportion of their N derived from biological N fixation, a low N harvest index, and produce a substantial amount of both grain and biomass, and thus have a great potential to become part of such cropping systems (Sanginga et al. 2001). Additional advantages to the substantial amount of N fixation from the atmosphere associated with growing high biomass producing legumes in rotation with cereal include potential improvement of the soil available P status through rhizosphere processes operating near the root-zone of the legume crop (Lyasse et al. 2002), reduction in pest and disease pressure by e.g. *Striga* spp., and improved soil physical properties. These processes

Table 2. Place and time of production of organic matter (fallow species) relative to crop growth and the respective advantages/disadvantages of the organic matter production systems with respect to soil fertility management and crop growth. ‘Same place’ and ‘same time’ mean ‘in the same place as the crop’ and ‘during crop growth’. Source: adapted from Vanlauwe et al. (2001a).

Place and time of organic matter production – example of farming system	Advantages	Disadvantages
Same place, same time – alley cropping	<ul style="list-style-type: none"> – ‘Safety-net’ hypothesis (complementary rooting depths) – Possible direct transfer from N₂ fixed by legume species 	<ul style="list-style-type: none"> – Potential competition between crop and fallow species – Reduction of available crop land
Same place, different time – crop residues – legume–cereal rotation – improved tree fallows – manure, derived from livestock fed from residues collected from same field	<ul style="list-style-type: none"> – ‘Rotation’ effects (N transfer, improvement of soil P status...) – Potential inclusion of ‘dual purpose’ legumes – In-situ recycling of less mobile nutrients – No competition between fallow species and crops 	<ul style="list-style-type: none"> – Land out of crop production for a certain period – Decomposition of organic matter may start before crop growth (potential losses of mobile nutrients, e.g. N, K...) – Extra labour needed to move organic matter (manure)
Different place – cut-and-carry systems – household waste – animal manure, not originating from same field	<ul style="list-style-type: none"> – Utilisation of land/nutrients otherwise not used – No competition between fallow species and crops 	<ul style="list-style-type: none"> – Extra labour needed to move organic matter – No recycling of nutrients on crop land – Need for access to extra land – Manure and household waste often have low quality

yield benefits to a cereal crop beyond available N but are often translated into N fertiliser equivalency values. Obviously, values greater than 100% should be expected sometimes.

In cut-and carry systems, which involve the transfer of nutrients from one area to another, it is necessary to determine how long soils can sustain vegetation removal before collapsing, especially soils which are relatively poor and where vegetative production can be rapid. Cut-and-carry systems without use of external inputs may be a 'stay of execution' rather than a sustainable form of soil fertility management. Of further importance is the vegetation succession that will occur after vegetative removal. It is possible that undesirable species could take over the cut-and-carry field once it is no longer able to sustain removal of the vegetation of the selected species. Where an intentionally planted species is used, the natural fallow species needs to be compared to determine what advantage, if any, is being derived from the extra effort to establish and maintain the planted species.

Soil fertility gradients

There is a substantial amount of evidence that the soil fertility status of the various fields within a farm can be quite variable, often leading to gradients in which soil fertility decreases as one moves away from the household (Table 3). These gradients are commonly caused by long-term, site-specific soil management by the farmer, and have a considerable influence on crop yield (Fig. 6). Most soil fertility research has been targeted at the plot level, but decisions are made at the farm level, taking into account the production potential of all plots. In Western Kenya, for example, farmers will preferably grow sweet potato on the most degraded fields, while bananas and cocoyam occupy the most fertile fields (Tittonell 2003). As such variations in soil fertility status are likely to affect the use efficiency of mineral

inputs (see above), the potential growth of legumes, and other important processes regulating ISFM options, it is important to take such gradients into account when formulating recommendations for ISFM. One important condition of such recommendations, however, is that these should be related to local classification systems for soil fertility evaluation, as smallholder farmers are unlikely to analyse their soils before deciding on their management. The existence of different fields with varying soil fertility status at the farm level is also likely to determine which are the optimal spatial and temporal niches within a farm to produce organic resources.

Beyond the soil: links with other realms of capital

So far, this paper has focused mainly on the management of natural capital, with some inclusion of manufactured capital in the form of mineral inputs. However, as stated above, farmers' livelihoods consist of various realms of capital, all of which contribute to their decision-making about soil fertility management. One obvious factor affecting the way farmers manage their soils is related to their wealth in terms of access to other realms of capital, such as cash, labour, or knowledge. Rommelse (2001) reported that, in villages in Western Kenya, relatively wealthy farmers spend US\$102 on farm inputs per year compared with US\$5 for relatively poor farmers. Besides having an overall impact on the means to invest in soil fertility replenishment, farmers' wealth also affects the strategies preferred to address soil fertility decline. In two districts in western Kenya, Place et al. (2002) observed that wealthy farmers not only use mineral fertilisers more than do poor farmers, but also use a wider range of soil management practices. Farmer production objectives, which depend on a whole set of biophysical, social, cultural, and economic factors, also take into account the fertility gradients existing within their farm boundaries.

Table 3. Soil fertility status of various fields within a farm in Burkina Faso. Home gardens are near the homestead, bush fields furthest away from the homestead and village fields at intermediate distances. Source: Prudencio et al. (1993).

Field	Organic C (g kg ⁻¹)	Total N (g kg ⁻¹)	Available P (mg kg ⁻¹)	Exchangeable K (mmol kg ⁻¹)
Home garden	11–22	0.9–1.8	20–220	4.0–24
Village field	5–10	0.5–0.9	13–16	4.1–11
Bush field	2–5	0.2–0.5	5–16	0.6–1

Finally, farmers are not the only stakeholders benefiting from proper land management. As stated earlier soils provide and regulate a series of important ecosystem services that affect every living organism and society as a whole, and maintaining those ecosystem service functions may be equally or more vital than maintaining the crop production functions. Unfortunately, little information is available on the potential trade-offs between the use of land for different ecosystem service functions, on the most appropriate way to create a dialogue between the various stakeholders benefiting from a healthy soil fertility status, and on the role policy needs to assume to resolve above questions. The INRM research approach is aiming at creating a basis for such trade-off analysis and stakeholder dialogue.

Putting it all together: user-friendly decision aids for ISFM

After having obtained relevant information as described above, two extra steps may be required to complete the development of a user-friendly decision aid: (i) all the above information needs to be synthesised in a quantitative framework, and (ii) that framework needs to be translated into a format accessible to the end users. The level of accuracy of such a quantitative framework is an important point to consider.

The generation of a set of rules of thumb is likely to be more feasible than software-based aids that generate predictive information for a large set of environments, although both tools are needed as they serve different purposes. The level of complexity is another essential point to take into consideration. For instance, if variation between fields within one farm is large and affects ISFM practices, then this may justify having this factor included in decision aids. Other aspects that will influence the way information and knowledge is condensed into a workable package are: (i) the targeted end user community, (ii) the level of specificity required by the decisions to be supported, and (iii) level of understanding generated about the technologies targeted. Van Noordwijk et al. (2001) prefer the term ‘negotiation support systems’ to avoid any connotation that the ‘decision support systems’ has the authority to make decisions that will then be imposed on the various stakeholders. In an INRM context, it is recognised that different stakeholders may have conflicting interests about certain specific soil management strategies, and that a certain level of negotiation may be required. Whatever the terminology, it should be clear that any single ‘decision’ aid is only one source of the wide range of information required by farmers to make their decisions.

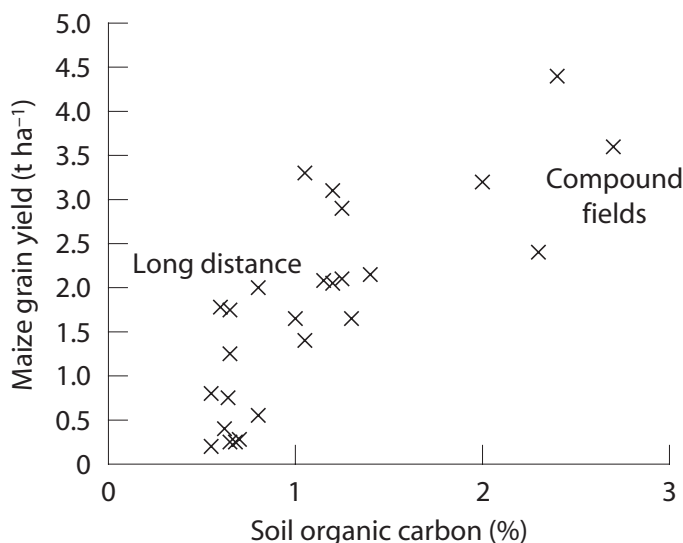


Figure 6. Relationship between the soil organic carbon content and maize grain yield for a set of fields varying in distance from a homestead in northern Nigeria. Source: Carsky et al. (1998).

In particular, the final format of the decision aid should take into account the realities in the field. Some of these realities are: (i) large-scale soil analyses are not feasible, so local soil quality indicators need to be included in decision aids, as farmers use these to appreciate existing soil fertility gradients within a farm; (ii) conditions within farms vary as does the availability of organic resources and fertiliser, therefore rules of thumb rather than detailed quantitative recommendations would be more useful to convey the message to farmers; (iii) farmers decision-making processes involve more than just soil and crop management; and (iv) access to computers, software and even electricity is limited at the farm level, necessitating hard-copy-based products.

Looking Ahead: the Future of the Science of Organic Resource Management

The following conclusions can be drawn from the material presented in this paper:

- (i) The perceived role for the contribution of organic resources in tropical soil fertility management has changed considerably over the years. Currently, organic resources are valued at a par with mineral inputs, as it is recognised that both inputs play essential but different roles in maintaining or improving soil fertility.
- (ii) ISFM involves the management of three sources of nutrients: soil-derived, organic- resource-derived, and fertiliser-derived. Interactions occur between these, and managing individual inputs and their interactions is an essential component of the ISFM research and development agenda.
- (iii) Organic resources are often not sufficiently available at the farm level. Improved germplasm of commonly grown crops that addresses various constraints to higher yields, is a valid entry point for targeting soil fertility depletion. Germplasm that generates multiple benefits is likely to be adopted more easily and potentially tackles several constraints simultaneously.
- (iv) There are no panaceas or solutions that will be optimal everywhere all the time. There is considerable variability between fields within a farm and between farmers within a community (e.g. different access to resources). Therefore, it is very important to identify the appropriate niches for specific ISFM

interventions. Such niches will have not only biophysical, but also economic and social dimensions.

- (v) Any recommendations for ISFM need to have a local soil knowledge basis, as this is the knowledge farmers are using to decide on the management of the resources (labour, fertiliser, organic resources etc.) available to them.

Future legume research and development could emphasise the following:

- (i) A considerable amount of information is available on ISFM interventions. There is an urgent need to synthesise this information to increase the impact of use and avoid duplication of effort. Syntheses should take the form both of databases and predictive models.
- (ii) The role of markets in creating added capital at the farm level is essential. ISFM options will have a greater chance of being adopted if they provide extra resources (labour, improved use efficiency of inputs etc.) to the farmer.
- (iii) It is essential to identify biophysical, social, and economic niches at the farm scale to introduce organic resource production options, as, under most conditions, organic resources are in short supply. Special attention should be given to multipurpose options.
- (iv) Much emphasis is often placed on maintaining the SOM. It remains a big question at what level SOM is needed to maintain the crop production and ecosystem service roles of SOM. To increase SOM usually involves a lot of investment in labour and land and, consequently, efforts to determine such threshold levels are essential. The role of organic resource quality in such endeavours should receive the attention it needs.
- (v) Further exploration of the detail and value of local knowledge systems and how these correlate to formal knowledge is essential in disseminating ISFM interventions.

References

- Cadisch, G. and Giller, K.E. 1997. Driven by nature: plant litter quality and decomposition. Wallingford, UK, CAB International.
- Carsky, R.J., Jagtap, S., Tian, G., Sanginga, N. and Vanlauwe, B. 1998. Maintenance of soil organic matter and N supply in the moist savannah zone of West Africa. In: Lal, R., ed., Soil quality and agricultural sustainability. Chelsea, Michigan, USA, Ann Arbor Press, 223–236.

- DFID (Department for International Development) 2000. Sustainable livelihoods guidance sheets. London, UK, DFID.
- FAO (Food and Agriculture Organization of the United Nations) 1989. Fertilizers and food production. The FAO Fertilizer Programme 1961–1986. Rome, Italy, FAO.
- Giller, K.E. 2000. Translating science into action for agricultural development in the tropics: an example from decomposition studies. *Applied Soil Ecology*, 14, 1–3.
- Handayanto, E., Cadisch, G. and Giller, K.E. 1997. Regulating N mineralization from plant residues by manipulation of quality. In: Cadisch, G. and Giller, K.E., ed., *Driven by nature: plant litter quality and decomposition*. Wallingford, UK, CAB International 175–185.
- Harborne, J.B. 1997. Role of phenolic secondary metabolites in plants and their degradation in nature. In: Cadisch, G. and Giller, K.E., ed., *Driven by nature: plant litter quality and decomposition*. Wallingford, UK, CAB International, 67–74.
- IITA (International Institute of Tropical Agriculture) 1992. Sustainable food production in sub-Saharan Africa: 1. IITA's contributions. Ibadan, Nigeria, IITA.
- Izac, A.-M.N. 2000. What paradigm for linking poverty alleviation to natural resources management? Proceedings of an international workshop on integrated natural resource management in the CGIAR: approaches and lessons, 21–25 August 2000, Penang, Malaysia.
- King, J.G.C. and Heath, G.W. 1967. The chemical analysis of small samples of leaf material and the relationship between the disappearance and composition of leaves. *Pedobiologia*, 7, 192–197.
- Lyasse, O., Tossah, B.K., Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R. 2002. Options for increasing P availability from low reactive rock phosphate. In: Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R., ed., *Integrated plant nutrient management in sub-Saharan Africa: from concept to practice*. Wallingford, UK, CABI, 225–237.
- Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G. and Giller, K.E. 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, Ecosystems and Environment*, 83, 27–42.
- Palm, C.A., Myers, R.J.K. and Nandwa, S.M. 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: Buresh, R.J., Sanchez, P.A. and Calhoun, F., ed., *Replenishing soil fertility in Africa*. Soil Science Society of America Special Publication Number 51, Washington, DC, USA, 193–217.
- Palm, C.A. and Sanchez, P.A. 1991. Nitrogen release from the leaves of some tropical legumes as affected by their lignin and polyphenolic contents. *Soil Biology and Biochemistry*, 23, 83–88.
- Place, F., Franzel, S., Dewolf, J., Rommelse, R., Kwasiga, F., Niang, A. and Jama, B. 2002. Agroforestry for soil fertility replenishment: evidence on adoption processes in Kenya and Zambia. In: Barrett, C.B., Place, F. and Abdillahi, A.A., ed., *Natural resources management in African agriculture: understanding and improving current practices*. Wallingford, UK, CAB International, 155–168.
- Prudencio, C.Y. 1993. Ring management of soils and crops in the West African semi-arid tropics: the case of the Mossi farming system in Burkina Faso. *Agriculture, Ecosystems and Environment*, 47, 237–264.
- Rommelse, R. 2001. Economic analyses of on-farm biomass transfer and improved fallow trials in western Kenya. Natural Resources Problems, Priorities and Policies Programme Working Paper 2001–2, Nairobi, Kenya, International Centre for Research in Agroforestry.
- Sanchez, P.A. 1976. Properties and management of soils in the tropics. New York, USA, John Wiley and Sons.
- 1994. Tropical soil fertility research: towards the second paradigm. State-of-the-art lecture. Proceedings of the 15th International Soil Science Congress, Acapulco, Mexico, 65–68.
- Sanginga, N., Okogun, J.A., Vanlauwe, B., Diels, J., Carsky, R.J. and Dashiell, K. 2001. Nitrogen contribution of promiscuous soybeans in maize-based cropping systems. In: Tian, G., Ishida, F. and Keatinge, J.D.H., ed., *Sustaining soil fertility in West Africa*. Madison, WI, USA, Soil Science Society of America, Special Publication Number 58, 157–178.
- Shepherd, K.D., Palm, C.A., Gachengo, C.N. and Vanlauwe, B. 2004. Rapid characterization of organic resource quality for soil and livestock management in tropical agroecosystems using near infrared spectroscopy. *Agronomy Journal*, in press.
- Smaling, E.M.A. 1993. An agro-ecological framework of integrated nutrient management with special reference to Kenya. Wageningen, The Netherlands, Wageningen Agricultural University.
- Swift, M.J. 1984. Soil biological processes and tropical soil fertility: a proposal for a collaborative programme of research. Paris, France, International Union of Biological Sciences, *Biology International Special Issue 5*.
- 1985. Tropical soil biology and fertility: planning for research. Paris, France, International Union of Biological Sciences, *Biology International Special Issue 9*.
- 1986. Tropical soil biology and fertility: inter-regional research planning workshop. Paris, France, International Union of Biological Sciences, *Biology International Special Issue 13*.
- Swift, M.J., Bohren, L., Carter, S.E., Izac, A.M. and Wooster, P.L. 1994. Biological management of tropical soils: integrating process research and farm practice. In: Wooster, P.L. and Swift, M.J., ed., *The biological*

- management of tropical soil fertility. Chichester, UK, John Wiley and Sons, 209–228.
- Swift, M.J., Heal, O.W. and Anderson, J.M. 1979. Decomposition in terrestrial ecosystems. Oxford, UK, Blackwell Scientific Publications, Studies in Ecology 5.
- Theng, B.K.G. 1991. Soil science in the tropics — the next 75 years. *Soil Science*, 151, 76–90.
- Tittonell, P. 2003. Soil fertility gradients in smallholder farms of western Kenya. Their origin, magnitude and importance. Wageningen, The Netherlands, MSc thesis, Wageningen University.
- TSBF (Tropical Soil Biology and Fertility Institute) 2002. Soil fertility degradation in sub-Saharan Africa: leveraging lasting solutions to a long-term problem. Conclusions from a workshop held at the Rockefeller Foundation Bellagio Study and Conference Centre, 4–8 March 2002.
- Vanlauwe, B., Aihou, K., Aman, S., Iwuafor, E.N.O., Tossah, B.K., Diels, J., Sanginga, N., Merckx, R. and Deckers, S. 2001b. Maize yield as affected by organic inputs and urea in the West-African moist savannah. *Agronomy Journal*, 93, 1191–1199.
- Vanlauwe, B., Diels, J., Aihou, K., Iwuafor, E.N.O., Lyasse, O., Sanginga, N. and Merckx, R. 2002b. Direct interactions between N fertilizer and organic matter: evidence from trials with ¹⁵N labelled fertilizer. In: Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R., ed., *Integrated plant nutrient management in sub-Saharan Africa: from concept to practice*. Wallingford, UK, CAB International, 173–184.
- Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R. 2002a. Integrated plant nutrient management in sub-Saharan Africa: from concept to practice. Wallingford, UK, CAB International, 352 p.
- Vanlauwe, B. and Sanginga, N. 1995. Efficiency of the use of N from pruning and soil organic matter dynamics in *Leucaena leucocephala* alley cropping in southwestern Nigeria. In: Dudal, R. and Roy, R.N., ed., *Integrated plant nutrition systems*. Rome, Italy, FAO, 279–292.
- Vanlauwe, B., Wendt, J. and Diels, J. 2001a. Combined application of organic matter and fertilizer. In: Tian, G., Ishida, F. and Keatinge, J.D.H., ed., *Sustaining soil fertility in West Africa*. Sustaining soil fertility in West Africa. Madison, WI, USA, Soil Science Society of America, Special Publication Number 58, 247–280.
- Van Noordwijk, M., Toomich, M.T.P. and Verbist, B. 2001. Negotiation support models for integrated natural resource management in tropical forest margins. *Conservation Ecology*, 5, 21.
- Van Soest, P.J. 1963. Use of detergents in the analysis of fibrous feeds. II. A rapid method for the determination of fibre and lignin. *Journal of the Association of Official Analytical Chemists*, 46, 829–835.
- Van Soest, P.J. and Wine, R.H. 1968. Determination of lignin and cellulose in acid-detergent fibre with permanganate. *Journal of the Association of Official Analytical Chemists*, 51, 780–785.

2.2

Modelling Release of Nutrients from Organic Resources Using APSIM

M.E. Probert* and J.P. Dimes†

Abstract

In the context of integrated nutrient management, the performance of a crop model depends mainly on its ability to adequately describe the release of nutrients from diverse inputs and their uptake by the crop. The wide range of input materials found in tropical farming systems brings new challenges for modelling. In particular there are ‘quality factors’ that influence the decomposition and nutrient-release processes, while the range of manures encountered are quite different, both physically and chemically, from plant residues.

The APSIM modelling framework contains a set of biophysical modules that can be configured to simulate biological and physical processes in farming systems. In terms of the dynamics of both carbon and nitrogen in soil, APSIM SoilN deals with the below-ground aspects, and APSIM RESIDUE with the above-ground crop residues. APSIM MANURE is a recent addition to simulate nutrient availability to crops following addition of materials of highly variable carbon and nitrogen content. It has not been widely tested against measured field-response data.

The objectives of the ACIAR-funded project LWR2/1999/03 ‘Integrated nutrient management in tropical cropping systems: improved capabilities in modelling and recommendations’, were to evaluate and enhance capabilities in APSIM to predict nutrient availability and subsequent crop growth following the addition of organic and inorganic sources of N and P. This paper briefly describes the capabilities of APSIM to simulate the dynamics of N as they existed at the start of the project.

Models that simulate the growth of crops have been around for more than 40 years. In order that they respond sensibly to climate, soil and management, such models tend to have similar features. Notably, they need to represent the processes that are understood to occur. Typically, they operate at a daily time-step, reflecting on the one hand the availability of weather data, and on the other the fact that this is an appropriate time-step for capturing the more important effects of management on the supply of

nutrients and water from the soil and demand by the plant.

Of the many factors that potentially affect the growth of plants, the two that are most responsive to management are water and nitrogen. It is therefore not surprising that most crop models include routines to handle responses to water and nitrogen. Less frequently do models attempt to describe limitations due to other soil constraints (Probert and Keating 2000).

In the context of integrated nutrient management, the performance of a model depends mainly on its ability to adequately describe the release of nutrients from diverse inputs and their uptake by the crop. In many situations, especially in low input agricultural systems in the developing world, crop growth is limited by nutrients other than N, particularly by

* CSIRO Sustainable Ecosystems, 306 Carmody Road, St Lucia, Queensland 4067, Australia
<merv.probert@csiro.au>.

† International Crops Research Institute for Semi-Arid Tropics, PO Box 776, Bulawayo, Zimbabwe
<j.dimes@cgiar.org>.

inadequate phosphorus. Accordingly, to be useful for exploring strategies for improving crop nutrition of crops, models need to predict the responses to both N and P. The main objectives of the ACIAR-funded project LWR2/1999/03 'Integrated nutrient management in tropical cropping systems: improved capabilities in modelling and recommendations' were to evaluate and enhance the capabilities in APSIM (McCown et al. 1996; Keating et al. 2003) to predict nutrient availability and subsequent crop growth following the addition of organic and inorganic sources of N and P.

In this paper, we briefly describe the capabilities of APSIM to simulate the dynamics of N as they existed at the start of the ACIAR project. Other papers in these proceedings will report on efforts to improve the ability to describe the release of N from materials typical of those used in many tropical farming systems (Probert et al. 2004), and the new capability to simulate response to P-limiting conditions (Probert 2004).

The Agricultural Production Systems Simulator (APSIM)

The APSIM modelling framework contains a set of biophysical modules that can be configured to simulate biological and physical processes in farming systems (Keating et al. 2003; web site <www.apsim.info>). The foremost reason for its development was as a modelling framework for sim-

ulation of cropping systems in response to climate and management.

Two modules provide the representation within APSIM of the dynamics of both carbon and nitrogen in soil. APSIM SoilN deals with the below-ground aspects, and APSIM RESIDUE with the above-ground crop residues. These modules have been described by Probert et al. (1998).

Soil organic matter and nitrogen

APSIM SoilN is the module that simulates the mineralisation of nitrogen and thus the N supply available to a crop from the soil and residues/roots from previous crops. Its development (Probert et al. 1998) can be traced back via CERES models (e.g. Jones and Kiniry 1986) to PAPRAN (Seligman and van Keulen 1981). SoilN provides an explicit balance for carbon and nitrogen so that it is better able to deal with longer-term changes in soil organic matter.

The greatest change from CERES is that the soil organic matter in SoilN is treated as a three pool system, instead of the two pools used in CERES (see Figure 1). The dynamics of soil organic matter is simulated in all soil layers. Crop residues or roots added to the soil comprise the fresh organic matter pool (FOM). Decomposition of FOM results in formation of soil organic matter comprising the soil microbial biomass (BIOM) and HUM pools. The BIOM pool is notionally the more labile organic matter associated with soil microbial biomass; while it makes up a relatively small part of the total soil organic matter, it

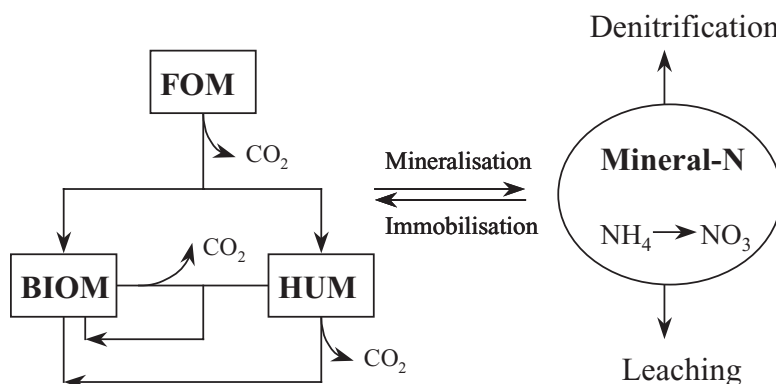


Figure 1. Schematic representation of the processes affecting soil organic matter and nitrogen transformations in the APSIM SoilN module. FOM = fresh organic matter, i.e. roots and incorporated crop residues; BIOM = labile soil organic matter pool; HUM = remainder of soil organic matter.

has a higher rate of turnover than the bulk of the soil organic matter.

The reasons for introduction of an additional soil organic matter pool were to better represent situations where 'soil fertility' improves following a legume ley (Dimes 1996). A single soil organic matter pool cannot deal realistically with the changes in mineral N supply following the cumulative additions of high N material to soil organic matter. The concepts depicted in Figure 1 have much in common with other models, such as the Rothamsted Nitrogen Turnover Model (Bradbury et al. 1993).

The release of nitrogen from the decomposing organic matter pools is determined by the mineralisation and immobilisation processes that are occurring. The carbon that is decomposed is either evolved as CO₂ or is synthesised into soil organic matter. SoilN assumes that the pathway for synthesis of stable soil organic matter is predominantly through initial formation of BIOM, though some carbon may be transferred directly to the more stable pool (HUM). The model further assumes that the soil organic matter pools (BIOM and HUM) have C:N ratios that are unchanging through time. The C:N ratio of the BIOM pool is typically set at 8, while that of the HUM pool is based on the C:N ratio of the soil, which is an input at initialisation of a simulation. The formation of BIOM and HUM thus creates an immobilisation demand that has to be met from the N released from the decomposing pools and/or by drawing on the mineral N (ammonium and nitrate) in the layer. Any release of N above the immobilisation demand during the decomposition process results in an increase in the ammonium-N.

The FOM pool is assumed to comprise three sub-fractions (FPOOLS), sometimes referred to as carbohydrate-, cellulose- and lignin-like, each with a different rate of decomposition. In this manner, the decomposition of added plant material under conditions of constant moisture and temperature is not a simple first-order process.

The rates of decomposition of the various soil organic matter pools are dependent on the temperature and moisture content of the soil layers where decomposition is occurring. In circumstances where there is inadequate mineral N to meet an immobilisation demand, as can occur where the C:N ratio of the FOM pool is high, the decomposition process is limited by the N available to be immobilised.

Other processes dealt with in SoilN are nitrification, denitrification and urea hydrolysis (following

application of urea as fertiliser). Fluxes of nitrate-N between adjoining soil layers are calculated based on movement of water by the water balance module. Ammonium-N and all soil organic matter pools are assumed to be non-mobile.

Surface residues

In APSIM, crop residues that are on the soil surface are handled by the RESIDUE module (see Figure 2), described by Probert et al. (1998). This has been done so that surface residues can affect the soil water balance through run-off and evaporation.

Crop residues are accounted for as a single surface residue pool that is described in terms of its mass, the cover it provides for the soil surface, and its nitrogen content. When new residues are added, either because of senescence and detachment or at harvest, new weighted (mass) average values are calculated to describe the total amount of residues present.

The amount of residue decreases through one of three processes. Firstly, by removal of residue (for example by burning or collection for animal feed); such action does not alter the C:N ratio of the residues. Secondly, through the incorporation of residues into the soil. A tillage event transfers a specified proportion of the surface residues into the soil FOM pools to a nominated depth. Finally, by decomposition *in situ*. The decomposition routine is similar to that used for the soil organic matter pools in the SoilN module in order to maintain balances of both carbon and N. Any immobilisation demand is met from the uppermost soil layer, while the soil organic matter formed and ammonium-N mineralised are added to the uppermost soil layer. The temperature dependency for decomposition of residues is related to daily ambient temperature. As the soil water balance does not include the litter layer, the moisture dependency is assumed to be unconstrained immediately after a rainfall event, with decomposition rate declining as litter dries, based on potential evaporation. The rate of decomposition is also sensitive to the amount of residues on the soil surface. A 'contact' factor accounts for the opposing effects of mulch separation from the soil surface and a modified moisture environment in the mulch layer as the amount of surface material increases. Thorburn et al. (2001) have investigated the importance of the contact factor for sugarcane systems that involve large amounts of surface residues (up to 20 t ha⁻¹).

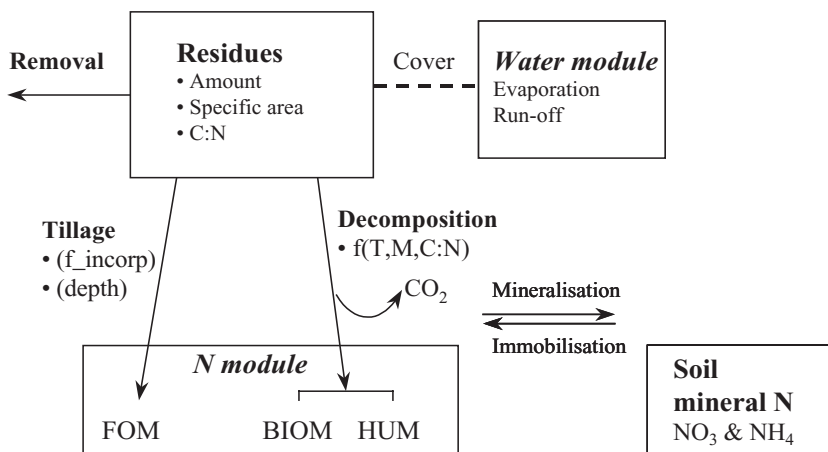


Figure 2. Schematic representation of the processes dealt with in the APSIM RESIDUE module. Note the linkage with the water module whereby the amount of residues will influence components of the water balance.

Manures

In many low-input systems, manures are the sole source of nutrients applied to croplands. These manures are often of low quality. Studies in eastern Kenya (Probert et al. 1995) have shown that the manures being used on farms are grossly inadequate as a source of nitrogen, and are probably being used inefficiently as a source of phosphorus. This is true also in other parts of the semi-arid tropics.

In these environments, improved management of soil fertility calls for efficient use of scarce supplies of manure, integrating its use with other sources of nutrients in crop residues (particularly where legumes are grown) and augmenting these sources where necessary with purchased fertilisers. It is the location of this complexity of nutrient supply investments in a climate with high rainfall uncertainty that makes a simulation model a valuable tool for comparing management options. But, to be useful, the simulation model must adequately represent the nutrient value of the manures, involving their decomposition patterns and the availability of the nutrients for crop growth.

The development of the APSIM MANURE module has progressed towards filling this need. It should be noted that the concern has been with farming systems employing generally low quality manure that is normally incorporated into soil before sowing. Had the interests evolved elsewhere, with

higher quality manures and slurries, say, as occur in intensive livestock systems, the approaches taken may have been different (e.g. volatilisation losses as ammonia).

Manures vary greatly in composition (Lekasi et al. 2003), being a complex mixture of animal excreta and plant residues that has undergone varying degrees of composting/decomposition and might have been mixed with considerable amounts of soil (as in the Kenyan boma system; Probert et al. 1995). Some of the nutrients are in forms that are immediately available for uptake by plants, and some will have to undergo decomposition before they become available. This concept of nutrient availability implies a time dimension, with the nutrients in manure exhibiting a wide range of availabilities, ranging from components that are water soluble to very recalcitrant.

A simple characterisation is to divide each nutrient into two fractions: one part that is immediately available with the rest being treated as an initially unavailable, organic input that must decompose in order for its nutrients to become available. The concept for the organic portion has obvious similarities with how APSIM represents decomposition of crop residues and roots, but with two important differences. In crop residues, carbon content varies little (Palm et al. 2001), and for most plant material APSIM assumes 40% in the dry matter; this is not so for manures.

Also, APSIM SoilN assumes that the carbon in crop residues and roots added to the soil FOM is distributed between the three FPOOLS in the ratio 20:70:10; one suspects that this would not hold true for manures.

The schema for the APSIM MANURE module is shown in Figure 3. An application of manure is specified in terms of its mineral N components and the organic portion. For a surface application, it is assumed that the mineral components are leached into soil in response to rainfall, and the organic portion will decompose *in situ* in an analogous manner to decomposition of surface residues. Incorporation of the manure transfers both the mineral and organic components into the soil to the specified depth, with the organic portion becoming part of the FOM in the APSIM SoilN module.

In early tests of the sensibility of the MANURE module it was supposed that different quality manure could be represented by variation in the FPOOLS comprising the organic fraction (e.g. Carberry et al. 2002). The paper by Probert et al. (2004) explores the extent to which this is feasible.

Discussion

Models have evolved as they have been applied to different agricultural systems, and this is particularly true for the simulation of nutrient dynamics. It is instructive to reflect on the relatively short history that covers the development of APSIM to its present capability.

The early modelling experiences of those who were to become the developers of APSIM were with models of the CERES family, particularly CERES-Maize (Jones and Kiniry 1986). These models had been developed primarily to simulate the growth of crops in high-input systems. As long as N fertiliser inputs met a substantial proportion of the crop nutrient needs there was not much pressure on the model to accurately predict N mineralisation from soil.

However, attempts to apply such models to low-input systems exposed this problem, and efforts were made to improve the soil mineralisation routines (Probert et al. 1998). In particular, it was recognised that a full accounting of both C and N was needed,

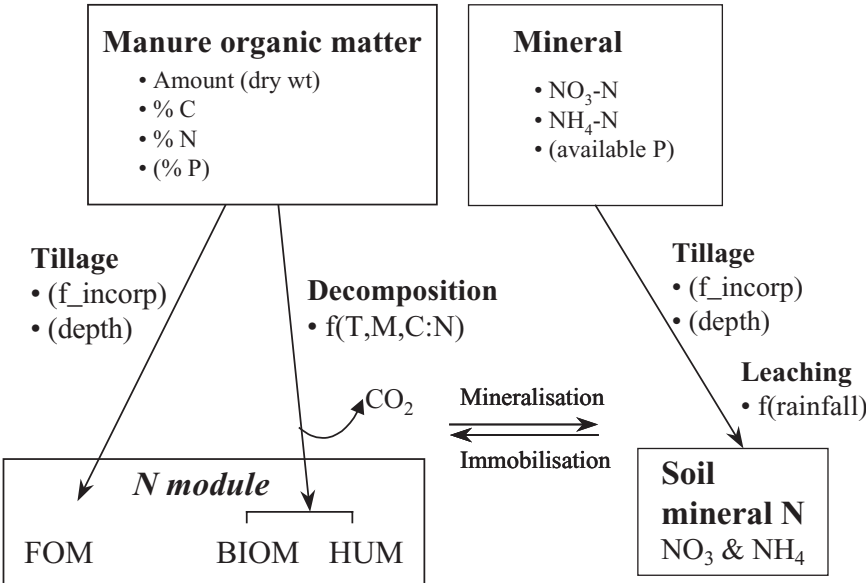


Figure 3. Diagram showing processes considered in the APSIM MANURE module. Manure on the surface of the soil can have an effect on the water balance in similar manner to surface residues (not shown). The schema has provision for manure to also contain phosphorus, which would be transferred to the APSIM SoilP module when manure is incorporated into soil or decomposes.

and that all soil organic matter was not the same with respect to its susceptibility to decomposition (this latter effect being particularly important with soil organic matter in subsoil layers).

Modelling the growth of single crops, with the soil being initialised just before sowing, masked the ability of the models to adequately represent crop residues and roots. Indeed, many crop models can do a satisfactory job in predicting crop yields without considering roots (e.g. the RESCAP model of Monteith et al. (1989)). The desire to model sequences of crops (i.e. a true farming system rather than a single crop) exposes such inadequacies. The amount of roots and residues remaining, and their quality, have major effects on the N supply to following crops. These might be positive in the case of a legume–cereal sequence, or detrimental when cereal residues with a high C:N ratio cause immobilisation of N. For the materials encountered in typical arable cropping systems, the mineralisation/immobilisation of N can be represented as the outcome of the decomposition of the organic sources and the synthesis of soil organic matter. In such materials, the carbon concentration is close to 40%, and concentrations of lignin and polyphenols are generally small. Thus, N concentration (or C:N ratio) is the dominant factor controlling N release.

Most recently there has been recognition of the need to simulate the nutrient release from a wider range of organic inputs, especially manures. For example, Palm et al. (1997) asserted

... current simulation models do not yet fully meet the needs of research and extension workers in developing countries ... The major issues that need attention are the capacity to simulate P dynamics and the decomposition of the range of crop residues and organic materials that are encountered in tropical farming systems.

The wider range of materials found in tropical systems brings new challenges for modelling. In particular, there are other ‘quality factors’ that influence the decomposition and nutrient release processes (Heal et al. 1997), while the manures encountered are quite different, both physically and chemically, from plant residues. The purpose of the project reported in these proceedings was to evaluate current predictive performance of APSIM in these tropical farming systems, and to implement further improvements to the model based on understanding of the experimental data.

References

- Bradbury, N.J., Whitmore, A.P., Hart, P.B.S. and Jenkinson, D.S. 1993. Modelling the fate of nitrogen in crop and soil in the years following application of ¹⁵N-labelled fertilizer to winter wheat. *Journal Agricultural Science* (Cambridge), 121, 363–379.
- Carberry, P.S., Probert, M.E., Dimes, J.P., Keating, B.A. and McCown, R.L. 2002. Role of modelling in improving nutrient efficiency in cropping systems. *Plant and Soil*, 245, 193–303.
- Dimes, J.P. 1996. Simulation of mineral N supply to no-till crops in the semi arid tropics. PhD thesis, Griffith University, Queensland.
- Heal, O.W., Anderson, J.M. and Swift, M.J. 1997. Plant litter quality and decomposition: an historical overview. In: Cadisch, G. and Giller, K.E., ed., *Driven by nature: plant litter quality and decomposition*. Wallingford, UK, CAB International, 3–30.
- Jones, C.A. and Kiniry, J.R., ed. 1986. *CERES-Maize: a simulation model of maize growth and development*. College Station, Texas A&M University Press, 194 p.
- Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy*, 18, 267–288.
- Lekasi, J.K., Tanner, J.C., Kimani, S.K. and Harris, P.J.C. 2003. Cattle manure quality in Maragua District, Central Kenya: effect of management practices and development of simple methods of assessment. *Agriculture, Ecosystems and Environment*, 94, 289–298.
- McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P. and Freebairn, D.M. 1996. APSIM: A novel software system for model development, model testing, and simulation in agricultural research, *Agricultural Systems*, 50, 255–271.
- Monteith, J.M., Huda, A.K.S. and Midya, D. 1989. RESCAP: A resource capture model for sorghum and pearl millet. In: Virmani, S.M., Tandon, H.L.S. and Alagarswamy, G., ed., *Modelling the growth and development of sorghum and pearl millet*. Patancheru, A.P., India, International Crops Research Institute for the Semi Arid Tropics (ICRISAT) Research Bulletin No. 12.
- Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G. and Giller, K.E. 2001. Organic inputs for fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, Ecosystems and Environments*, 83, 27–42.
- Palm, C. A., Myers, R. J. K. and Nandwa, S. M. 1997. Combined use of organic and inorganic nutrient sources

- for soil fertility maintenance and replenishment. In: Buresh, R.J., Sanchez, P. A. and Calhoun, F., ed., *Replenishing soil fertility in Africa*. Soil Science Society of America Special Publication No. 51, 193–217.
- Probert, M.E. 2004. A capability in APSIM to model P responses in crops. These proceedings.
- Probert, M.E., Delve, R.J., Kimani, S.K. and Dimes, J.P. 2004. The APSIM Manure module: improvements in predictability and application to laboratory studies. These proceedings.
- Probert, M.E., Dimes, J.P., Keating, B.A., Dalal, R.C. and Strong, W.M. 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agricultural Systems*, 56, 1–28.
- Probert, M.E. and Keating, B.A. 2000. What soil constraints should be included in crop and forest models? *Agriculture, Ecosystems and Environment*, 82, 273–281.
- Probert, M.E., Okalebo, J.R. and Jones, R.K. 1995. The use of manure on small-holders' farms in semi-arid eastern Kenya. *Experimental Agriculture*, 31, 371–381.
- Seligman, N.G. and van Keulen, H. 1981. PAPRAN: a simulation model of annual pasture production limited by rainfall and nitrogen. In: Frissel, M.J. and van Veen, J.A., ed., *Simulation of nitrogen behaviour of soil-plant systems*. Wageningen, The Netherlands, PUDOC, 192–221.
- Thorburn, P.J., Probert, M.E. and Robertson, F.A. 2001. Modelling decomposition of sugarcane surface residues with APSIM-Residue. *Field Crops Research*, 70, 223–232.

2.3

Linking Simulation Modelling to Participatory Research in Smallholder Farming Systems

Peter Carberry,* Christy Gladwin† and Steve Twomlow§

Abstract

Simulation models have proven beneficial to commercial farmers in Australia when applied within a participatory action research approach. This paper reports on an attempt to combine a participatory research approach and computer-based simulation modelling to engage smallholder farmers in Africa on issues of soil fertility management. A three-day interaction with farmers in one village in Zimbabwe provided evidence that the farmers found the simulation outputs to be credible and meaningful in a manner that allowed ‘virtual’ experiential learning to take place. The paper concludes that simulation applied within an action research framework may have a role in direct interventions with smallholder farmers in such regions

Simulation modelling has struggled for relevance in real-world agriculture and for impact on farmer decision-making, as outlined in two recent reviews. McCown et al. (2002) reflected on the impacts and learning in developing and applying computerised decision-support systems (DSS) through the collated experiences from nine substantive efforts of researchers in delivering DSS to farmers. All case studies were from developed countries (Australia, USA, Europe), and most incorporated dynamic simulation models within the applied DSS. Based on these experiences, McCown (2002) concluded ‘the DSS has fallen far short of expectations in its influence on farm management’.

Matthews and Stephens (2002) reviewed the application of simulation models in developing countries and sought examples of where such models

have been useful in smallholder farming systems. Unfortunately, this extensive review largely failed to identify any noteworthy examples of where crop simulation models had impacted on the practices of smallholder farmers. The 11 examples presented to demonstrate possible impact (Matthews et al. 2002) were mostly via influence on research direction, e.g. designing new rice plant types to increase yield potential or weed competitiveness (Dingkuhn et al. 1997), or in the training of local researchers, e.g. the SARP project (ten Berge 1993).

In the past, model applications have generally meant abstract analyses whereby researcher-designed management scenarios are tested under hypothetical situations, and recommended actions are suggested on what managers should do, generally without any reference to real-world testing. Most attempts to justify modelling approaches refer to multitudes of such context-free analyses (Meinke et al. 2001; Hammer et al. 2002; Matthews and Stephens 2002), but few examples are provided on where farming practices have benefited from such modelling studies.

Given past failures in DSS implementation and the increasingly unenthusiastic reaction of journals and

* Agricultural Production Systems Research Unit (APSRU), CSIRO Sustainable Ecosystems, PO Box 102, Toowoomba, Queensland 4350, Australia
<peter.carberry@csiro.au>.

† University of Florida, PO Box 110240, Gainesville, FL, USA <chgladwin@mail.ifas.ufl.edu>.

§ ICRISAT, PO Box 776, Bulawayo, Zimbabwe
<s.twomlow@cgiar.org>.

research peers to such simulation analyses, which are easily generated and relate to no place in particular, the future for many modellers has been to retreat from 'trying to be practical' and seek a 'market' elsewhere. Some argue that models used in a normative manner could have input into public policy (Goldsworthy and Penning de Vries 1994), but again there are few reported examples of where models have actually influenced policy implementation. More recently, Hammer et al. (2002) have promoted a new hope for modelling in directing plant breeding, through identifying and assessing plant traits through gene-to-phenotype modelling. Modelling input into setting research directions or in plant breeding, in education and training, or as input into public policy probably does provide sufficient rationale for the continued development and application of models. But what of simulation modelling as an aid to farm decision-making?

While realistic about the past impacts of simulation modelling, both McCown (2002) and Matthews and Stevens (2002) are not dismissive of the prospects of modelling contributing to improved farmer decision-making. Both suggest that simulation modelling using a participative approach may be the future. Farmer participatory research stresses the co-learning of researchers and farmers who work together to explore the different options open to farmers through conducting experiments to test new agricultural inputs and practices. Participatory approaches allow researchers and farmers to jointly learn about farmer conditions in order that both can help each other design sustainable development interventions (Ashby and Sperling 1994; Okali et al. 1994).

A substantive example indicating possible success with a participatory application of simulation modelling is the FARMSCAPE experience (Carberry et al. 2002). FARMSCAPE (Farmers, Advisers, Researchers, Monitoring, Simulation, Communication And Performance Evaluation) is a program of participatory research with Australian farming communities that explicitly researched whether farmers and their advisers could benefit from simulation modelling. Carberry et al. (2002) provide performance indicators of impact on farming practices and reflect on what was learnt from this experience. They suggest that the active participation of farmers and their advisers, who work with researchers in the context of their own farming operations, was the key ingredient in the

design, implementation and interpretation of the FARMSCAPE approach to decision support.

Dimes et al. (2003) agree that there can be synergies between simulation models and participatory research and suggest that, for smallholder farming systems, there are four areas of possible application: (i) the interpretation of on-farm experiments, (ii) exploration of investment options and risk analysis, (iii) assessment of new technologies and (iv) engaging farmers directly with simulation models in order to create virtual 'experiential learning' opportunities that are difficult or risky in real life. While the first three areas are consistent with past proposals for model applications, it is the fourth suggestion which may surprise, especially in the case of smallholder farmers. Dimes et al. (2003) briefly reported on an experience of using models with a group of smallholder farmers in Zimbabwe. The purpose of this paper is to provide greater detail and analysis of this experience of engagement of researchers with smallholder farmers in semi-arid Zimbabwe.

Background

In October 2001, a workshop was convened at ICRISAT-Bulawayo in Zimbabwe to explore the complementarities between farmer participatory research approaches and computer-based simulation modelling in addressing soil fertility management issues at the smallholder level (Twomlow 2001). To test the complementarities of these two approaches, six teams were assembled, made up of computer simulation modellers trained in the use of the cropping systems model APSIM (Keating et al. 2003), participatory researchers (agronomists, economists and social scientists) trained in participatory rural appraisal and rapid rural appraisal tools and methods, and local researchers knowledgeable on African farming systems. The six teams then worked with farmers in six villages in the Tsholotsho and Zimuto districts, Zimbabwe, for three days. They used participatory tools to build realistic farm scenarios for the computer simulations, which were then run for the farmers to get their reactions and suggestions for improvements. This paper is the report on what happened and what was learnt from one of those teams which interacted with 30 farmers in the village of Mkhubazi, Tsholotsho, Zimbabwe.

The APSIM cropping systems model was selected for use in this study because it had been previously tested in simulating crops in smallholder farming

systems in Zimbabwe (Robertson et al. 2000; Shamudzarira and Robertson 2000; Shamudzarira et al. 2000). Likewise, soil and agronomic data were available to parameterise APSIM for the analyses to be undertaken in this study (Dimes et al. 2003). Climate data collected at Tsholotsho (less than 20 km from Mkhubazi) were used in the subsequent simulation scenarios.

Farmer Focus Group Meeting

On the first of the three days of interaction with a group of farmers in the village, a focus group meeting was held. About half the group were women. Over the three days, the number of farmers increased from 21 on day 1 to over 30 on day 3. All group discussions were mediated by a local interpreter. Some farmers in the group had a degree of English language competence.

The facilitator started the discussion by eliciting the local taxonomy of soils in the village. The smallholders in Mkhubazi recognise four types of soil. They crop two most frequently: *ihlabathi* soils, which are whitish sandy soils that do not hold water well and need large amounts of manure to be productive, and *ipane* soils, which are sodic, don't store much water and are prone to waterlogging, sometimes leaving maize plants standing in water for a week at a time. The less-fertile *ihlabathi* soils are the more common of the two. All villagers present at the focus group discussion have and plant crops on *ihlabathi* soils, whereas only 7 or 8 of the 20 villagers have *ipane* soils.

Given this picture of the local soil constraints, an agricultural activity calendar was then elicited from farmers, showing the details of dates of planting, weeding, and harvesting for different crops grown on both kinds of soils. It showed, for instance, that farmers plant crops of maize and sorghum first on *ipane* soils, if they have them, because they get poor germination on these soils if they plant late. Moreover, they plant early on these soils so that the plants are established to survive the waterlogging when the 'main rains' come in December. If *ipane* soils are planted after the main rains come, farmers might not be able to enter the ponded fields to plough. This means, for farmers with both kinds of soils, that maize and sorghum are planted first on *ipane* soils, followed by millet and legumes (groundnuts, cowpeas, and bambara nuts) on *ihlabathi* soils, as farmers

report a striga problem with sorghum and maize planted on *ihlabathi* soils. Farmers with only *ihlabathi* soils can be expected to plant when 'the rains come' in the sequence specified by the activity calendar: maize and groundnuts in November, followed by sorghum and pearl millet and groundnuts in mid-December. Cowpeas can be planted from mid-November to mid-January.

Farmers say they weed maize, groundnuts, and bambara nuts twice, the first being 2 weeks after planting and the second depending on the amount of weed infestation. Millet and sorghum, however, are weeded once, four weeks after emergence. Different patterns of crop rotations on the same plot or portion of a big plot are reported, e.g. small 1 acre (1 acre = 0.4 ha) plots of legumes (groundnuts, cowpeas, bambara nuts) followed by 1–5 acre plots of maize followed by larger plots (4–8 acres) of millet followed by smaller plots (1–2 acres) of sorghum. Crops are also rotated in the homestead field or garden managed by women.

An hour's discussion ensued about inorganic and organic fertiliser use. Farmers say they do not buy chemical fertiliser from the trade store for use on grain crops; but all have been exposed to the nutrient advantages of chemical fertiliser. Farmers apply manure if they have cattle and/or goats, preferably on land planted to maize and then sorghum. Yet, when asked which soil should they put manure on, more farmers said *ihlabathi* (sandy) soils than *ipane* (sodic-like) soils. The amount of manure applied varied a great deal, from 3 to 8 scotch-carts (about 600 kg) hectare⁻¹ every 2–5 years. These discussions were followed by small-group discussions with the eight team members interviewing small groups of four to five farmers. Some team members asked individual farmers about their individual farming practices, household food security, and household composition.

Work resumed on day 2 with a short summary by the team. The group then broke into small groups of four to five farmers to develop resource allocation maps (RAM) (Defoer and Budelman 2000). The RAM for each farm provided a diagrammatic representation of the farm infrastructure and assets and the seasonal flows of materials and labour between farm units (household, garden, fields etc.). A well-specified RAM for an individual farm enabled specification of actual and planned crop production strategies.

Describing a Computer Model to Smallholder Farmers

In the afternoon of day 2, the concept of a computer model was introduced to the farmers. Although many of the farmers had not previously seen a computer, a number had lived and worked in the city and had some understanding of a computer and its ability to calculate. These few provided valuable support to the interpreter in describing what followed.

Hand-drawn diagrams on flipcharts were used to help describe a computer model (Fig. 1). Firstly, the concept of measuring daily rainfall was discussed, with its accumulation representing what rain falls throughout the cropping season. Good and bad seasons were related to frequency and amount of rainfall events. Next, the process of growing a maize crop was discussed, starting with inputs of seed and manure applied to a particular field and the subsequent development and growth of the maize from seedlings to maturity. The linkage between rainfall events and crop growth was discussed.

Growing the same crop 'on the computer' was then proposed by providing it with the same information as what happened in real-life; i.e. what rain fell, how many seeds were planted to what field and soil type,

how much manure was applied etc. A notebook computer, as drawn in Figure 1a, was displayed to the group. Once the interpreters and the few farmers with some knowledge about computers had completed long discussions with the less aware farmers, the idea of using the computer to ask 'What if?' questions was proposed (Figure 1b). If maize was planted in a field with a small amount of manure and yielded two bags, what yield would the computer suggest with more manure? Or with inorganic fertiliser?

In attempting to better relate computer simulation to the reality of farming at Tsholotsho, actual rainfall and simulated crop yields for maize, sorghum, and groundnut from 1991–2001 were presented as hand-drawn graphs (Figure 2). Yields were represented as number of 50 kg bags of grain acre^{-1} , units that appeared to be understood by the farmers during the RAM interviews. Crop management rules were aligned with information collected in interviews on the previous day, and soil characteristics were likewise informed by farmer information supplemented by local researcher knowledge. These simulations were completed before the meeting and the notebook computer was not used during this session.

Immediately after the Figure 2 graphs were presented, Sevi, a female farmer, asked the question:

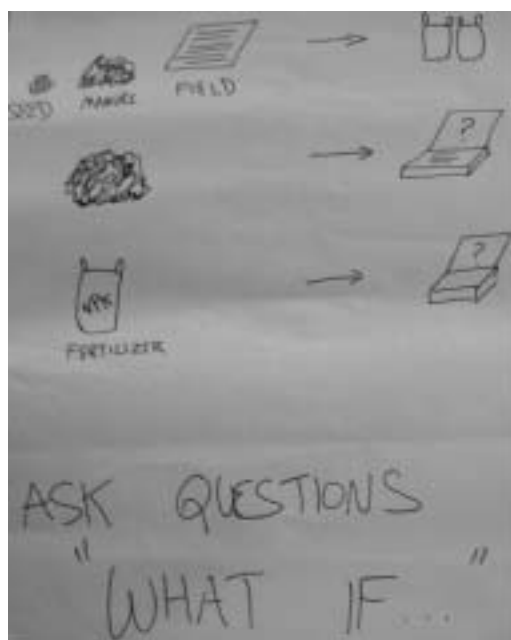
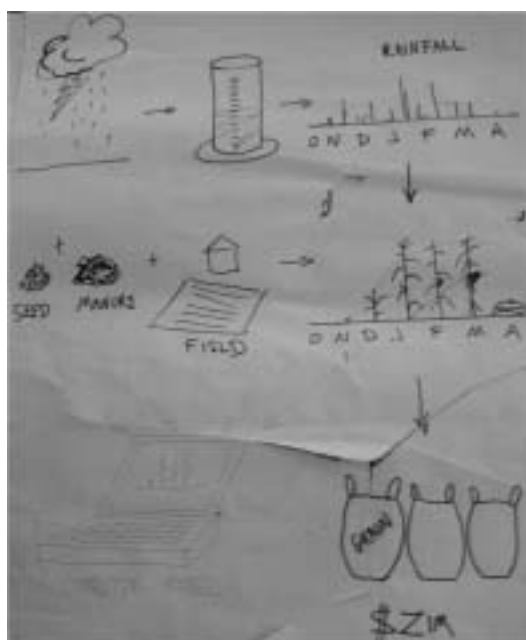


Figure 1. Photos of hand-drawn diagrams on flip charts used to help describe a computer model.

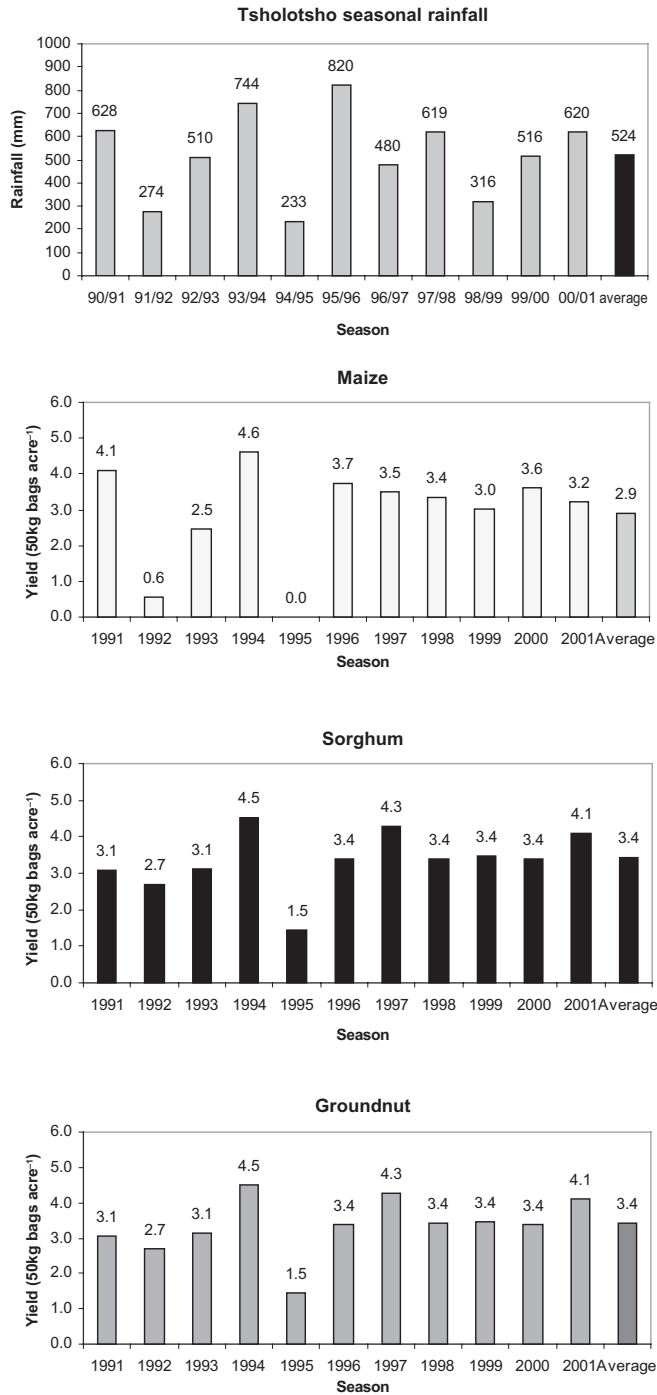


Figure 2. Seasonal rainfall for Tsholotsho and simulated crop yields for maize, sorghum, and groundnut for 1991–2001.

why was the simulated sorghum yield in a year with >800 mm rainfall (1995–96) less than the yield in a year of only 480 mm rainfall (1996–97)? This one unsolicited question was the catalyst for increased engagement between the researchers and the farmers. It ‘broke the ice’ for discussion about a range of issues on which both farmers and researchers had knowledge, the former with local knowledge, the latter with scientific knowledge.

Subsequent discussion concentrated around the matching of seasonal rainfall, simulated yields and farmer experience over the previous 11 years. We initially concentrated on the previous season (2000–01) by presenting the season’s daily rainfall, and benchmarked simulated yields of maize and groundnut against experiences volunteered by a few farmers. Closest consensus was reached in relation to the simulated drought-affected maize yields in years 1992 and 1995. It was concluded that three types of years could be distinguished between 1989 and 1998: one very bad year (1992), four bad years and five normal years.

This second day’s interaction ended without significant indicators that many farmers had understood the description of computing or crop modelling. The farmers were polite but mostly reserved. Some in the group did engage in comparing their experience over recent years with that presented by the researchers.

Running Simulation ‘What If?’ Discussions with Smallholder Farmers

Day 3 began with an intention to engage the farmers with simulation output. Preparation for the day involved selection of four case-study farmers and issues which emerged from the focus group meeting and the RAM exercise. Using these data, initial simulations were conducted overnight and results transferred to flip charts as pre-meeting preparations.

This day’s meeting at Mkhubazi commenced without a concise agenda on how the farmers would be engaged using the simulation output. While some in the research group were sceptical of progressing beyond simple presentation of simulation results, all were hopeful of achieving higher levels of interaction. Therefore, the subsequent farmer–researcher engagement was guided by two hypotheses: that an action research approach, whereby what to do next would be informed by what was learnt from previous

actions, could inform the engagement process, and that the engagement process employed in the FARM-SCAPE experience (Carberry et al. 2002) would be a sensible framework for initiating the interactions with smallholder farmers using simulation output.

The selected case studies were conducted for four farmers:

- *Samuel*, the leader of the farmer group and a relatively wealthy farmer when judged by land area, cattle number and wives. Samuel had access to 14 scotch carts of manure year⁻¹ which could be applied to 2.5 ha of cropland. Baseline simulations for Samuel covered the issue of the benefit of application of manure.
- *Sevi*, one of the leading and younger women farmers with modest farm resources. Sevi was clearly someone thinking about her farming system and she was an initiator of questions and contributed freely to discussions.
- *Derrick*, a farmer with less resources in the group with few cattle and low production.
- *Ester*, an older woman farmer with limited resources and cattle.

Each of these case studies and the interactions between farmers and researchers are described in the following section, with greater detail supplied on the first example.

(i) Samuel

The meeting started with presentation of simulated results from the overnight runs for the first case study farmer (Samuel). This baseline simulation, using climate data for Tsholotsho for 11 years (1991–2001), was for maize cultivar sc501 grown on *ihlabathi* soil with no applications of manure or inorganic fertiliser. Also presented was the same simulation but with 14 scotch carts (8000 kg ha⁻¹) of good quality manure (C:N ratio of 20) applied to the maize crop before planting (results not shown).

This first presentation of hand-drawn graphs started as a lecture without feedback sought from nor volunteered by farmers during its interpretation by the presenting researcher. When asked for their reaction after presentation, Samuel and the other farmers remained detached and non-committal. The meeting was heading towards an early and frustrating ending! Then one of the older, clearly respected farmers stood up and, through the interpreter, commented that the maize cultivar sc501 was poorly adapted to the region and few in the village now used this variety. In

his opinion, the results were not relevant to his farm. This was the opportunity needed to engage. Let's redo the simulations using the variety you recommend, was the suggestion put to the farmers. They agreed and chose cultivar sc401, a shorter season variety. The new runs were completed within minutes and the changes in bags acre^{-1} (relative to cultivar sc501) were presented on flip charts for each year of simulation and for the average. Figure 3(a,b) presents these simulation results, but with the base-line simulation using cultivar sc401.

The initiating farmer volunteered his reaction; that he expected sc401 to perform better than sc501 in most years and he was pleased that the presented results were now better aligned with his experience. Other farmers agreed and good discussion followed on why this was the case. The 1999 and 2000 seasons were remembered as low rainfall years when a short season variety was advantaged but last season (2001) had sufficient rainfall to support the longer season sc501. The farmers also seemed satisfied with the simulated yields — they expected to produce in the order of 5–6 bags $\text{acre}^{-1} \text{ year}^{-1}$, but have had years with no production (1995 was well remembered as a bad drought) and other years when 9–10 bags acre^{-1} were produced.

The alignment of farmer experience with simulated output for a common experience (a change in maize cultivar) seemed to generate considerable credibility with the farmers and a subsequent willingness to proceed with further simulations. Let's see what difference other changes would make to the outcome was the suggestion accepted by the more proactive members of the group. When asked, Samuel asked that the impacts of manure application next be redone with the variety sc401.

The FARMSCAPE experience (Carberry et al. 2002) helped guide the process here. While the new simulations were being run, the farmers were asked to nominate what change they would expect from the manure application. Each farmer was asked in turn to nominate how many extra bags of grain would be produced with the application of 14 scotch carts of high quality manure (Table 1). The simulated yield change ranged from 0–1.5 extra bags acre^{-1} (Figure 3c), with an expected (average) value of 0.8 bags acre^{-1} . This result was less than the experience of most farmers. Comment was sought from those farmers who nominated the larger benefits (5–9 bags acre^{-1}) and it appeared that they included farmers without access to such large quantities of manure and so without relevant experience. Active discussion

ensued for some time between the local farmers and the researchers on manure and its use within their farming systems. This discussion led to the possible use of inorganic fertilisers (undoubtedly introduced by the researchers). At this point, the question was asked whether the farmers wanted to redo the simulation with applied fertiliser. The response was an enthusiastic yes. Samuel nominated applying 1 bag of fertiliser acre^{-1} (44 kg N acre^{-1}).

Table 1. Number of farmers who nominated changes in bags acre^{-1} from manure and N fertiliser applications in case study 1.

	Yield difference (bags acre^{-1})									
	0	1	2	3	4	5	6	7	8	9
Manure application	0	2	14	10	1	2	1	0	0	0
N fertiliser application	0	2	6	4	8	4	0	0	2	1a

^a This difference was volunteered by the modeller before he ran the simulation.

The same procedure was followed, whereby farmers were asked by a show of hands before presentation of simulation results to nominate their expectations for the change in yield with applied fertiliser (Table 1). At this point the engagement became more light-hearted, animated and inclusive of more farmers. Many started debating amongst themselves the likely outcome and several changed their nomination as a result. The modeller gained a great laugh by joining in and nominating a changed yield larger than anyone else — the farmers accused him of cheating through 'insider-knowledge'! As the changes in yield were read out and recorded—plus 22 bags acre^{-1} , –1, 19, 21 ... (Figure 3d) — the farmers' reactions were a mix of amazement, disbelief and excitement. The simulated yield changes were significantly greater than any farmer had imagined. Great debate ensued, with most farmers asking if such returns could really be possible. One female farmer volunteered that she had once achieved 16 bags acre^{-1} and so she believed such yields were achievable. This discussion enabled input from several researchers on the mechanism of crop response to soil N and on-farm experimental evidence with fertilisers. The variability in yield change, with even a negative response, had to be emphasised by the researchers — high yields were not assured with applied fertiliser.

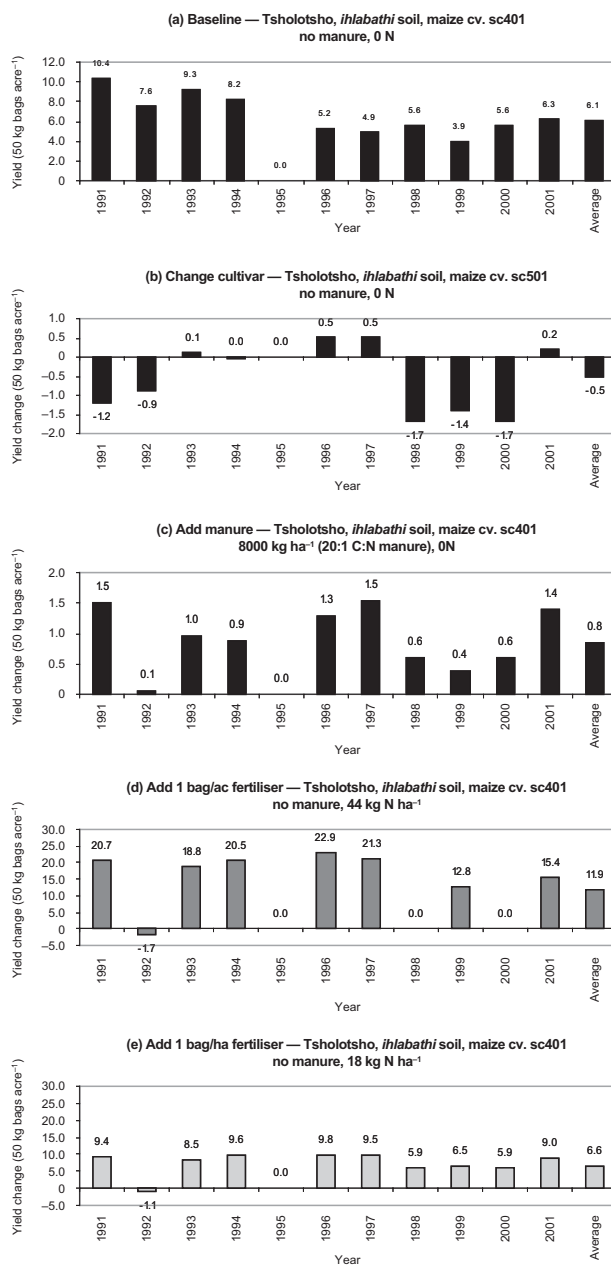


Figure 3. (a) Baseline simulation, using climate data for Tsholotsho for 11 years (1991–2001), was for maize cultivar sc401 grown on *ihlabathi* soil with no applications of manure nor inorganic fertiliser, and the changes in maize yields (bags acre⁻¹), (b) for cultivar sc501 relative to sc401, (c) for manure application, (d) for applying 1 bag fertiliser acre⁻¹ (44 kg N ha⁻¹), and (e) for 18 kg N/ha applied as fertiliser.

When asked his reaction, Samuel said he found it too difficult to believe such high yields were possible and, besides, he could not afford such a high fertiliser rate. He asked what if he spread one bag of fertiliser over his whole farm ($44 \text{ kg N acre}^{-1}$ over 2.5 acres)? The simulations were rerun with 18 kg N ha^{-1} applied as fertiliser (Figure 3e). This result (expected return of 7 bags acre^{-1}) greatly interested Samuel and other farmers. Small applications of N fertiliser could return significant benefits in most seasons. More requests were proposed, to try even lower rates of fertiliser, but close to 2 hours had been spent on the one case and three other farmers were waiting for their results. It was decided to change cases.

By the close of the first case study, the farmers seemed to now have little difficulty in participating in our evolved process: i.e. initially present the overnight runs for each case study as bags acre^{-1} for a baseline and a new practice, calculate the difference in yield, discuss suggestions for alternative options, ask the farmers to nominate their answers, run the new simulations, write changes in bags acre^{-1} , discuss results in a manner which leads to the next iteration of simulations. Indicators of a consensual process were: not having to re-explain the request for

their estimates, the ready volunteering of estimates with animated debate on likely outcomes between farmers, and the unsolicited queries on what the next simulation should be from different farmers.

(ii) Sevi

The second case study, for Sevi, aimed at benchmarking the performance of her maize and groundnut crops grown on *ihlabathi* soil in the previous 2001 season. On the first rainfall events in early November, Sevi was able to plant her garden plot to maize and field one to groundnut. However, due to labour shortages and delayed rainfall, she was not able to plant maize in field two until early December. The question, which had emerged through discussions the previous day, was: What if she had given priority to planting her main crop of maize in field two on the early rains and delayed planting the groundnut until December?

The simulation used rainfall data for Tsholotsho for the 2001 season (Figure 4a) and showed simulated yields for the late-sown maize crop to be significantly less than for the crop sown early in the garden plot (Figure 4b). The simulation suggested that, if

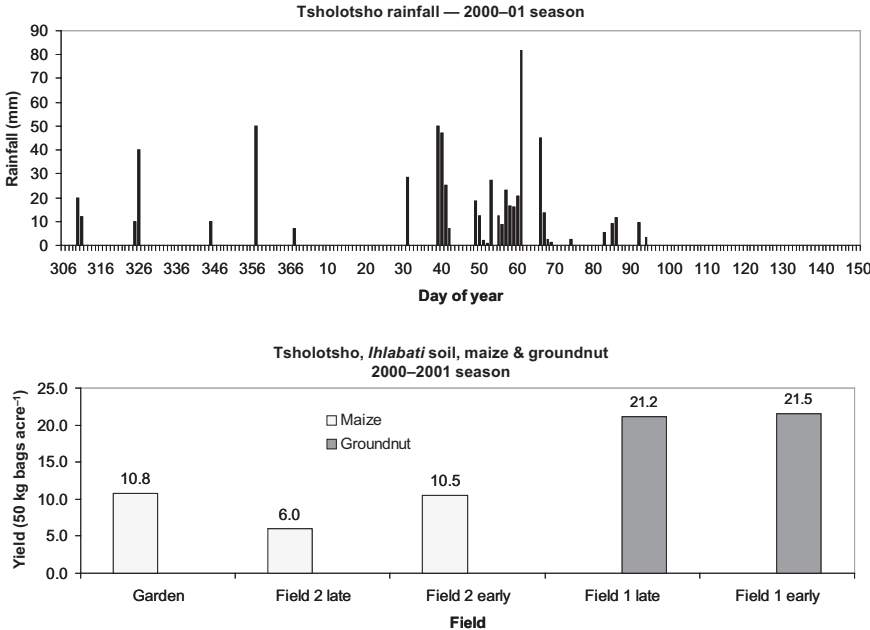


Figure 4. (a) Daily rainfall for Tsholotsho for the 2001 season, and (b) simulated yields for the garden plot and early and late sown maize and groundnut crops.

Sevi had given priority to sowing all her maize early, she would have achieved greater maize production without significant effect on the production of groundnut sown later (Figure 4b).

This case study challenged the planting priority for different crops, with the objective of planting the main maize crop before the lesser-priority groundnut crop. While this action appeared attractive to the researchers, as it did not involve additional resources, one farmer commented that early planted maize, outside the fenced garden plot, ran the risk of being grazed by cattle due to the scarcity of alternative feed.

(iii) Derrick

In the RAM interviews on day two, Derrick indicated that he did not use manure or fertiliser as he owned only two cattle and had few spare resources. His initial question was to ask about the value of four scotch carts (2500 kg) of low quality manure (C:N ratio of 35) applied to 1 acre of maize grown on a *ipane* soil.

Interestingly, during case study 1, where large returns from fertiliser were simulated, compared with small returns from manure, Derrick volunteered that his interest had shifted from manure to fertiliser (*'the effort from manure is not worth it'*). The first runs for Derrick's farm initially confirmed his new view that there was no return from the application of low quality manure (Figure 5a,b). The facilitated discussion then addressed why there was so little response to manure application and what he could do about it. All farmers joined this discussion with the researchers, on the N immobilisation phenomenon of such manure. The farmers and researchers together reached consensus to rerun the simulation but to concentrate the available 1000 kg manure on a smaller area (1/2 acre) and improve its quality (Figure 5c,d). These new runs showed modest returns to manure (0–2 bags acre⁻¹) which was attractive to Derrick as it involved no higher dollar investment and it was something new that he could do himself. He could collect manure in a manner that maintained its quality and this was something he could start on tomorrow. Derrick stated that *'this is what I will do'*.

(iv) Ester

The first three case studies had consumed close to five hours of discussion and lunch was ready. Even so, the fourth case study farmer, Ester, asked for her simulations. These were discussed over lunch with a

smaller group of farmers huddled around the notebook computer. Ester wanted to explore the application of low versus high quality manure for her own circumstance (results not presented). These runs were undertaken and discussed one-to-one with Ester but limited time prevented exploration of further scenarios.

Farmer Meeting Conclusion

After lunch, the farmers and researchers reconvened to conclude the meeting, despite enthusiasm by some farmers for continuation – a female farmer interjected *'since this is our last day, we want to learn more'*. Samuel (our first case study farmer) gave a speech thanking the researchers for visiting him and his neighbours over the past three days. He identified record keeping by farmers of their yields and rainfall as an important learning from the meeting. He also asked for access to fertiliser and seed so that the village's farmers could increase their productivity in ways discussed over the previous days.

The leader of the research visitors responded with gratitude to the village farmers for attending the three days of the workshop and for their attention and interest. He offered to return the following week to discuss with interested farmers opportunities for follow-up, on-farm trials on issues raised during the discussions. He therefore asked that the farmers be proactive and meet themselves to discuss options for collaborative on-farm trials in the coming season.

The day was concluded with the villagers singing and dancing for the departing researchers.

Follow-up Activities

A week following the simulation workshop, ICRISAT researchers returned to the village of Mkhubazi to negotiate on-farm trials with interested farmers. The meeting started with a recap of what had been discussed during the simulation workshop. The farmers were then asked to present what they wished to do as a follow-up activity.

The discussions focused on the modelling results from the previous week's workshop and what could be done during the current season. Some of wealthier farmers referred to the huge potential benefit that the model showed when 1 bag of ammonium nitrate was applied acre⁻¹ compared with the normal practice of no N fertiliser. However, this was quickly dismissed

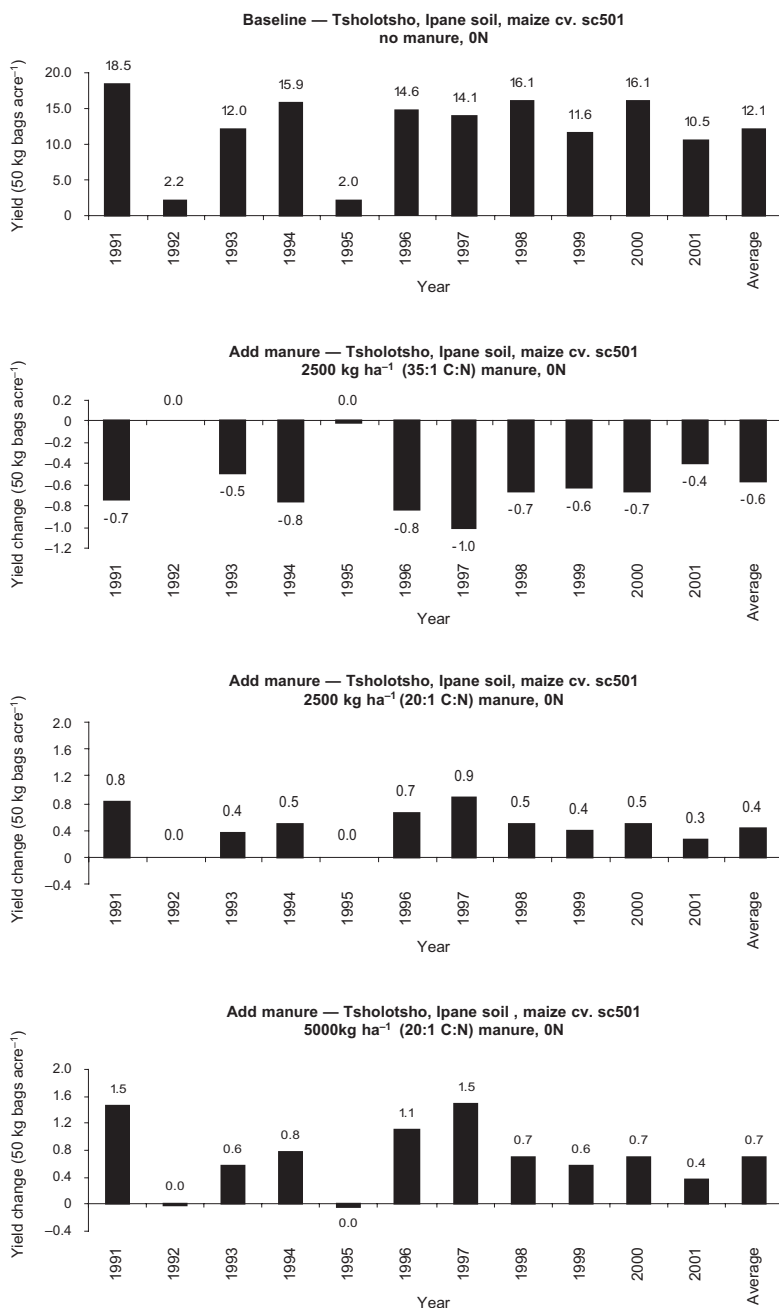


Figure 5. (a) Baseline simulation, using climate data for Tsholotsho for 11 years (1991–2001), was for maize cultivar sc501 grown on *ipane* soil with no applications of manure or inorganic fertiliser; and the changes in maize yields (bags acre⁻¹); (b) for the application of low quality manure; (c) for the application of high quality manure; and (d) for the application of high quality manure concentrated on a smaller area (0.5 acre).

as a possible experimental treatment, as the farmers agreed that they could not afford to apply such high rates. In addition, such high returns to N fertiliser may not be achievable in these systems if other constraints were also evident (e.g. P deficiency, weeds etc.). When the rate of fertiliser was reduced to a realistic 10 kg acre⁻¹, the simulations had showed a yield advantage of an additional 3–4 bags acre⁻¹ indicating that investment in fertiliser pays in many years.

During this discussion, the issue of the cost of fertiliser was approached by suggesting that 10 kg of fertiliser at then current prices equated to seven bottles of beer. The beer comparison posed the question, is beer an investment in the future? Women farmers responded by saying that it would be better to invest in crops than in beer, while some male farmers were not keen to answer the question, although they did make it clear that inorganic fertilisers were not available locally and asked could ICRISAT help? A local trade store owner was subsequently identified by the group and ICRISAT included him in an agents program supplying ammonium nitrate fertiliser in 10 kg bags rather than the standard 50 kg bags.

The ICRISAT team now referred to the workshop, at which farmers had indicated an interest to do trials on manure and fertiliser interactions. From the ideas farmers had suggested in discussions, five researchable areas emerged:

- how much manure?
- how much nitrogen?
- seed variety?
- anthill soil?
- ash?
- legume responses to phosphorus?

The farmers then broadly divided themselves into three groups. Eleven farmers would look at manure and inorganic nitrogen interactions; eleven would look at legumes (groundnuts or bambara) and their responses to various forms of phosphorus; and five would continue with their original ideas.

Despite a significant drought in Zimbabwe and the political upheavals associated with the 2002 presidential elections, which severely restricted travel by researchers, the farmers in Mkhubazi implemented and managed the trials that had been agreed (Twomlow 2003). These results support the southern African teams investment in participatory approaches linked with simulation modelling, and the empowerment it gives to rural communities and change agents.

What Did We Learn?

The experience recounted here centred around the use of a cropping systems simulator with smallholder farmers in Zimbabwe as a way of allowing the farmers to experiment with alternative management options for their own farms. While this approach has proved successful with commercial farmers in Australia (Carberry et al. 2002), it was a surprise that computer simulation was apparently relevant to smallholder farmers in Zimbabwe. Evidence of relevance included the ready participation of farmers in specifying questions to be simulated, in volunteering likely outcomes, in rationalising their expectations with simulated outputs and in re-specifying the question for the next simulation run. The farmers in this engagement were not passive participants, rather they acted as experts in their own domain, using the simulator to explore possible consequences of altered management. All the researchers left the focus meeting with the feeling that real engagement and learning had occurred.

What Process for Engagement?

The farmer meeting commenced with a feeling amongst the researchers of being uncomfortable about planning to use APSIM with farmers, of whom few would have prior knowledge of computers let alone a cropping systems model. However, by day 3, the researchers were readily engaging with the farmers using the model. The approach was to ensure that simulations were presented in a manner that facilitated thinking by all participants—the process was equivalent to playing a farming game. Using a particular farmer for the runs, eliciting his questions, getting other farmers' views, confirming the specifics of the run to be done, asking for their assessment of the outcome, revealing the results and debating what had happened, appeared an appropriate process for this engagement.

Asking the farmers for their estimate of the simulation outcome before presentation worked very well. This process had the farmers thinking about the question. In trying to rationalise the presented attributes of the simulation, it maintained involvement of all farmers, as opposed to just the case study farmer, and it provided them with a challenge which was mildly competitive with their peers. There appeared little sign that a consensus view dominated, as answers varied among groups and between simulations.

Once, when not all views were recorded for an upcoming simulation, the farmers drew attention to their answer for recording. On many occasions, farmers were volunteering their answers before being asked. Answers for early runs (range 1–4 bags, no zeros, no high returns) showed a far narrower range in distribution than the later simulations (0 to >10 bags, included low and high returns). Initially, the farmers seemed to be reluctant to risk being too different from prevailing views, but later this attitude dissipated as they started to think more about the outcomes; they became caught up in the questions being asked rather than worrying about the views of others. These observations were regarded as indicators of learning and confidence in the simulation approach.

Using recent historical rainfall, simulations for each year and asking questions such as ‘*what is your expected (average) benefit?*’ and ‘*how often one would win or lose?*’ worked well. Presentation of the yield difference between the base practice and a new practice worked better than just presenting yields for both practices and expecting farmers to visualise the contrast from graphs and assuming that all will do their own calculations on the difference. The presentation process evolved into not presenting the yields for added simulations but just presenting the differential in bags acre⁻¹ and this worked well.

Why Did Farmers Give the Simulations Credibility?

The participating farmers had no prior knowledge of computer modelling, yet appeared to readily engage in a process of using the model to explore their farming practices. Initially they undoubtedly accommodated the visit because the researchers came to the village as ICRISAT representatives and were joined by the local extension person who was known to the farmers. However, the energy and eagerness of farmers to participate, the ready emergence of new questions, the willingness of farmers to predict the likely results and to explain why certain results occurred, were indicators of real engagement and acceptance of the process.

The process of ‘credibility generation’ commenced by concentrating on last season (2000–01) as a benchmark. The general pattern of daily rainfall was depicted and the performance of maize and groundnut crops was simulated, with simulated yields matching farmer experience impressively

well. Next, the past 11 years of annual rainfall amounts were presented and the focus of discussion was on correspondence of rainfall and simulated yields with farmer experience (e.g. the 1992, 1995 droughts). Again, simulated yields generally conformed with farmer experience.

The meeting changed dramatically from a traditional presentation approach to one of inquiry and discovery-learning during the first case study, when one game farmer challenged the relevance of the information being presented due to use of an inappropriate cultivar in the analyses. By shifting from cultivar sc501 to sc401 at the request of the farmers, rerunning the simulation and simulating their expected change, significant approval seemed to be created, both in giving legitimacy to local knowledge and in demonstrating a process for using the simulator interactively in a discussion.

Farmers’ behaviour indicated that, in addition to finding the simulation outputs to be credible, they found them *meaningful*, apparently because the simulations were specified in the context of a particular farmer and a relevant question. A process in which they could ask questions and related results were available immediately and in a manner where follow-on queries could be addressed was clearly appreciated by the farmers and effective in achieving the researchers’ aims. Researchers to whom this approach was new were comparing this to field experimentation, which often relates to no individual farmer and where results are not available for months and are biased by the influence of one season.

As the meeting progressed the farmers tended to be less critical, accepting the simulation results without due questioning. For example, after the 50 kg fertiliser simulation (yields simulated > 20 bags acre⁻¹), the farmers had to be reminded to be sceptical of simulated results and to reflect on whether such yields are indeed possible and why. The researchers’ intent was to instil in the farmers a view that the simulations were not truth but rather an approximation that is close enough to allow ‘virtual’ experiential learning to take place. Even if such learning were only tentative, it might play an important role in farmers’ future adaptation of their practices.

The Role of Researchers

There can be a clear difference between the approach of external experts trying to think of solutions for farmer clients and an alternative approach of facili-

tating farmers to explore their own options. Some researchers in the group initially wanted to recommend practices in response to simulations rather than ask farmers for their reaction and encourage them to explore the results by questioning them. The idea of such engagements is to make it interactive and an opportunity to learn using the simulator to gain 'virtual experience'. For some research experts, unaccustomed to a facilitation approach, to see the power of this approach and not jump too quickly into lecturing mode proved to be a significant learning experience.

The issue of what is a relevant question emerged as important and problematic amongst the researchers during the farmer interaction. One view was that the high fertiliser option (44 kg N acre⁻¹) in the first case study was not appropriate, as it was beyond the resources of all the participating farmers. Yet, the farmer, Samuel, nominated this option. This simulated scenario actually sparked significant interest and debate amongst the farmers (see description in case study one). Here was an example of taking advantage of simulations which created discrepancies between farmer expectation of results (return on fertiliser 1–5 bags acre⁻¹) and simulated output (1–30 bags acre⁻¹). This helped facilitate discussion and learning about the issue of investing scarce cash resources in fertiliser. It also highlighted the importance of allowing the dialogue among farmers and researchers to *unfold* in accordance with farmers' inquiry, rather than to be overly designed and directed by scientists.

A Learning About the 'Best Place' for the Computer

Over lunch the offer of doing more runs for individual farmers did not create great demand. While one farmer requested an additional run, which was undertaken with her and several other observers, the interaction was clearly not as rich as when the simulations were undertaken as part of a group activity. The results were also presented on the computer rather than transferred to flip charts. This created a distraction of the computer, with the farmers wanting to touch the computer themselves (e.g. to write their name). Having the computer central to running and presenting the results clearly distracted from the results themselves. The process of transferring simu-

lation outputs to flip charts avoided the problem of the computer getting in the way.

Conclusions

Why does a short, three-day interaction warrant such reporting? As a group of research and extension professionals coming from a range of disciplines and perspectives, we started this activity all sceptical that simulation could be directly relevant to smallholder farmers. Our three-day interaction tested this hypothesis and provided evidence that challenges the prevailing view that models may be relevant only as an implement for policy research in smallholder systems (Lynam 1994). Our engagement of smallholder farmers with simulation modelling provided a unique, surprising and exciting experience from which there is opportunity to rethink the role of simulation within an action research framework for direct intervention with farmers in such regions.

Acknowledgments

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References

- Ashby, J. and Sperling, L. 1994. Institutionalising participatory, client-driven research and technology development in agriculture. Agricultural Administration (Research and Extension) Network Paper 49, London, UK, Overseas Development Institute, 21 p.
- Carberry, P.S., Hochman, Z., McCown, R.L., Dalgliesh, N.P., Foale, M.A., Poulton, P.L., Hargreaves, J.N.G., Hargreaves, D.M.G., Cawthray, S., Hillcoat, N. and Robertson, M.J. 2002. The FARMSCAPE approach to decision support: Farmers, Advisers, Researchers' Monitoring, Simulation, Communication, And Performance Evaluation. *Agricultural Systems*, 74, 179–220.
- Defoer, T. and Budelman, A. 2000. Managing soil fertility in the tropics. A resource guide for participatory learning and action research. Amsterdam, The Netherlands, Royal Tropical Institute

- Dimes, J.P., Twomlow, S. and Carberry, P.S. 2003. Application of new tools: exploring the synergies between simulation models and participatory research in smallholder farming systems? ICRISAT Working Paper Series, in press.
- Dingkuhn, M., Jones, M.P., Fofana, B. and Sow, A. 1997. New high yielding, weed competitive rice plant types drawing from *O. sativa* and *O. glaberrima* gene pools. In: Kropff, M.J., Teng, P.S., Aggarwal, P.K., Bouma, J., Bouman, B.A.M., Jones, J.W. and van Laar, H.H., ed., Applications of systems approaches for sustainable agricultural development. Dordrecht, The Netherlands, Kluwer Academic Publishers, 37–52.
- Goldworthy, P. and Penning de Vries, F.W.T., ed. 1994. Opportunities, use, and transfer of systems research methods in agriculture to developing countries. Dordrecht, The Netherlands, Kluwer Academic Publishers, 366 p.
- Hammer, G.L., Kropff, M.J., Sinclair, T.R. and Porter, J.R. 2002. Future contributions of crop modelling—from heuristics and supporting decision making to understanding genetic regulation and aiding crop improvement. *European Journal of Agronomy*, 18, 15–31.
- Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy*, 18, 267–288.
- Lynam, J.K. 1994. Sustainable growth in agricultural production: the links between production, resources, and research. In: Goldworthy, P. and Penning de Vries, F.W.T., ed., Opportunities, use, and transfer of systems research methods in agriculture to developing countries. Dordrecht, The Netherlands, Kluwer Academic Publishers, 3–27.
- McCown, R.L. 2002. Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. *Agricultural Systems*, 74, 179–220.
- McCown, R.L., Hochman, Z. and Carberry, P.S., ed., 2002. Special Issue: probing the enigma of the decision support system for farmers: learning from experience and from theory. *Agricultural Systems*, 74, 1–10.
- Matthews, R.B. and Stephens, W., ed., 2002. Crop–soil simulation models: applications in developing countries. Wallingford, UK, CABI Publishing, 277 p.
- Matthews, R.B., Stephens, W. and Hess, T. 2002. Impacts of crop–soil models. In: Matthews, R.B. and Stephens, W., ed., Crop–soil simulation models: applications in developing countries. Wallingford, UK, CABI Publishing, 195–205.
- Meinke, H., Baethgen, W.E., Carberry, P.S., Donatelli, M., Hammer, G.L., Selvaraju, R. and Stockle, C.O. 2001. Increasing profits and reducing risks in crop production using participatory systems simulation approaches. *Agricultural Systems*, 70, 493–513.
- Okali, C., Sumberg, J. and Farrington, J. 1994. Farmer participatory research. London, Intermediate Technology Publications, 159 p.
- Robertson, M.J., Benson, T. and Shamudzarira, Z. 2000. Simulating nitrogen fertilizer response in low-input farming systems of Malawi. 1. Validation of crop response. Risk Management Working Paper, Mexico, D.F., CIMMYT Series 00/01.
- Shamudzarira, Z. and Robertson, M.J. 2000. Simulating the response of maize to nitrogen fertilizer in semiarid Zimbabwe. Risk management working paper, Mexico, D.F., CIMMYT Series 00/03.
- Shamudzarira, Z., Waddington, S., Robertson, M.J., Keating, B.A., Mushayi, P., Chiduza, C. and Grace, P. 2000. Simulating N fertilizer response in low-input farming systems. 1. Fertiliser recovery and crop response. Risk management working paper, Mexico, D.F., CIMMYT Series 00/05.
- ten Berge, H.F.M. 1993. Building capacity for systems research at national agricultural research centres: SARP's experience. In: Penning de Vries, F.W.T., Teng, P.S. and Metselaar, K., ed., Systems approaches for agricultural development. Dordrecht, The Netherlands, Kluwer Academic Publishers, 515–538.
- Twomlow, S.J. 2001. Linking Logics II: Taking simulation models to the farmers. *British Society of Soil Science Newsletter*, December 2001, No. 40, 12–14.
- 2003. International Crops Research Institute for the Semi-Arid Tropics Global Theme 3: Water, Soil and Agro-diversity Management for Ecosystem Resilience. Annual Report 2002. Matopos Research Station, PO Box 776, Bulawayo, Zimbabwe: International Crops Research Institute for the Semi-Arid Tropics, in press.

**Characterisation of Organic Sources,
and Relevance to Model Parameterisation**

3.1

Chemical Characterisation of a Standard Set of Organic Materials

Catherine N. Gachengo,* Bernard Vanlauwe,* Cheryl A. Palm[†] and George Cadisch[§]

Abstract

This paper reports on the chemical characterisation of a standard sample set prepared for a cross-methods analysis to identify potential proximate analysis methods for the parameterisation of simulation models. In the subsequent sections, these samples are analysed using aerobic incubations, in vitro dry matter digestibility and near infrared reflectance spectrometry. Thirty-two organic materials were collected from various locations in Kenya, comprising plant samples (leaves, stems, leaflets), sawdust and cattle manure. Data obtained from chemical analysis of the materials were used to group the materials into the following quality classes: Class I, %N >2.5%, lignin <15% and soluble polyphenols <4%; Class II, %N > 2.5%, lignin >15% and soluble polyphenol >4%; Class III % N <2.5%, lignin <15%; and Class IV %N <2.5%, lignin >15%. Results showed that materials high in %N were also high in other nutrients (P, Ca, Mg), but potassium was not correlated with N concentration. Class I materials were mainly leaves of leguminous species. Class II comprise mainly *Calliandra calothyrsus* from different locations, as they had polyphenol contents higher than the critical value of 4% and had high protein-binding capacities. They were also low in K concentration (< 1%). Materials in quality class II were subdivided into three categories depending on their polyphenol and lignin contents. Class III materials were crop residues (except for one sample) and were generally low in N, polyphenols and lignin, while class IV (low in N and high in lignin) comprise stems and leaf-litter materials.

Organic materials play a critical role in both short-term nutrient availability and longer-term maintenance of soil organic matter in most smallholder farming systems in the tropics. Over the last decade, the formulation of research hypotheses related to residue quality and N release has led to a vast amount of research aimed at validation of these hypotheses.

Based on much of this work, a minimum data set of resource quality parameters has been proposed for the purpose of identifying robust plant quality indices that provide improved prediction of decomposition, nutrient release and soil organic matter factors which can be coupled with decomposition models (Palm and Rowland 1997).

Plant materials containing at least 2.5% N are usually described as being of high quality, where the application of these materials to soil is likely to result in net release of nitrogen if lignin and polyphenol are <15% and <4%, respectively. On the other hand, plant materials containing less than 2.5% N are considered to be of low quality as they are likely to temporarily immobilise N during decomposition (Palm et al. 2001).

* Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT), PO Box 30677-00100, Nairobi, Kenya <c.gachengo@cgiar.org; b.vanlauwe@cgiar.org>.

[†] The Earth Institute at Columbia University, PO Box 1000 117 Monell Building, 61 Route 9W, Lamont Campus, Palisades, New York 10964-8000, USA <c.palm@cgiar.org>.

[§] Department of Agricultural Sciences, Imperial College London, Wye Campus, Wye, Kent, TN25 5AH, UK <g.cadisch@ic.ac.uk>.

Representation of these quality parameters in simulation modelling is limited, with C:N and lignin content the only parameters presently used by most models. Also, lack of standardisation of analysis has to date not identified robust and cheap methods that can be used to generate the data required for simulation model parameterisation. Therefore, 32 organic materials commonly used in soil fertility management in Kenya, and that covered the four resource categories of Palm et al. (2001) (see Figure 1 of Vanlauwe and Sanginga (2004)), were collected (Table 1) and characterised as an initial step in the process of describing their nutrient supply characteristics.

This paper reports on the proximate analysis conducted by the Tropical Soil Biology and Fertility Institute of CIAT and the analyses of protein-binding capacity conducted by Imperial College at Wye.

Materials and Methods

Total nutrient analysis

Materials were oven dried at 30–35°C and ground to pass through 1 mm sieve. Plant nutrients (N, P, K, Ca and Mg) were analysed through complete oxidation of 0.3 g of material by Kjeldahl digestion using

Table 1. Organic materials and their place of collection.

	Sample name	Place of collection
1	<i>Zea mays</i> stover	W. Kenya
2	<i>Croton megalorapus</i> leaves	W. Kenya
3	<i>Senna spectabilis</i> leaflets	W. Kenya
4	<i>Lantana camara</i> leaves	W. Kenya
5	<i>Calliandra calothyrsus</i> leaflets	W. Kenya
6	<i>Senna siamea</i> leaflets	W. Kenya
7	<i>Crotalaria ochroleuca</i> leaflets	W. Kenya
8	<i>Crotalaria grahamiana</i> leaflets	W. Kenya
9	<i>Tithonia diversifolia</i> leaves	W. Kenya
10	<i>Gliricidia sepium</i> leaflets	W. Kenya
11	<i>Gliricidia sepium</i> leaflets	Machakos
12	<i>Senna siamea</i> leaflets	Machakos
13	<i>Flemingia congesta</i> leaflets	Machakos
14	<i>Senna spectabilis</i> leaflets	Machakos
15	<i>Calliandra calothyrsus</i> leaves	KARI-Embu (Embu provenance)
16	<i>Calliandra calothyrsus</i> leaflets	KARI-Embu (Embu provenance)
17	<i>Calliandra calothyrsus</i> leaves	KARI-Embu (Patalul provenance)
18	<i>Calliandra calothyrsus</i> leaflets	KARI-Embu (Patalul provenance)
19	<i>Calliandra calothyrsus</i> leaves	KARI-Embu (San Ramon Provenance)
20	<i>Calliandra calothyrsus</i> leaflets	KARI-Embu (San Ramon Provenance)
21	<i>Saccharum officinarum</i> stover	Nairobi
22	<i>Lantana camara</i> leaves	Nairobi
23	<i>Lantana camara</i> stems	Nairobi
24	Cattle manure	W. Kenya
25	<i>Tithonia diversifolia</i> leaves	Nairobi
26	<i>Gliricidia sepium</i> stems	Muguga
27	<i>Senna spectabilis</i> leaves	Muguga
28	<i>Sesbania sesban</i> leaves	Muguga
29	<i>Gliricidia sepium</i> leaflets	Muguga
30	<i>Sesbania sesban</i> stems	Muguga
31	<i>Eucalyptus saligna</i> leaf litter	Muguga
32	Sawdust	Muguga

sulfuric acid, hydrogen peroxide and selenium digestion mixture (Anderson and Ingram 1993). Nitrogen and potassium were determined from 5 mL of aliquot of the digestion mixture using an autoanalyser. Phosphorus was determined by adding ammonium molybdate/antimony potassium tartrate solution and ascorbic acid and the absorbance read at 880 nm. Calcium and magnesium were determined by adding 10 mL of 0.15% lanthanum chloride and analysis in an atomic absorption spectrophotometer.

Total carbon analysis

Total carbon was determined by oxidation with concentrated sulfuric acid and 1 M aqueous potassium dichromate mixture with external heating, followed by titration against 0.2 M ferrous ammonium sulfate solution using 1,10 phenanthroline ferrous sulphate indicator (Anderson and Ingram 1993).

Table 2. Quality parameters of organic materials (grouping adapted from Palm et al. (2001)).

Sample name	Plant part	%N	%P	%K	%Ca	%Mg	%C	%PP	% lignin	% soluble carbon	C:N	Protein Binding capacity BSA mg/g plant material
Quality class I (High N, low lignin and PP*)												
<i>Croton megalorapus</i>	leaf	3.38	0.14	1.96	1.54	0.57	41.63	3.09	8.68	7.54	12.3	35.9
<i>Senna spectabilis</i>	leaflets	4.18	0.22	1.56	1.61	0.21	44.25	2.73	8.20	11.94	10.6	18.9
<i>Crotalaria ochroleuca</i>	leaflets	5.32	0.24	1.57	0.91	0.44	45.46	3.13	3.55	10.44	8.6	22.1
<i>Crotalaria grahamiana</i>	leaflets	3.42	0.16	0.64	1.84	0.53	37.82	2.77	4.85	10.12	11.1	21.0
<i>Gliricidia sepium</i>	leaflets	3.79	0.16	0.90	1.89	0.81	43.67	2.87	10.77	13.80	11.5	29.2
<i>Senna spectabilis</i>	leaflets	3.42	0.17	1.27	1.88	0.18	46.45	3.68	9.64	12.85	13.6	11.5
<i>Senna spectabilis</i>	leaf	4.58	0.23	2.04	1.33	0.17	45.46	1.89	11.27	9.94	10.0	26.1
<i>Sesbania sesban</i>	leaf	4.48	0.24	1.13	5.34	0.49	37.02	2.30	2.54	15.10	8.3	30.2
Quality class II (High N, high PP, high lignin)												
<i>Calliandra calothyrsus</i>	leaflets	3.53	0.13	0.50	1.82	0.58	41.90	10.04	14.53	9.21	11.9	117.8
<i>Calliandra calothyrsus</i>	leaflets	3.20	0.10	0.49	1.23	0.39	44.48	9.46	15.79	9.46	13.9	197.8
<i>Flemingia congesta</i>	leaflets	2.90	0.18	0.46	1.64	0.41	40.41	8.63	16.11	11.35	14.0	171.3
Quality class II(High N, high PP, low lignin)												
<i>Lantana camara</i>	leaf	3.45	0.21	2.26	1.53	0.44	41.00	6.15	11.60	8.38	11.9	47.9
<i>Calliandra calothyrsus</i>	leaflets	4.09	0.16	0.60	1.38	0.55	44.45	9.54	8.84	7.60	10.9	163.8
<i>Senna siamea</i>	leaflets	2.93	0.13	0.53	2.39	0.13	44.85	7.23	11.27	9.78	15.3	24.1
<i>Tithonia diversifolia</i>	leaf	3.29	0.27	3.36	1.95	0.48	39.82	5.97	8.16	9.21	12.1	29.3
<i>Calliandra calothyrsus</i>	leaf	3.03	0.12	0.49	1.35	0.47	43.83	14.01	9.78	11.43	14.5	294.7
<i>Calliandra calothyrsus</i>	leaf	3.03	0.11	0.61	0.91	0.40	46.40	14.48	6.21	12.75	15.3	287.6
<i>Calliandra calothyrsus</i>	leaflets	3.10	0.10	0.49	0.89	0.35	46.28	14.77	12.09	12.04	14.9	322.0
<i>Calliandra calothyrsus</i>	leaf	2.61	0.08	0.48	0.99	0.41	45.08	12.26	12.93	10.42	17.3	280.4
<i>Lantana camara</i>	leaf	4.51	0.33	2.59	1.49	0.66	43.67	5.15	6.20	8.51	9.70	12.6
<i>Tithonia diversifolia</i>	leaf	4.25	0.26	4.03	1.93	0.41	37.68	4.85	4.56	9.53	8.9	24.1
Quality class II (High N, high lignin, low PP)												
<i>Gliricidia sepium</i>	leaflets	3.58	0.16	1.44	3.23	0.73	40.53	2.56	15.68	11.86	11.3	21.1
<i>Cattle manure</i>		2.54	0.62	3.56	1.08	0.68	36.98	1.05	17.27	3.74	14.6	48.3
<i>Gliricidia sepium</i>	leaflets	3.78	0.16	2.12	1.85	0.48	40.68	3.50	16.67	11.59	10.8	33.6
Quality class III (Low N, low lignin)												
<i>Zea mays</i>	stover	0.59	0.03	0.80	0.33	0.34	41.30	1.06	4.62	4.84	70.9	14.7
<i>Senna siamea</i>	leaflets	1.99	0.10	0.62	3.25	0.28	43.56	8.14	10.45	11.90	21.8	22.1
<i>Saccharum officinarum</i>	stover	1.22	0.15	2.18	0.28	0.10	40.16	1.51	4.72	4.85	33.4	18.9
<i>Lantana camara</i>	stems	0.95	0.07	1.33	0.32	0.11	42.57	1.48	16.40	3.11	45.0	21.0
Quality class IV (Low N, high lignin)												
<i>Gliricidia sepium</i>	stems	1.64	0.09	2.67	0.97	0.36	42.08	1.30	20.44	5.01	25.7	26.1
<i>Sesbania sesban</i>	stems	0.82	0.04	0.76	0.62	0.12	44.38	0.84	15.09	3.24	54.4	25.2
<i>Eucalyptus saligna</i>	leaf litter	1.03	0.03	0.43	0.95	0.13	46.13	10.83	23.68	8.94	44.8	182.9
saw dust		0.14	0.01	0.05	0.08	0.02	48.57	1.74	29.45	1.40	348.8	19.9

Water-soluble carbon analysis

Water-soluble carbon was obtained by wet oxidation using potassium dichromate. Twenty mL of deionised water was added to 0.03 g plant material in a glass bottle followed by hand shaking. The bottles were placed in a water bath at 100°C for 1 hour with occasional shaking. After filtration, 2 mL of 0.16 M potassium dichromate was added to 10 mL extract in digestion tubes. Another 10 mL of concentrated sulfuric acid was added while mixing on a vortex mixer. The digestion tubes were placed in a pre-heated block at 150°C for 30 minutes, then let cool. Samples were read on a spectrophotometer at 600 nm to obtain carbon concentration.

Total soluble polyphenols

Total soluble polyphenols were determined by the Folin-Ciocalteu method (Constantinides and Fownes 1994). This involved extraction of 0.1 g material with 50% methanol in a water bath at a temperature of 77–80°C for 1 hour. The extract was filtered into a 50 mL conical flask and made to volume with distilled water. Folin-Ciocalteu reagent (2.5 mL) and 10 mL of 17% sodium carbonate was added to 1 mL extract in a 50 mL conical flask, made to volume and left to stand for 30 minutes for colour development. Standard samples of known tannic acid concentration were treated in the same way, and absorbance of the standards and samples was read in a spectrophotometer at 760 nm. Concentration of samples was obtained by plotting absorbance against concentration of standard samples. Percent polyphenol (expressed as tannic acid equivalent) was calculated as:

$$\% \text{ total soluble polyphenols} = (C \times 250)/W$$

where C = corrected concentration of sample in mg mL⁻¹

W = moisture corrected weight of sample in g
250 = a dilution factor.

Lignin content analysis

Lignin was determined through acid detergent fibre (ADF) via Ankom Technology. Plant materials (0.5 g) were placed into fibre bags that were then sealed with a heat sealer. These were placed in an Ankom Machine into which was added 2 litres of extracting solution (solution of sulfuric acid and centyltrimethyl ammonium bromide). Extraction was done for 1 hour at

100°C. The samples were then washed with boiling water, followed by repeated washing with acetone to remove plant pigments. They were then oven dried at 80° C and weighed to determine ADF. The samples were further hydrolysed with 72% sulfuric for 3 hours and washed repeatedly with boiling water followed by drying at 80° C to obtain lignin plus ash. Ashing was done in a muffle furnace at 550°C for 3 hours to destroy lignin and obtain ash. Lignin was then obtained by weight loss upon ashing, using the following formula:

$$\% \text{ lignin} = (W2 - W3)/W1 \times 100$$

where $W1$ = moisture free weight of sample

$W2$ = lignin plus ash weight

$W3$ = ash weight.

Protein-binding capacity

Protein binding capacity of polyphenols was determined by extracting the material using 50% aqueous methanol at 95°C. The extract was centrifuged and applied to chromatographic paper, followed by reaction with bovine serum albumin (BSA). Bound BSA was stained with Ponceou S and its absorbance read at 525 nm followed by conversion of absorbance to protein units using a calibration curve (Handayanto et al. 1994).

Results and Discussion

The proximate analysis enabled the differentiation of the standard sample set into different quality classes depending on their nitrogen, lignin and polyphenol contents (Table 2). Materials in quality class II were further grouped into three categories depending on their polyphenol and lignin contents.

Nitrogen was linearly correlated with all parameters except K and PBC (Table 3). Thus, materials high in N (classes I and II) were also high in phosphorus, calcium and magnesium concentrations, but low in lignin concentration. Potassium concentration was, however, not correlated with N content. Class II materials (mainly *Calliandra calothyrsus*) were generally high in polyphenol contents, and had high protein-binding capacity. Class III materials were low in soluble carbon, polyphenols and protein-binding capacity (except for one material). Class IV materials comprised mainly stems and were generally low in nutrients but high in lignin.

Table 3. Simple linear correlation coefficients for quality parameters.

	%C	%N	%P	%K	%Ca	%Mg	%PP	% Lignin	% Soluble carbon	C:N	PBC
%C	1.00	-0.166	-0.518**	-0.554**	-0.419*	-0.455**	0.001	0.326	0.001	0.366*	0.353
%N		1.00	0.510**	0.275	0.500**	0.556**	0.683**	-0.539**	0.683**	-0.580**	-0.009
%P			1.00	0.687**	0.234	0.480**	0.073	-0.265	0.073	-0.352*	-0.250
%K				1.00	0.041	0.241	-0.173	-0.218	-0.173	-0.277	-0.464**
%Ca					1.00	0.371*	0.662**	-0.313	0.662**	-0.365*	-0.202
%Mg						1.00	0.364*	-0.267	0.364*	-0.443*	0.068
%PP							1.00	0.011	0.419*	-0.210	0.902**
% Lignin								1.00	-0.421*	0.561**	0.106
% Soluble carbon									1.00	-0.542**	0.278
C:N										1.00	-0.133
PBC											1.00

* and ** refer to significance at 5 and 1% confidence levels, respectively, PBC = protein-binding capacity of polyphenols; PP = total soluble polyphenols.

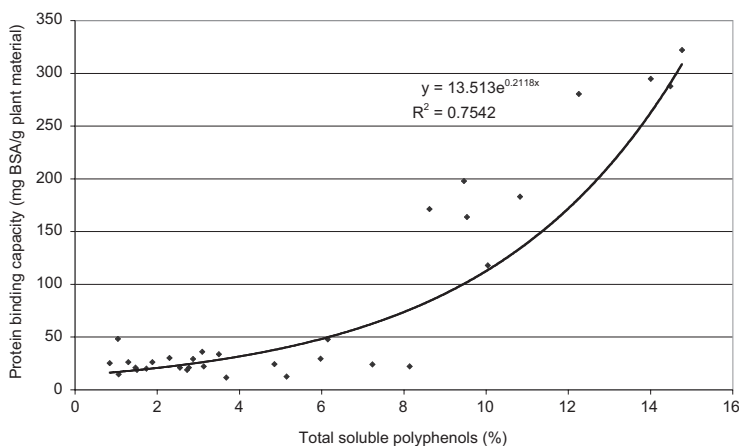


Figure 1. Relationship between total soluble polyphenols and protein binding capacity.

The relationship between protein-binding capacity and total soluble polyphenols is twofold (Fig. 1). From the data, it appears that the relationship can best be described using broken-stick models (see also Handayanto et al. (1997)), with an initial phase (up to about 8% total soluble PP) with few active polyphenols, followed by a linear relationship between total extractable PP and PBC. Polyphenol contents below ~8% resulted in protein-binding capacity < 50 mg BSA g⁻¹.

On the other hand, polyphenol contents above 10% resulted in PBC > 100 mg BSA g⁻¹. Correlation between soluble polyphenols and protein binding capacity ($r = 0.90$) was highly significant (Table 3).

Conclusion

Proximate analysis of the 32 organic materials showed that they covered the four resource quality classes that relate to nutrient release. Materials high in N were low in lignin and high in other nutrients (except K) and, as expected, the soluble polyphenols correlated significantly with protein-binding capacity at higher levels.

References

- Anderson, J.M. and Ingram, J.J. 1993. Tropical soil biology and fertility (TSBF), A handbook of methods (2nd ed.). Wallingford, UK, CAB International, 221 p.
- Constantinides, M. and Fownes, J.H. 1994. Tissue to solvent ratio and other factors affecting determination of soluble polyphenols in tropical leaves. *Communications in Soil Science and Plant Analysis*, 25, 3221–3227.
- Handayanto, E., Cadisch G. and Giller, K.E. 1994. Nitrogen release from prunings of legume hedgerow trees in relation to quality of prunings and incubation method. *Plant and Soil*, 160, 237–248.
- Handayanto, E., Cadisch, G. and Giller, K.E. 1997. Regulating N mineralization from plant residues by manipulation of quality. In: Cadisch, G. and Giller, K.E., ed., *Driven by nature – plant litter quality and decomposition*. Wallingford, UK, CAB International, 175–186.
- Palm C.A., Gachengo C.N., Delve R.J., Cadisch G. and Giller K.E. (2001). Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, Ecosystems and Environment*, 83, 27–42.
- Palm, C.A. and Rowland, A.P. 1997. Chemical characterization of plant quality for decomposition. In: Cadisch, G. and Giller, K.E., ed., *Driven by nature: plant litter quality and decomposition*. Wallingford, UK, CAB International, 379–392.
- Vanlauwe, B. and Sanginga, N. 2004. The multiple roles of organic resources in implementing integrated soil fertility management strategies. These proceedings.

3.2

Mineralisation Patterns of Selected Organic Materials

Catherine N. Gachengo,* Bernard Vanlauwe* and Cheryl A. Palm†

Abstract

Thirty-two standard organic materials were mixed with a sandy soil (at 40% field capacity) at a rate equivalent to 5 t ha⁻¹ and incubated aerobically under controlled conditions at 25°C for 28 days. Sampling for mineral N determination and CO₂ evolution was conducted at 3, 7, 14 and 28 days. Released CO₂ was related to resource quality, with those materials high in N, low in lignin and low in polyphenol concentrations releasing higher percentages of their initial C. In vitro dry matter digestibility (IVDMD) was linearly correlated with carbon breakdown, with correlation coefficients of 0.91, 0.92, 0.92 and 0.84 for sampling times of 3, 7, 14 and 28 days, respectively. Initial N concentration was significantly positively correlated with C breakdown at all sampling times. Nitrogen mineralisation was influenced mainly by initial N concentration of the materials, with materials having at least 2.3% N releasing N throughout the 28-day period.

Organic materials constitute a major soil input in many agricultural systems in the tropics. The effect of these materials on crop production is mainly through their contribution to soil available nutrients, improvement in soil moisture status, especially in relatively dry areas, contribution to organic matter build-up in the soil and enhancement in soil microbial populations that improve nutrient release and availability to plants. Most soils in the tropics are deficient in major plant nutrients such as nitrogen, phosphorus and potassium. The contribution of these materials to soil nutrient availability is subject to nutrient release during the process of decomposition. This process is influenced by several factors, among them quality of the material (Swift et al. 1979). Among the major quality parameters influencing

nutrient release, are nitrogen (N), lignin and soluble polyphenol concentrations. Materials rich in N, and low in soluble polyphenols and lignin, generally readily release nutrients once incorporated into the soil, subject to favourable environmental conditions. Materials low in nitrogen and high in lignin and polyphenol concentrations are likely to immobilise nitrogen during decomposition.

A study was carried out to determine nutrient release patterns of organic materials collected from different parts of Kenya. These materials comprised 30 plant materials (different parts), one cattle manure and one sample of sawdust.

Materials and Methods

Thirty-two organic materials were collected from different parts of Kenya, oven dried at 30–35°C and ground to pass through a 1 mm sieve (Gachengo et al. 2004). Fifty grams of oven-dry soil (78% sand, 4% clay, 8% silt, pH (in water) 5.4, total carbon 0.48%, total N 0.04%) was used. The soil was brought to 40% of field capacity and kept at room temperature

* Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT), PO Box 30677-00100, Nairobi, Kenya <c.gachengo@cgiar.org>; <b.vanlauwe@cgiar.org>.

† The Earth Institute at Columbia University, PO Box 1000 117 Monell Building, 61 Route 9W, Lamont Campus, Palisades, New York 10964-8000 <c.palm@cgiar.org>.

for 2 weeks. The organic materials were thoroughly mixed with the soil at a rate of 5 t ha⁻¹ dry weight basis in 60 mL bottles. These were placed in 250 mL incubation jars containing 10 mL of distilled water to maintain moisture levels during the incubation.

A vial containing sodium hydroxide (10 mL of 0.5 N) was placed in each incubation jar to trap CO₂ released during decomposition of the materials. The jars were tightly sealed with masking tape to avoid leakage of CO₂ produced by the respiring soil and kept in a temperature controlled room at 25°C. Each treatment was replicated three times in a completely randomised design.

Sampling for CO₂ and mineral N determination (nitrate plus ammonium) was done at 3, 7, 14 and 28 days. Determination of mineral N was also done at the beginning of the experiment (time 0). N mineralisation was calculated as net N mineralisation, where the sum of nitrate and ammonium N for each treatment was corrected by subtraction of the control.

Carbon dioxide trapped in the sodium hydroxide solution was determined by titration with 0.5 N hydrochloric acid. Ammonium and nitrate-nitrogen in the soil were determined by extraction using 100 mL of 2 N KCl (Dorich and Nelson 1984).

The amount of carbon released was calculated as:

$$\text{CEVOL} = (\text{BLNKTIT} - \text{SAMTIT}) \times 6 \times N_{\text{HCL}}$$

where CEVOL = evolved C (mg C)

BLNKTIT = volume of standard HCl used to titrate the NaOH in containers from positive controls (mL)

SAMTIT = volume of standard HCl used to titrate the NaOH in containers exposed to the soil atmosphere (mL)

N_{HCL} = normality of standard HCl.

Results and Discussion

Carbon breakdown

The 32 organic materials analysed have been grouped into 6 quality classes depending on their N, lignin and polyphenol contents as described in Gachengo et al. (2004). During the incubation experiment, the high-quality materials (Class I) released the highest amounts of their initial C (Figure 1(a)). By the end of 28 days, materials high in N, high in lignin and high in polyphenols (Figure 1(b)) had released the least amount of their initial C. It appears that there may be interaction between polyphenols and lignin in their

influence on carbon breakdown. Materials high in either lignin or polyphenols alone but high in N (Figure 1(c) and (d)) released more of their initial carbon than those high in both lignin and polyphenols (Figure 1(b)). However, polyphenols appear to play a bigger role in limiting C breakdown than lignin. Materials low in both N and lignin (Figure 1(e)) released more of their initial carbon than those low in N and high in lignin (Figure 1(f)).

Carbon breakdown correlated well (Table 1) with most chemical constituents of the materials (Gachengo et al. 2004). Carbon released at 14 days by various materials linearly correlates well with in vitro dry matter digestibility (data reported by Barrios et al. (2004)). Correlation between the two parameters resulted in four clusters of materials (Figure 2). Cluster 1 represents materials with initial N > 2.5%, lignin and soluble polyphenol contents <15 and <4%, respectively (quality class I). Cluster 2 comprise materials both low and high in N, lignin and polyphenols (classes I, II, III), while cluster 3 consists of materials with N <2.5% and low lignin or polyphenol contents (class III). Cluster 4 is primarily made up of materials of low quality with N < 2.5% and lignin > 15% (class IV). Sawdust would be expected to fall within this cluster, but it lies on its own, probably due to its very high lignin content (29%) and low initial N (0.14%).

Significant positive linear correlation was also found between C released and N concentration. Lignin concentration showed significant negative correlation, while polyphenol concentration had no significant correlation with carbon release. However, on leaving out polyphenol data for stems, manure and stover materials (these are usually very low in polyphenols and nutrients, but high in lignin (Palm et al. 2001), there was a high negative correlation ($r = -0.86$) between carbon release and polyphenol concentration for leaf materials (Figure 3). The same applies to protein-binding capacity.

Multiple linear regression to determine the contribution of N, lignin and polyphenols resulted in the equation with an R^2 value of 0.6598:

$$\text{C28} = 49.69 + 1.687\text{N} - 1.406\text{PP} - 1.144\text{Lignin}$$

where C28 = percentage of initial carbon evolved by 28 days

N = per cent N in material

Lignin = per cent lignin in material

PP = per cent polyphenol in material.

Table 1. Simple linear correlation coefficients for mineralisation of N and C.

	%N	%P	%K	%Ca	%Mg	% total soluble polyphenols	% lignin	% soluble carbon	C:N	% in vitro dry matter digestibility	Protein- binding capacity BSA mg/g plant material
Nitrogen											
Day 3	0.826**	0.445*	0.297	0.510**	0.593**	-0.005	-0.181	0.524**	-0.393	0.414*	-0.038
Day 7	0.836**	0.450*	0.299	0.526**	0.579**	0.022	-0.183	0.563**	-0.407*	0.429*	-0.026
Day 14	0.896**	0.506**	0.351*	0.581**	0.615**	0.065	-0.334	0.651**	-0.589**	0.554**	-0.021
Day 28	0.915**	0.526**	0.352*	0.570**	0.648**	0.109	-0.415*	0.690**	-0.636**	0.621**	0.001
Carbon											
Day 3	0.709**	0.271	0.214	0.681**	0.435*	-0.233	-0.626**	0.662**	-0.449**	0.910**	-0.365*
Day 7	0.656**	0.328	0.290	0.631**	0.408*	-0.310	-0.673**	0.588**	-0.451**	0.925**	-0.432*
Day 14	0.639**	0.279	0.267	0.579**	0.395*	-0.362*	-0.706**	0.523**	-0.458**	0.923**	-0.454**
Day 28	0.418*	0.147	0.205	0.502**	0.225	-0.471**	-0.651**	0.409*	-0.423*	0.848**	-0.538**

* and ** refer to significance at 5 and 1% levels, respectively.

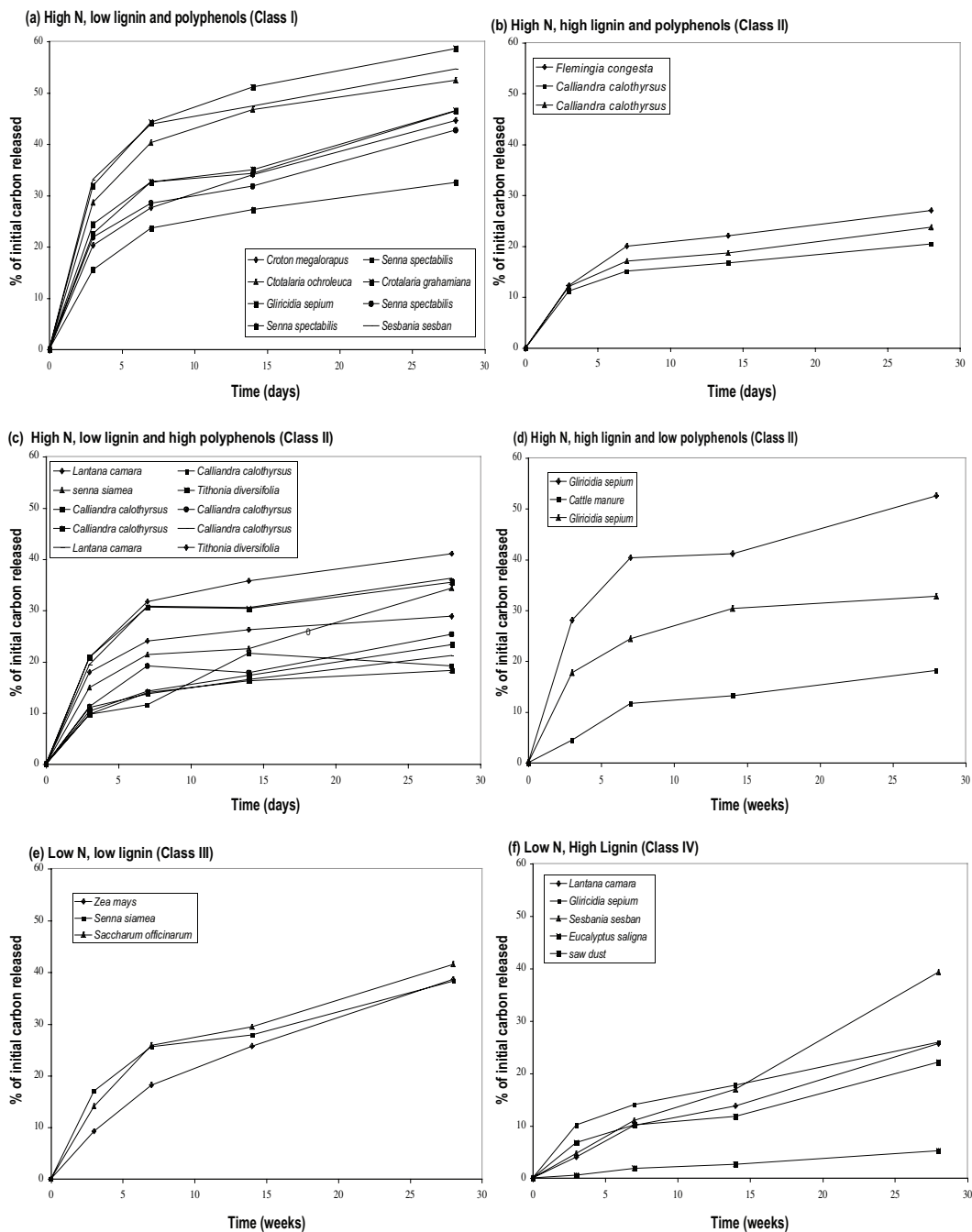


Figure 1. Carbon mineralisation patterns of different quality classes.

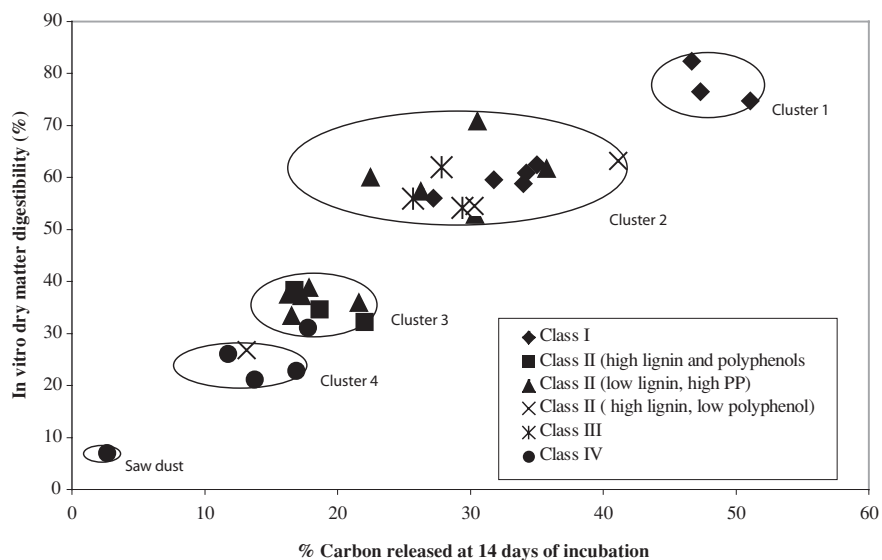


Figure 2. Relationship between in vitro dry matter digestibility and carbon release.

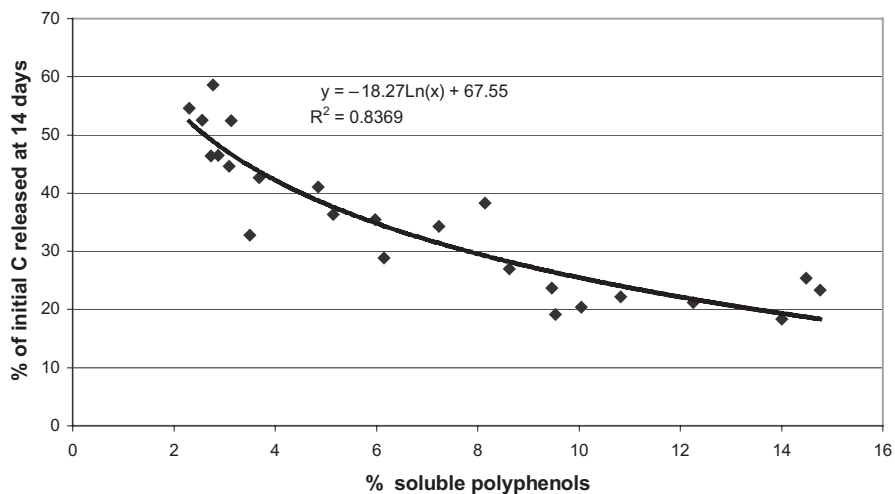


Figure 3. Effect of soluble polyphenols on carbon release of organic materials.

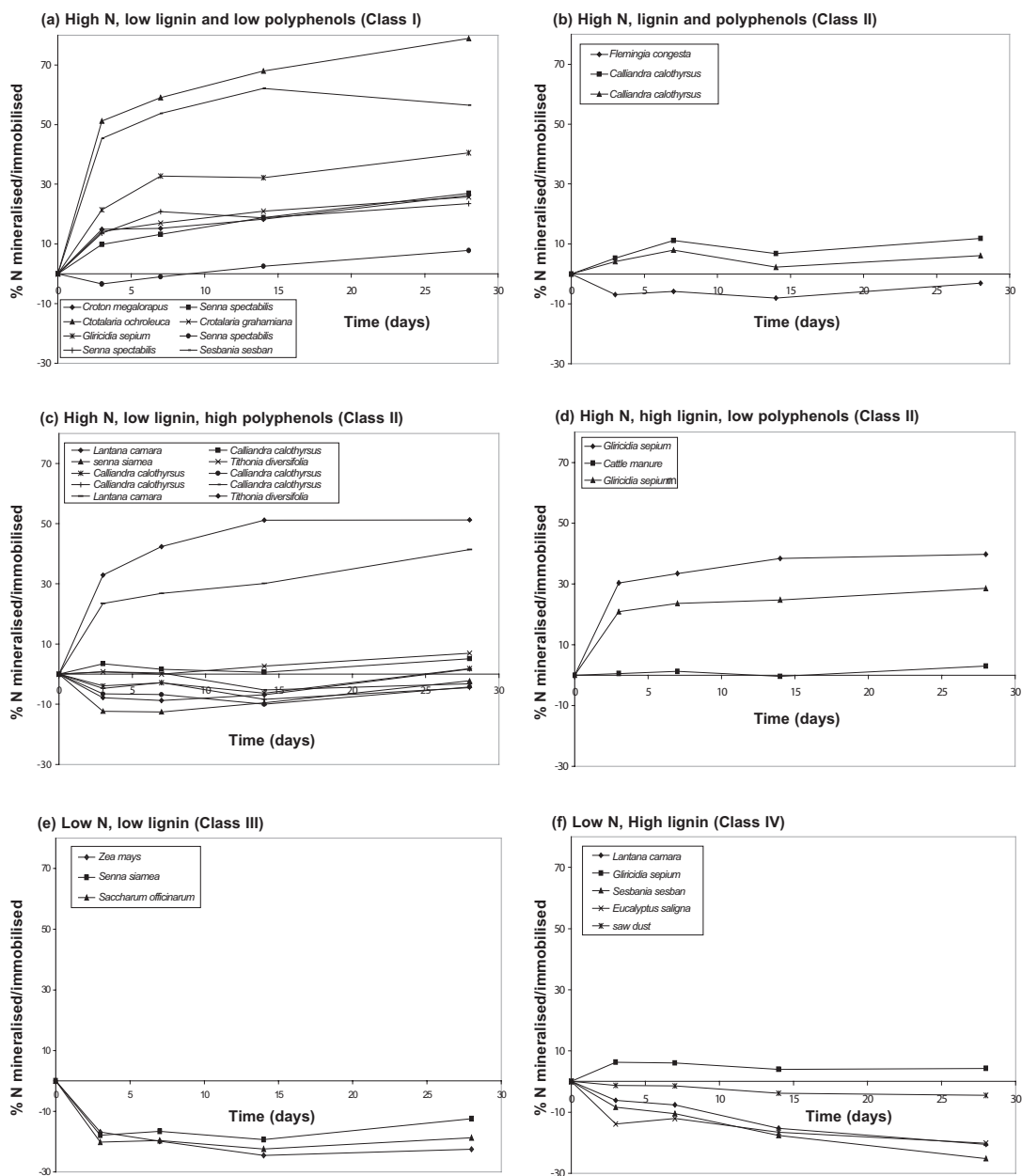


Figure 4. Nitrogen mineralisation patterns from organic materials.

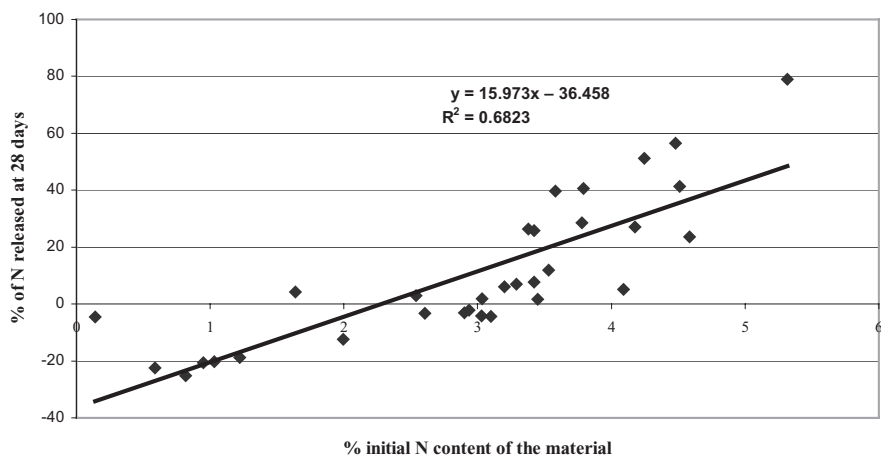


Figure 5. Effect of initial N content on N mineralisation.

Thus, about 66% of variation in carbon mineralised by 28 days was accounted for by N, lignin and polyphenols contents of the materials.

Nitrogen mineralisation

Organic materials in Class I released N through the 28-day period except for one material that immobilised N during the first 7 days of incubation (Figure 4 (a)). This may be explained by its polyphenol content (3.81%), which was very close to the critical level (4%) required for net N mineralisation to occur. Most materials high in both N and polyphenol (but low in lignin) (Figure 4(c)) immobilised N for some time or throughout the 28 days, while those high in N and lignin (but low in polyphenols) (Figure 4(d)) mineralised N throughout the study period. Thus, polyphenols had a higher influence in limiting N mineralisation than lignin. Materials in class III immobilised N throughout the 28 days due to their low initial N content. However, there was a reduction in immobilisation after 14 days of incubation. Materials in class IV immobilised N, increasingly with time. The trend does not show any indication of net mineralisation taking place in the near future (Figure 4(f)).

The most significant positive correlation for nitrogen release at 28 days was with the N concentration of the materials (Table 1). Most materials whose nitrogen concentration was at least 2.3% released nitrogen (Figure 5). Materials with %N above 2.3% but soluble polyphenol above 4% immo-

bilised N. *Gliricidia sepium* stems, though low in N (1.64%) and high in lignin (20.44%), did not immobilise N probably due to their low polyphenol concentration (1.3%). This suggests that N mineralisation of the materials was controlled mainly by their N and polyphenols contents.

Multiple regression analysis showed N mineralisation was mainly influenced by N concentration in the materials (Table 1), the following equation having an R^2 value of 0.846:

$$N28 = -97.81 - 0.00021PP + 28.85N + 0.698Lignin$$

where N28 = percentage of initial N mineralised by 28 days.

Conclusion

Mineralisation is a complex process that is governed by several factors, among them quality of the material. During the early stages of decomposition, it appears that N and polyphenol contents are the main quality parameters that determine mineralisation of nitrogen. For net N mineralisation to take place during the early stages of decomposition, a combination of low polyphenol and high nitrogen concentrations is required. Carbon breakdown was also influenced by the presence of lignin, with materials high in both lignin and polyphenols releasing less C. However, lignin did not appear to influence N mineralisation significantly, at least during the first 28 days of decomposition.

References

- Barrios, E. 2004. The *in vitro* dry matter digestibility method. These proceedings.
- Dorich, R.A. and Nelson, D.W. 1984. Evaluation of manual cadmium reduction methods for determination of nitrate in potassium chloride extracts of soils. Soil Science Society of America Journal, 48, 72–75.
- Gachengo, C.N., Vanlauwe, B., Palm, C.A. and Cadisch, G. 2004. Chemical characterisation of a standard set of organic materials. These proceedings.
- Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G. and Giller, K.E. 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agriculture, Ecosystems and Environment, 83, 27–42.
- Swift, M.J, Heal, O.W. and Anderson, J.M. 1979. Studies in terrestrial ecosystems. Oxford, UK, Blackwell Scientific Publication, 118–165.

3.3

The In Vitro Dry Matter Digestibility (IVDMD) Method

Edmundo Barrios*

Abstract

In vitro dry matter digestibility (IVDMD) is reported for a standard set of organic materials. IVDMD ranged from 82% for leaflets of the legume *Crotalaria ochroleuca* to 7% for sawdust.

In a review by Chesson (1997) it was proposed that decomposition processes in the rumen and in the soil, although different, were sufficiently similar to be considered for comparative plant tissue studies. Studies by Tian et al. (1996) supported this hypothesis, by showing that plant degradation during in situ ruminant nylon bag assay correlated with decomposition in a litter-bag study. More recently, Cobo et al. (2002) showed that the in vitro dry matter digestibility (IVDMD) method, which simulates in vitro processes taking place in the rumen of cattle during plant digestion, was closely related with decomposition processes for 12 plant materials with different tissue qualities (Figure 1).

The highly significant ($P < 0.001$) correlations obtained during this study between IVDMD and plant decomposition suggested that laboratory-based IVDMD tests could be used as surrogates for decomposition of plant tissues in the field (Cobo et al. 2002). In the present study, the importance of this finding to model parameterisation was further evaluated by assessing their IVDMD values of 32 standard organic materials covering a wider range of tissue qualities.

Method

The IVDMD is a laboratory test used as a plant quality index for animal feed by animal nutritionists (Tilley and Terry 1963; Harris 1970). The method includes two consecutive digestion phases. During the first digestion phase in this study, plant materials were incubated under anaerobic conditions with rumen microorganisms for 48 hours at 39°C. This was followed by a 24 hour acid-pepsin digestion phase at 39°C, under anaerobic conditions. Following this 72 hour incubation, residual plant materials were collected and oven dried (105°C for 12 hours). Ash contents were determined by combustion (550°C for 2 hours) and these data used to correct plant sample weight for potential contamination with soil.

Calculations were made using the following equation:

$$\%IVDMD = (1 - wd - wb/ws) \times 100$$

where wd = weight of dry plant residue, wb = weight of dry residues from blank, and ws = dry weight of original plant sample.

Results and Discussion

The IVDMD method showed a wide range of qualities in the 32 plant materials tested related to their differing chemical compositions (Table 1). The highest IVDMD value (82.4%), corresponding to

* Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT), CIAT, A. A. 6713, Cali, Colombia <e.barrios@cgiar.org>.

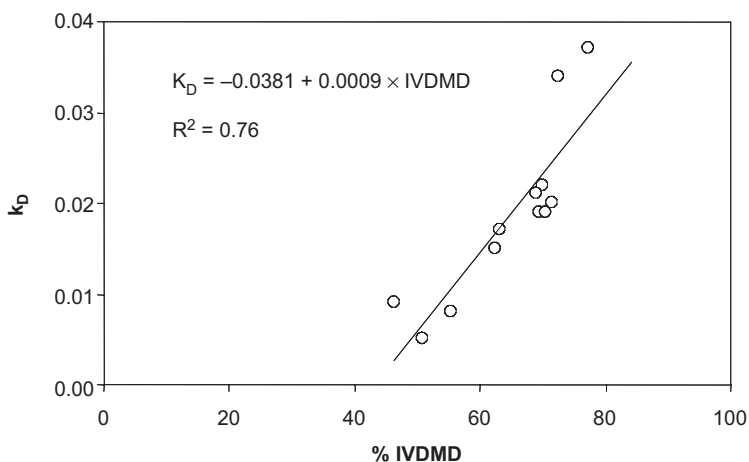


Figure 1. Linear regression between in vitro dry matter digestibility (IVDMD) of plant materials and their respective rates of decomposition (K_D). N=12. Reproduced from Cobo et al. (2002).

Table 1. In vitro dry matter digestibility (IVDMD) values for 32 standard organic materials.

Lab ID	Plant name	Plant part	IVDMD (%)
TSBF1	<i>Zea mays</i>	Stover	55.91
TSBF2	<i>Croton megalocarpus</i>	Leaf	58.78
TSBF3	<i>Senna spectabilis</i>	Leaflets	60.88
TSBF4	<i>Lantana camara</i>	Leaf	57.36
TSBF5	<i>Calliandra calothyrsus</i>	Leaflets	35.88
TSBF6	<i>Senna siamea</i>	Leaflets	60.03
TSBF7	<i>Crotalaria ochroleuca</i>	Leaflets	82.37
TSBF8	<i>Crotalaria grahamiana</i>	Leaflets	74.73
TSBF9	<i>Tithonia diversifolia</i>	Leaf	52.85
TSBF10	<i>Gliricidia sepium</i>	Leaflets	62.48
TSBF11	<i>Gliricidia sepium</i>	Leaflets	63.21
TSBF12	<i>Senna siamea</i>	Leaflets	61.94
TSBF13	<i>Flemingia congesta</i>	Leaflets	32.21
TSBF14	<i>Senna spectabilis</i>	Leaflets	59.59
TSBF15	<i>Calliandra calothyrsus</i>	Leaves	37.51
TSBF16	<i>Calliandra calothyrsus</i>	Leaflets	38.36
TSBF17	<i>Calliandra calothyrsus</i>	Leaves	38.85
TSBF18	<i>Calliandra calothyrsus</i>	Leaflets	37.18
TSBF19	<i>Calliandra calothyrsus</i>	Leaves	33.41
TSBF20	<i>Calliandra calothyrsus</i>	Leaflets	34.64
TSBF21	<i>Saccharum officinarum</i>	Stover	54.12
TSBF22	<i>Lantana camara</i>	Leaves	70.83
TSBF23	<i>Lantana camara</i>	Stems	21.15
TSBF24	Cattle manure		26.84
TSBF25	<i>Tithonia diversifolia</i>	Leaves	61.67
TSBF26	<i>Gliricidia sepium</i>	Stems	31.08
TSBF27	<i>Senna spectabilis</i>	Leaflets	58.06
TSBF28	<i>Sesbania sesban</i>	Leaves	76.48
TSBF29	<i>Gliricidia sepium</i>	Leaflets	54.52
TSBF30	<i>Sesbania sesban</i>	Stems	22.80
TSBF31	<i>Eucalyptus saligna</i>	Leaf litter	26.02
TSBF32	Sawdust		6.99

rapid decomposition rates, was found for leaflets of the legume *Crotalaria ochroleuca*. Intermediate values were found for leaves of *Calliandra calothyrsus* (38.9%). The lowest IVDMD value (7%), corresponding to slow decomposition rates, was measured for sawdust.

The IVDMD results were consistent with expected results based on existing information in the literature and in our databases. This observation further confirms the potential of this test to save time and variability associated with decomposition studies in the field. This finding could also be of practical importance for screening plant materials for different farm uses and could be linked to decision-tree schemes similar to those reported by Palm et al. (2001).

References

- Chesson, A. 1997. Plant degradation by ruminants: parallels with litter decomposition in soils. In: Cadisch, G. and Giller, K.E., ed., *Driven by nature: plant litter quality and decomposition*. Wallingford, Oxon, CAB International, 47–66.
- Cobo, J.G., Barrios, E., Kass, D.C.L. and Thomas, R.J. 2002. Decomposition and nutrient release by green manures in a tropical hillside agroecosystem. *Plant and Soil*, 240, 331–342.
- Harris, L.E. 1970. *Métodos para el Análisis Químico y la Evaluación Biológica de Alimentos para Animales*. Center for Tropical Agriculture, Feed Composition Project, University of Florida. 183 p.
- Palm, C.A., Giller, K.E., Mafongoya, P.L. and Swift, M.J. 2001. Management of organic matter in the tropics: translating theory into practice. *Nutrient Cycling in Agroecosystems*, 61, 63–75.
- Tian, G., Kang, B. and Lambourne, L.J. 1996. Ruminant assay for rapidly estimating plant residues decomposability in the field. *Pedobiologia*, 40, 481–483.
- Tilley, J.M.A. and Terry, R.A. 1963. A two stage technique for the in vitro digestion of forage crops. *Journal of the British Grassland Society*, 18, 104–111.

3.4

Predicting Decomposition Rates of Organic Resources Using Near Infrared Spectroscopy

Keith D. Shepherd*

Abstract

Organic resources constitute a major source of nutrient inputs to both soils and livestock in smallholder tropical production systems. Information on decomposition characteristics is needed for sound management of organic resources. Measurement of C and N mineralisation rates and dry matter digestibility using current laboratory methods is both time-consuming and costly. This study tested near infrared (wavelengths from 1.0 to 2.5 μm) reflectance spectroscopy (NIRS) for rapid prediction of C and N mineralisation rates and in vitro dry matter digestibility for a diverse range of organic resources ($n = 32$). The organic resource samples were aerobically incubated in a sandy soil and amounts of C and N mineralised determined after 28 days. Organic resource attributes were calibrated to first derivative reflectance using partial least squares regression. Cross-validated r^2 values for actual versus predicted values were 0.82 for percentage of added C mineralised, 0.84 for percentage of added N mineralised, and 0.88 for in vitro dry matter digestibility. NIRS can be used for routine prediction of decomposition and nutrient release characteristics of organic resources. Construction of spectral calibration libraries in central laboratory facilities would greatly increase the efficiency of NIRS use for routine organic resource characterisation in laboratories throughout the world.

Organic resources constitute a major source of nutrient inputs to both soils and livestock in smallholder tropical production systems. The quality of organic resources regulates the potential rate of decomposition and availability of those nutrients, both in the soil and the rumen. Although the actual rate and degree of decomposition are moderated by the local activity of the decomposer organisms and the environmental conditions, plant litter quality is the factor most amenable to management in agricultural systems (Giller and Cadisch 1997; Heal et al. 1997). Recently, efforts have been undertaken to compile global information on decomposition and resource quality attributes as a basis for more systematic experimentation and development of predictive models (Palm et al. 2001). Using this diverse

collection, Shepherd et al. (2004) demonstrated that near infrared spectroscopy (NIRS) can be used as a non-destructive method for rapid analysis of N, total soluble polyphenol and lignin concentration in organic resources. These quality attributes of organic resources largely determine their decomposition and nutrient release rates. The objectives of this study were to test the robustness of NIRS for direct prediction of C and N mineralisation rates and in vitro dry matter digestibility for a diverse set of samples from the organic resource database.

Methods

Thirty-two samples were selected from the organic resource database to represent a range of N, total soluble polyphenol and lignin concentrations (Gachengo et al. 2004b). The plant materials were aerobically incubated in sandy soil for 28 days as

* World Agroforestry Centre (ICRAF), PO Box 30677-00100, Nairobi, Kenya <k.shepherd@cgiar.org>.

described by Gachengo et al. (2004a). The total amounts of C and N mineralised after 28 days were expressed as a percentage of their respective initial amounts added. The incubations were conducted in triplicate. In vitro dry matter digestibility was determined on the same materials in duplicate using standard methods (Barrios 2004). Diffuse reflectance spectra were recorded for each sample using a FieldSpec™ FR spectroradiometer (Analytical Spectral Devices Inc., Boulder, Colorado) at wavelengths from 1.0 to 2.5 μm , with a spectral sampling interval of 0.001 μm . Dried and ground (<1 mm) plant material was placed into 7.4 cm diameter Duran glass Petri dishes to a thickness of about 1 cm. The samples were scanned through the bottom of the Petri dishes using a high intensity source probe (Analytical Spectral Devices Inc., Boulder, Colorado). The probe illuminates the sample (4.5 W halogen lamp giving a correlated colour temperature of 3000 K; WelchAllyn, Skaneateles Falls, NY) and collects the reflected light from a 3.5 cm diameter sapphire window through a fibre-optic cable.

To sample within-dish variation, reflectance spectra were recorded at two positions, successively rotating the sample dish through 90° between readings. The average of 25 spectra (the manufacturer's default value) was recorded at each position to minimise instrument noise. Before reading each sample, 10 white reference spectra were recorded using calibrated spectralon (Labsphere®, Sutton, NH) placed in a glass Petri dish. Reflectance readings for each wavelength band were expressed relative to the average of the white reference readings. With this method, a single operator can comfortably scan 500 samples a day.

The raw spectral reflectance data were pre-processed before statistical analysis as follows. Relative reflectance spectra were resampled by selecting every hundredth-micrometre value from 1.0 to 2.5 μm . This was done to reduce the volume of data for analysis and to match it more closely to the spectral

resolution of the instrument (0.003–0.01 μm). The reflectance values were then transformed with first derivative processing (differentiation with second-order polynomial smoothing with a window width of 0.02 μm) using a Savitzky-Golay filter, as described by Fearn (2000). Derivative transformation is known to minimise variation among samples caused by variation in grinding and optical set-up (Marten and Naes 1989). Multiplicative scatter correction (used to compensate for additive and/or multiplicative effects in spectral data) and normalisation (sample-wise scaling) of the reflectance data (both described in Vandeginste et al. (1998)) did not improve calibrations and so were not used. Wavebands in regions of low signal-to-noise ratio or displaying noise due to splicing between the individual spectrometers (Analytical Spectral Devices Inc. 1997) were omitted leaving 148 wavebands for analysis. The omitted bands were 1.00–1.01 μm , and 2.50 μm .

The data from the laboratory reference methods were calibrated against the reflectance wavebands using partial least squares regression, using 'The Unscrambler' (Camo ASA, Oslo) software. Hold-out-one full-cross validation was used to evaluate the stability of the calibrations. Jack-knifing was performed to eliminate unreliable (non-significant) wavebands, in order to simplify the final model and make it more reliable. Prediction success was evaluated on reference and actual observations using the coefficient of determination (r^2), root mean square error (RMSE) and bias.

Results and Discussion

Robust partial least squares calibrations were obtained for all the three reference methods (Table 1). There was more scatter in the calibration at low than high nitrogen mineralisation values (Figure 1), most likely reflecting imprecision in the laboratory

Table 1. Statistics for calibration and full-cross validation models for predicting decomposition reference values from near infrared reflectance.

Reference method	Calibration			Validation		
	r^2	RMSE	Bias	r^2	RMSE	Bias
C mineralisation	0.92	3.2	-8.9E-7	0.84	4.6	0.08
N mineralisation	0.89	13	1.7E-6	0.84	16	0.22
IVDM digestibility	0.95	3.9	-9.3E-7	0.88	6.3	-0.15

RMSE = root mean square error of calibration.

IVDM = in vitro dry matter digestibility.

measurements at very low plant nitrogen concentrations. The lowest calibration point for in vitro dry matter digestibility (sawdust sample) was underestimated in the cross-validated predictions (Figure 2). Having more samples with low digestibility in the calibration data set would improve the calibration.

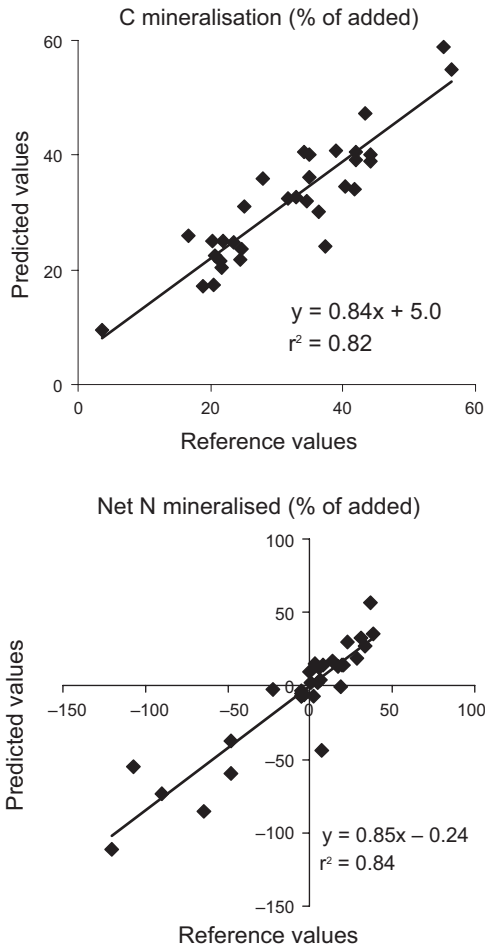


Figure 1. Spectrally predicted values versus laboratory reference values for amount of carbon and nitrogen mineralised from organic materials incubated in soil. The results are based on predictions using hold-out-one, full cross-validation.

Conclusion

NIRS shows promise for direct prediction of decomposition and nutrient-release characteristics of

organic resources, obviating the need for tedious determination of organic resource attributes in the laboratory and the development of predictive models based on these attributes. Large spectral calibration libraries (Shepherd and Walsh 2002) for organic resources decomposition and nutrient-release characteristics should be built up in central laboratories. Then sets of standards will be all that is needed to cross-calibrate individual laboratory spectrometers to the central laboratory spectrometer. In this way, the efficiency of analysis of organic resource quality can be greatly increased. Further work should compare the accuracy and precision of the NIRS predictions of decomposition rates with predictions derived from attributes of organic resource quality determined by conventional laboratory methods, or with actual breakdown and related soil changes or growth responses in the field. The potential for widespread use of NIRS of measuring residue quality will increase as the laboratory uses for NIRS increase and the relative cost declines.

Acknowledgments

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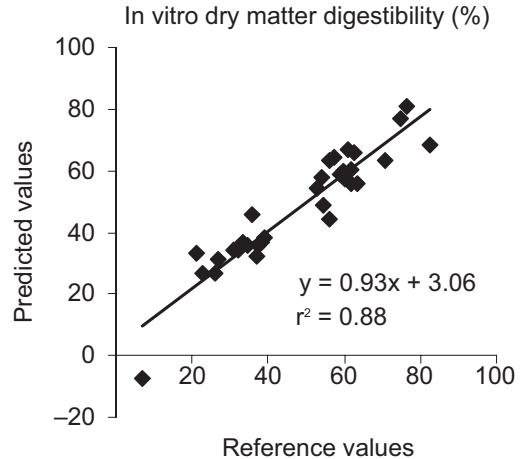


Figure 2. Spectrally predicted values versus laboratory reference values for in vitro dry matter digestibility of organic materials incubated in soil. The results are based on predictions using hold-out-one, full cross-validation

References

- Analytical Spectral Devices Inc. 1997. FieldSpec™ User's Guide. Boulder, Colorado, USA, Analytical Spectral Devices Inc.
- Barrios, E. 2004. The *in vitro* dry matter digestibility (IVDMD) method. These proceedings.
- Fearn, T. 2000. Savitzky-Golay filters. NIR News, 11(6), 14–15.
- Gachengo, C.N., Vanlauwe, B., and Palm, C.A. 2004a. Mineralization patterns of selected organic materials. These proceedings.
- Gachengo, C.N., Vanlauwe, B., Palm, C.A., and Cadisch, G. 2004b. Chemical characterization of a standard set of organic materials. These proceedings.
- Giller, K.E. and Cadisch, G. 1997. Driven by nature: a sense of arrival or departure. In: Cadisch, G. and Giller, K.E., ed Driven by nature: plant litter quality and decomposition. Wallingford, UK, CAB International, 393–399.
- Heal, O.W., Anderson, J.E. and Swift, M.J. 1997. Plant litter quality and decomposition: an historical overview. In: Cadisch, G. and Giller, K.E., ed Driven by nature: plant litter quality and decomposition. Wallingford, UK, CAB International, 3–30.
- Martens, H. and Naes, T. 1989. Multivariate calibration. Chichester, UK, Wiley.
- Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G. and Giller, K.E. 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agriculture Ecosystems and Environment, 83, 27–42.
- Shepherd, K.D., Palm, C.A., Gachengo, C.N. and Vanlauwe, B. 2004. Rapid characterization of organic resource quality for soil and livestock management in tropical agroecosystems using near infrared spectroscopy. Agronomy Journal, in press.
- Shepherd, K.D. and Walsh, M.G. 2002. Development of reflectance spectral libraries for characterization of soil properties. Soil Science Society of America Journal, 66, 988–998.
- Vandeginste, B.M.G., Massart, D.L., Buydens, L.M.C., De Jong, S., Lewi, P.J. and Smeyers-Verbeke, J. 1998. Handbook of chemometrics and qualimetrics: Part B. Data handling in science and technology—Volume 20B. Amsterdam, Elsevier.

3.5

Analysis of Organic Resource Quality for Parameterisation of Simulation Models

B. Vanlauwe*

Abstract

Updating of simulation models to incorporate new thinking on parameters that influence decomposition and hence nutrient release in the soil has been slow, with most models relying on N and lignin contents as determinants of decompositions. In addition, these analyses are expensive and time-consuming. This paper summarises the papers on analysis of the standard sample set of 32 different quality organic materials and how this can be linked to parameterisation and improvement of simulation models.

From this cross-method analysis, the minimum data set to assess organic resource quality consists of N, lignin and soluble polyphenol content, which is consistent with conclusions from earlier efforts. When considerations of cost and speed are included in the analysis, aerobic incubation is one of the cheapest, but also it's the slowest method. NIR, on the other hand, is the fastest method, but also most expensive until it is used for routine assessments.

Class III resources needed solely N content measured, whereas for Classes I and II there were no single quality indices. For Class III resources that show positive mineralisation with time, including polyphenol content in the decomposition routines of simulation models would increase the accuracy of prediction.

During the 1990s, the formulation of research hypotheses related to residue quality and N release led to a vast amount of projects aiming at validation of these hypotheses. Based on all this information, Palm et al. (2001) compiled the 'organic resource database' (ORD), which contains information on organic resource quality parameters including macronutrients, lignin and polyphenol contents of fresh leaves, litter, stems and/or roots from almost 300 species found in tropical agroecosystems. In addition, it contains many records of animal manures and livestock feed species. The database is available for downloading from the Internet at <http://www.ciat.cgiar.org/catalogo/producto.jsp?codigo=P0215>.

Following careful analysis of a large number of N-mineralisation studies using a wide range of organic resources, Palm et al. (2001) proposed a conceptual decision-support system (DSS) for organic N management. The DSS proposes four classes of organic resources, each having specific management options. Class I contains materials with high N (> 2.5%), low soluble polyphenol (< 4%), and low lignin (< 15%) content, and it is proposed that they be applied directly to a growing crop. The proposal for classes II and III is that they be mixed with either fertiliser or class I materials, as they have either a high N and high polyphenol content (class II) or a low N, low polyphenol and low lignin content (class III). Class IV materials have a low N and high lignin content and the recommendation is that they be applied as surface mulch.

Over the years, the range of organic resource quality characteristics found to affect the decomposition and mineralisation process has broadened.

* Tropical Soil Biology and Fertility Institute of CIAT, PO Box 30677, Nairobi, Kenya <b.vanlauwe@cgiar.org>.

Originally, the C/N ratio was seen to relate well with N availability. Mellilo et al. (1982) showed that the N and lignin content of hardwood leaf litter residues significantly affected their decomposition. Palm et al. (1997) introduced the soluble polyphenol content in organic resource quality–N-mineralisation relationships, while Handayanto et al. (1994) showed that the content of soluble polyphenols that were actively binding proteins was better related to decomposition than the total soluble polyphenol content itself. One of the ‘traditional’ assessments for C and N mineralisation is an aerobic incubation under controlled conditions for a number of weeks. Recently, some efforts have been made to short-cut this procedure by adapting *in vitro* approaches used by animal nutritionists (Tian et al. 1996; Cobo et al. 2002).

Description of a standard method(s) to establish resource quality characteristics that can be used to parameterise simulation models is needed. Therefore, the objectives of this work were to use a large and well-chosen range of organic resources covering the complete organic resource quality spectrum (Class I to Class IV) to measure resource quality and decomposition, in order to: (i) explore relationships between aerobic incubation, *in vitro* digestibility and near-infrared reflectance spectrometry approaches for assessing short-term organic resource decomposition; (ii) to evaluate relationships between short-term decomposition dynamics and organic resource characteristics; and (iii) to reflect on the minimum data set needed to predict short-term N mineralisation dynamics.

Materials and Methods

Organic materials were collected from different parts of Kenya (Gachengo et al. 2004b), and their resource quality was determined using a variety of standard and less commonly used characteristics. The C and N mineralisation of all organic resources was measured in an aerobic incubation experiment (Gachengo et al. 2004a) and through an *in vitro* dry matter digestibility (IVDMD) method (Barrios 2004). Near infrared reflectance spectroscopy (NIRS) (wavelengths from 1.0 to 2.5 μm) was used for rapid prediction of C and N mineralisation rates and IVDMD (Shepherd 2004).

Data analysis

Simple and multiple regression (STEPWISE method) techniques (SAS 1985) were used to relate decomposition dynamics with various organic resource characteristics. For C mineralisation and IVDMD data, a single multiple-regression model was used, while for the N mineralisation data, separate models were run for the treatments with negative and positive percentages of applied N mineralised. This was done because the ‘traditionally’ used calculation procedure results in a discontinuity when the percentage N mineralised is zero.

Results

Simple linear regression analysis shows that cumulative C release after 28 days is linearly related to especially the lignin content, the polyphenol/N ratio and the PBC/N ratio of the organic resources, where PBC is the protein-binding capacity (Table 1). Cumulative N release after 28 days is highly significantly related to the N content, soluble C content, and soluble C/N ratio of the organic materials. For the IVDMD, the resource quality parameters yielding the most significant relationships are the N content, the lignin content, and the PBC:N ratio.

NIRS first calibrated the organic resource attributes to first derivative reflectance using partial least squares regression. Cross-validated r^2 values for actual versus predicted values were 0.84 for percentage of added C mineralised, 0.84 for percentage of added N mineralised, and 0.88 for IVDMD (Shepherd 2004).

Multiple regression analysis shows that soluble C, polyphenol, and lignin content of the organic resources explain 86% of the variation in cumulative C mineralisation (Table 2). When using IVDMD data, soluble C and lignin content and PBC explain 89% of its variation. For residues with positive N-mineralisation values, the N and polyphenol content of the organic resources explain 60% of the variation in N mineralisation at day 28. For all other residues, 90% of the variation was explained by their N content (Table 2).

Figure 1 showed three classes of organic resources: one class with N-mineralisation values significantly above 0 (Class I), one class with values not different from 0 (Class II), and a third class with values significantly below 0 (Class III). When considering only Class III data, a highly significant

linear relationship was observed between N mineralisation and the N content of the organic resources (Figure 2a). For Class I data, no significant relationships between N mineralisation and any specific organic resources quality parameter were observed. Excluding the *Gliricidia* samples, however, N mineralisation was linearly related with the lignin/N ratio of the organic resource (Figure 2b).

For organic resources with high polyphenol or lignin content, the IVDMD assay-based assessment of decomposition correlated well with the aerobic incubation assay (Figure 3). This was, however, not true for organic resources with low polyphenol and

lignin content. This may not be surprising, as the IVDMD assay is based on an anaerobic microbial decomposition phase and an enzyme digestion phase. Both phases are unlikely to be affected by lack of N for optimal decomposition of the organic resources with low biochemical resistance against decomposition. In the aerobic decomposition process, however, lack of mineral N may hamper the decomposition of organic resources with low N. For organic resources with either high polyphenol or lignin content, the organic resources themselves show some biochemical protection against decomposition, independent of the availability of N.

Table 1. R^2 values of the simple linear regressions between selected decomposition parameters and commonly used organic resource characteristics.

Organic resource characteristic	Cumulative C release after 28 days (%)	Cumulative N release after 28 days (%)	In vitro dry matter digestibility (%)
N content (% DM ^a)	0.21 ^{**b}	0.82 ^{***}	0.45 ^{***}
C:N ratio	0.21 ^{**}	0.38 ^{***}	0.24 ^{**}
Polyphenol content (%DM)	0.21 ^{**}	0.01	0.06
Lignin content (% DM)	0.48 ^{***}	0.15 [*]	0.59 ^{***}
Soluble C content (% DM)	0.18 [*]	0.46 ^{***}	0.32 ^{***}
Protein-binding capacity (mg BSA g ⁻¹ DM)	0.29 ^{**}	0.00	0.19 [*]
Soluble C:N ratio	0.12	0.56 ^{***}	0.15 [*]
Polyphenol:N ratio	0.45 ^{***}	0.25 ^{**}	0.35 ^{***}
Lignin:N ratio	0.24 ^{**}	0.25 ^{**}	0.25 ^{**}
(Lignin+Polyphenol):N ratio	0.26 ^{**}	0.26 ^{**}	0.26 ^{**}
Protein binding capacity:N ratio	0.50 ^{***}	0.19 [*]	0.46 ^{***}

^a DM = dry matter.

^b *, **, and *** indicate significance at the 5, 1, and 0.1% level, respectively.

Table 2. Multiple regression analysis using selected decomposition parameters as dependent variables and C, N, P, polyphenol, lignin, and soluble C content and protein-binding capacity as independent variables.

Dependent variable	Multiple regression equation ^b	R^2
Cumulative C mineralisation at day 28 (%)	$37^{***} - 1.84 \times (\text{polyphenol content})^{***} - 0.92 \times (\text{lignin content})^{***} + 1.80 \times (\text{soluble C content})^{***}$	0.86
In vitro dry matter digestibility (% DM ^a)	$49^{***} - 1.51 \times (\text{lignin content})^{***} + 2.69 \times (\text{soluble C content})^{***} - 0.10 \times (\text{protein binding capacity})^{***}$	0.89
Cumulative N mineralisation at day 28 (%) for treatments with positive values	$-11 + 9.84 \times (\text{N content})^{***} - 1.59 \times (\text{polyphenol content})^*$	0.60
Cumulative N mineralisation at day 28 (%) for treatments with negative values	$-100^{***} + 34.1 \times (\text{N content})^{***}$	0.90

^a DM = dry matter.

^b *, **, and *** indicate significance of coefficients of regression at the 5, 1, and 0.1% level, respectively.

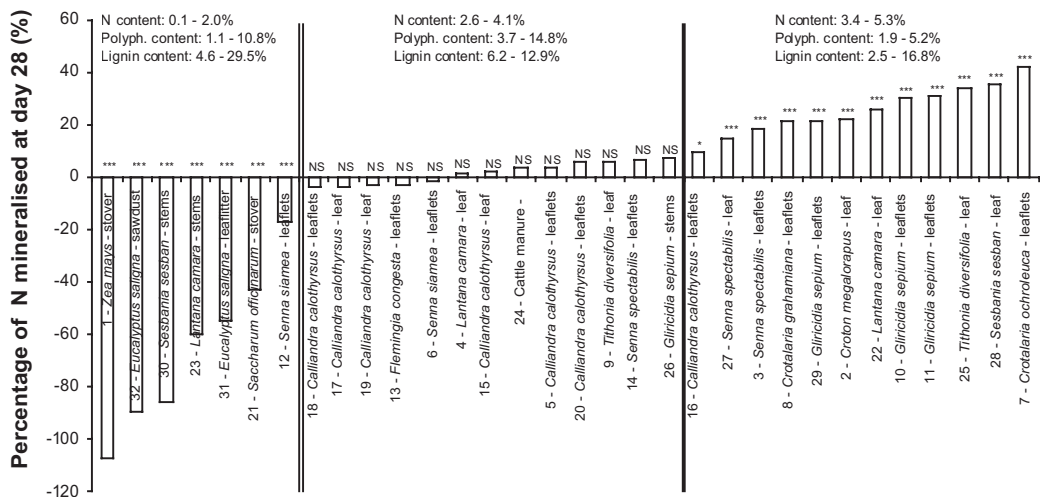


Figure 1. The percentage of added organic resource N mineralised after 28 days. “****”, “**” and “NS” signify significance at the 0.1%, the 5% level and not significant, respectively, as calculated with the LSMEANS option of the MIXED procedure (SAS 1992). The vertical bars delineate three groups of organic resources: a first group that has values significantly less than 0, a second group with values not different from 0, and a third group with values significantly larger than 0. The range of N, polyphenol, and lignin contents presented for the middle group excludes sample numbers 24 (cattle manure: 2.5% N, 1.1% polyphenols and 17.3% lignin) and 26 (*Gliricidia* stems: 1.6% N, 1.3% polyphenols and 20.4% lignin).

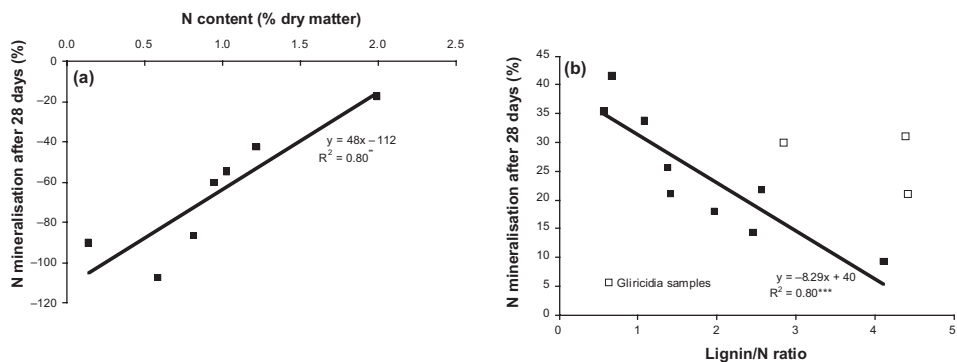


Figure 2. Relationship between the percentage of added N mineralised after 28 days and (a) the N content for organic materials with values significantly below 0, and (b) the lignin/N ratio for the organic materials with values significantly above 0. In Figure 2b, the *Gliricidia* leaves (samples 10, 11, and 29) were excluded from the regression.

Discussion

From the different methods used in this cross-method analysis, the minimum data set to assess organic resource quality appears to consist of N, lignin, and soluble polyphenol content, a finding that

is consistent with conclusions from earlier efforts. The various methods used to assess short-term mineralisation produced significant correlations to N and C mineralised after 28 days, with at least one of the three aforementioned characteristics.

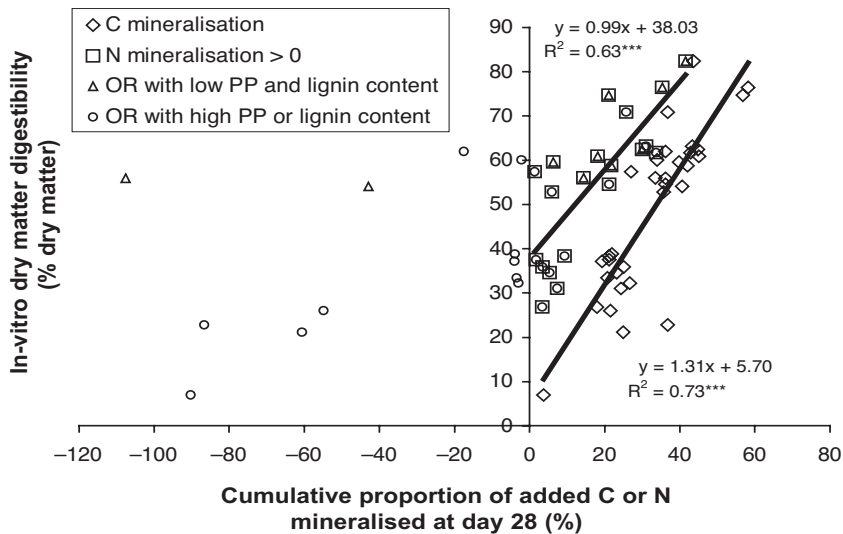


Figure 3. Relationships between C and N mineralisation as assessed using the aerobic incubation technique and the in vitro dry matter digestibility assay.

Cost and speed also need to be compared where more than one method is available. Aerobic incubations are one of the cheapest but slowest methods, compared with NIR, which is the fastest. Although NIR is expensive to purchase, for routine analysis of many samples it would be cost effective. Construction of spectral calibration libraries in central laboratory facilities would greatly increase the efficiency of NIRS use for routine organic resource characterisation in laboratories and dramatically reduce the costs of this analysis.

An issue that this analysis has raised is the inclusion of other parameters that should be included in simulation models to enhance their predictions of decomposition. This applies to only certain classes of resource quality. Only N content needs to be measured for Class III resources, whereas for Classes I and II there were no single quality indices.

For Class III resources that show positive mineralisation with time, including polyphenol content in the decomposition routines would increase the accuracy of prediction. Whitmore and Handayanto (1997) developed algorithms to include the polyphenol effect in decomposition and hypothesised the direct transfer of C and N to the stable soil organic matter, without any decomposition and loss of C.

References

- Barrios, E. 2004. The in vitro dry matter digestibility (IVDMD) method. These proceedings.
- Cobo, J.G., Barrios, E., Kass, D.C.L. and Thomas, R.J. 2002. Decomposition and nutrient release by green manures in a tropical hillside agroecosystem. *Plant and Soil*, 240, 331–342.
- Gachengo, C.N., Vanlauwe, B., and Palm, C.A. 2004a. Mineralisation patterns of selected organic materials. These proceedings.
- Gachengo, C.N., Vanlauwe, B., Palm, C.A. and Cadisch, G. 2004b. Chemical characterisation of a standard set of organic materials. These proceedings.
- Handayanto, E., Cadisch, G. and Giller, K.E. 1994. Nitrogen release from prunings of legume hedgerow trees in relation to quality of the prunings and incubation method. *Plant and Soil*, 160, 237–248.
- Melillo, J.M., Aber, J.D. and Muratore, J.F. 1982. Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. *Ecology*, 63, 621–626.
- Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G. and Giller, K.E. 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, Ecosystems and Environment*, 83, 27–42.

- Palm, C.A. and Rowland, A.P. 1997. Chemical characterization of plant quality for decomposition. In: Cadisch, G. and Giller, K. E., ed., *Driven by nature: plant litter quality and decomposition*. Wallingford, UK, CAB International, 379–392.
- SAS Institute Inc. 1985. *SAS user's guide: statistics*, 5 edition. Cary, NC, SAS Institute Inc., 957 p.
- 1992. The MIXED procedure. SAS Technical Report P-229: SAS/STAT software: changes and enhancements. Cary, NC, USA, SAS Institute Inc., 287–366.
- Shepherd, K.D. 2004. Predicting decomposition rates of organic resources using near infrared spectroscopy. *These proceedings*.
- Tian, G., Kang, B.T. and Lambourne, L.J. 1996. Ruminant assay for rapidly estimating plant residue decomposability in the field. *Pedobiologia*, 40, 481–483.
- Whitmore A.P. and Handayanto E. 1997. Simulating the mineralization of N from crop residues in relation to residue quality. In: Cadisch, G. and Giller K.E., ed., *Driven by nature, plant litter quality and decomposition*. Wallingford, UK, CAB International, 337–348.

**Simulating N and P Release
from Organic Sources**

4.1

The APSIM Manure Module: Improvements in Predictability and Application to Laboratory Studies

M.E. Probert,^{*} R.J. Delve,[†] S.K. Kimani[§] and J.P. Dimes[¶]

Abstract

Existing models are able to capture the pattern of N release from plant materials based on their C/N ratios. However, these models are unable to simulate the more complex pattern of N release reported for some animal manures, especially for manures that exhibit initial immobilisation of N even when the C/N ratio of the material suggests it should mineralise N.

This paper reports on progress towards developing a capability within the APSIM SoilN module to simulate nitrogen release from these manures. The SoilN module was modified so that the three pools that constitute added organic matter can be specified in terms of both the fraction of carbon in each pool and also their C/N ratios. The previous assumption that all pools have the same C/N ratio fails to adequately represent the observed behaviour for release of N from some organic inputs. By associating the model parameters with measured properties (the pool that decomposes most rapidly equates with water-soluble C and N; the pool that decomposes slowest equates with lignin-C) the model performed better than the unmodified model in simulating the N mineralisation from a range of livestock feeds and manure samples.

In the soil fertility management of many tropical farming systems, organic sources play a dominant role because of their short-term effects on nutrient supply to crops (Palm et al. 2001). Considerable literature exists reporting decomposition and nutrient-release patterns for a variety of organic materials and this information has been drawn together and used for improvement of soil fertility through better man-

agement of organic inputs (e.g. Giller and Cadisch 1997; Palm et al. 2001).

If simulation models are to be useful in helping to design farming systems that use various nutrient sources more effectively, it is a requirement that the models be able to reliably describe the release of nutrients from these different organic sources. Palm et al. (1997) pointed out that there is little predictive ability for making recommendations on combined use of organic and inorganic nutrient sources. One reason for this is the inability of models to adequately capture the short-term dynamics of the release of nutrients from organic materials.

The manner in which the dynamics of soil carbon and nitrogen are modelled in APSIM's SoilN module (Probert et al. 1998; Probert and Dimes 2004) is similar to what is found in many other models — see reviews by Ma and Shaffer (2001) and McGehean and Wu (2001). Briefly, crop residues and roots

^{*} CSIRO Sustainable Ecosystems, 306 Carmody Road, St Lucia, Queensland 4067, Australia
<merv.probert@csiro.au>.

[†] Tropical Soil Biology and Fertility Institute of International Centre for Tropical Agriculture, PO Box 6247, Kampala, Uganda <r.delve@cgiar.org>.

[§] Kenya Agricultural Research Institute, Muguga, PO Box 30148, Nairobi, Kenya <skimani@net2000ke.com>.

[¶] International Crops Research Institute for Semi-Arid Tropics, PO Box 776, Bulawayo, Zimbabwe
<j.dimes@cgiar.org>.

added to the soil are designated fresh organic matter (FOM) and are considered to comprise three pools (FPOOLs), sometimes referred to as the carbohydrate-like, cellulose-like and lignin-like fractions of the residue. Each FPOOL has its own rate of decomposition, which is modified by factors to allow for effects of soil temperature and soil moisture. For inputs of crop residues and roots, it has usually been assumed that the added C in the three FPOOLs is always in the proportions 0.2:0.7:0.1. In this manner, the decomposition of added residues ceases to be a simple exponential decay process as would arise if all residues were considered to comprise a single pool.

Although the three fractions have different rates of decomposition, they do not have different compositions in terms of C and N content. Thus, while an input might be specified in terms of the proportion in each of the FPOOLs, thereby affecting its rate of decomposition, the whole of the input will decompose without change to its C:N ratio. The model further assumes that the soil organic matter pools (BIOM and HUM) have C:N ratios that are unchanging through time. The formation of BIOM and HUM thus creates a gross immobilisation demand that has to be met from the N released from the decomposition of the FOM and/or by drawing on the mineral N (ammonium- and nitrate-N) in the system.

However, changing the pool sizes alone cannot alter whether a source exhibits initial net N mineralisation or immobilisation (since this is determined by the C:N ratio of the substrate). In studies of the mineralisation of N from various manures, Kimani and co-workers (unpublished) and Delve et al. (2001) encountered situations where there was an initial immobilisation of N, despite the fact that the overall C:N ratio of the material was such that it would be expected to result in net mineralisation. This behaviour cannot be modelled without assuming that the three FPOOLs also differ in their C:N ratios.

Modifications to the Model

Modifications were made to the APSIM SoilN module so that any input of organic material could be specified in terms of both its fractionation into the three FPOOLs, and the C:N ratios of each FPOOL. In the modified model, each FPOOL is assumed to decompose without changing its C:N ratio. The rates of decomposition of the three FPOOLs were not changed from the released version of APSIM (viz.

0.2, 0.05 and 0.0095 day⁻¹, respectively, under non-limiting temperature and moisture conditions).

Using the modified model, we explored three different approaches to simulate how an organic input decomposes:

1. using the released version of ASPIM SoilN (v 2.0)
2. changing the FPOOLs to have different fractional compositions and different C:N ratios, in the first instance with FPOOL1 differing from a common value for FPOOLs 2 and 3
3. with the fractional composition and C:N ratios differing between all three FPOOLs.

Materials and Methods

Simulation of mineralisation from hypothetical sources

The model was configured to simulate a simple incubation study, involving a single layer of soil under conditions of constant temperature (25°C) and at a soil water content that ensured there was no moisture restriction on decomposition. Initial nitrate-N concentration in the soil was 20 mg N kg⁻¹. The effect of different organic inputs was investigated by incorporating materials that contained a constant amount of N (100 mg N kg⁻¹ soil) but with varying C:N ratio. A control system was also simulated without any added organic input.

Simulation of laboratory incubation studies

The experimental data reported by Delve et al. (2001) were used to investigate whether the analytical data for a range of livestock feeds and manure samples can be used to specify the model to simulate the N mineralisation measured in a laboratory incubation experiment.

Using a leaching-tube incubation procedure (Stanford and Smith 1972), they measured net N mineralisation for feeds and manure samples resulting from cattle fed a basal diet of barley straw alone, or supplemented with 15 or 30% of the dry matter as *Calliandra calothyrsus*, *Macrotyloma axillare* or poultry manure. The soil used was a humic nitisol with organic C content of 31 g kg⁻¹, C/N ratio of 10 and pH (in water) of 5.9. The incubations were conducted at 27°C.

Kimani and co-workers (unpublished data) carried out a mineralisation study, using the same method-

ology as Delve et al. (2001), for a selection of manure samples collected on-station and from farms in central Kenya. Analytical data for these materials included total and water soluble C and N, but not fibre analyses.

Results

Experimental data (S.K. Kimani et al., unpublished data) that indicated the need to reconsider how N mineralisation from organic inputs is modelled are illustrated in Figure 1. For a wide range of manures, their results consistently show an initial immobilisation or delay in mineralisation lasting several weeks, even for materials that have overall C:N ratios of less than 20. This pattern of response is noticeably different to studies of N mineralisation from plant materials (e.g. Constantinides and Fownes 1994), where plant materials with low C:N typically exhibit positive net mineralisation from the start of the incubation period.

The manure samples studied by Delve et al. (2001), with C:N ratios in the range 20–27, had even more complex patterns of mineralisation; some materials showed initial net mineralisation before an extended period of immobilisation lasting for at least 16 weeks of incubation (see below).

Modelling N mineralisation from hypothetical sources

Simulation of mineralisation for sources with different C:N ratios using the released version of APSIM SoilN is shown in Figure 2. The results are in general agreement with experimental studies for plant materials where net N mineralisation is closely related to the N content and hence C:N ratio (e.g. Constantinides and Fownes 1994; Tian et al. 1992). For sources with C:N < 20, net mineralisation occurs from the outset. However, with C:N > 20, there is initially immobilisation of mineral-N and it is only as newly formed soil organic matter is re-mineralised that mineral-N in the system begins to increase.

Effects of changing the composition of the input by modifying the C:N ratios of the different FPOOLs are shown in Figures 3 and 4. In Figure 3, all materials have the same overall C:N ratio, but the C:N ratio of FPOOL1 is now greater than for the material in pools 2 and 3. The result is that the material in FPOOL1, which decomposes most rapidly, creates an immobilisation demand, and the higher the C:N ratio of FPOOL1 the greater the initial immobilisation. If, however, the C:N of FPOOL1 is higher, there must be compensating falls in the C:N ratios of the other pools. As incubation time increases, the differences between different materials decrease, so that there is little longer-term

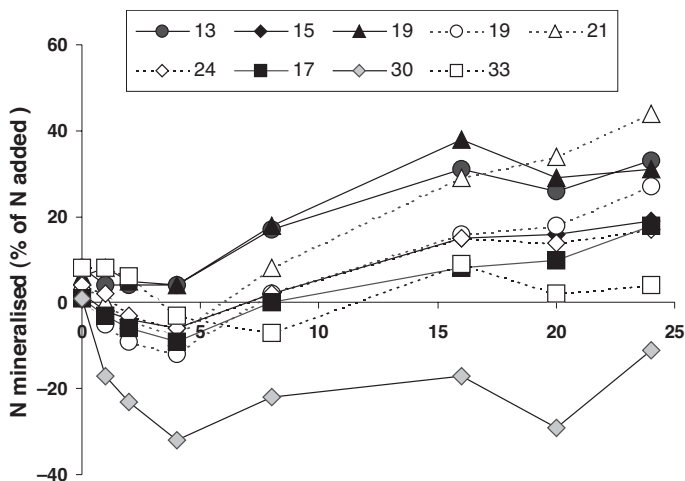


Figure 1. Net nitrogen mineralised from different manures in an incubation study lasting 24 weeks. C:N ratios of the manures are shown in the legend. Source: S.K. Kimani et al., unpublished data.

effect of the C:N ratios of the FPOOLS on net mineralisation, which is determined largely by the overall C:N ratio.

In Figure 4 the effect of varying the C:N ratios of FPOOLS 2 and 3 is shown. Again all materials have the same overall C:N ratio, with the C:N of FPOOL1 fixed at 10. With the low C:N in the rapidly decom-

posing pool, there can be an initial net mineralisation, especially when the C:N of FPOOL2 is also relatively low. However, as FPOOL1 is depleted, there can be a switch from net mineralisation to net immobilisation. Increasing the C:N of FPOOL2 results in increasing immobilisation and immobilisation persists for longer.

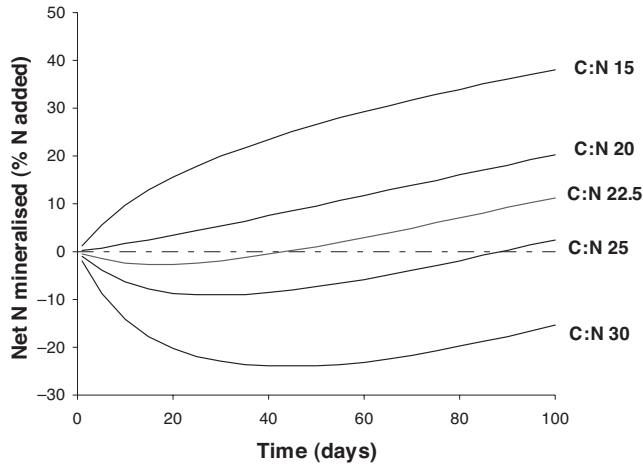


Figure 2. Simulation of nitrogen mineralisation from organic inputs with different C:N ratios using the released version of APSIM SoilN. The model assumes that all inputs have the same fractional composition in terms of the three FPOOLS (0.2:0.7:0.1), and that, for a given source, all FPOOLS have the same C:N ratio.

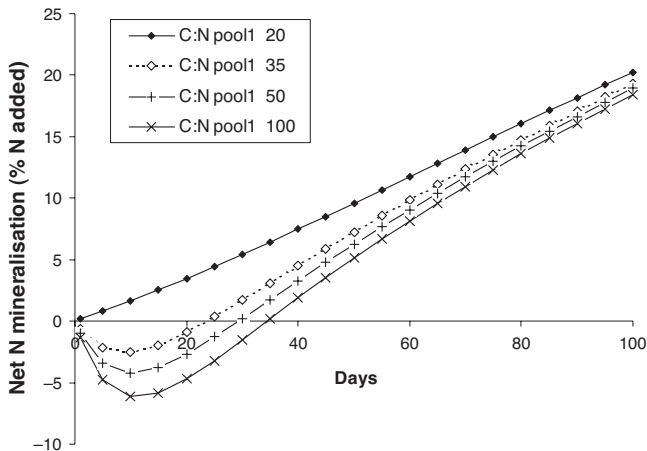


Figure 3. Effect of changing the composition of organic inputs by modifying the C:N ratios of the FPOOLS. In this example, the inputs have fractional composition of 0.2:0.7:0.1, overall C:N ratio of 20, and C:N ratio of FPOOL1 as shown in the legend (with C:N ratios of FPOOLS 2 and 3 being equal).

Modelling the mineralisation study of Delve et al. (2001)

The modelled net mineralisation from hypothetical sources display patterns of N release that are similar to experimental data. Notably, the several weeks delay before mineralisation became positive, as exhibited by several of the manures studied by Kimani and co-workers (Figure 1), is consistent with variation in the C:N ratio of FPOOL1 (Figure 3). On the other hand, the longer delay reported by Delve et al. (2001) is more like the pattern shown in Figure 4 associated with variation in FPOOL2 and 3.

We have attempted to use the analytical data reported by Delve et al. (2001) to specify the 'quality' aspects of organic inputs represented in the model. We assume the soluble components of C and N equate to FPOOL1; thus the analytical results are sufficient information to determine the proportion of total C in this pool and its C:N ratio. Also, we assume that acid detergent lignin (ADL; Van Soest et al. 1987), which is a proximate measure of lignin, equates to FPOOL3, permitting the fraction of C in

this pool to be estimated; the fraction of C in FPOOL2 is found by difference. Since the overall C:N ratio (on a total dry matter basis) is also known, the only missing information is the distribution of non-water soluble N between pools 2 and 3. A series of simulations was carried out for each source with different combinations of C:N in the two pools (constrained by the C:N of the total DM). This enabled selection of the C:N giving an acceptable fit to the observed data (see Figure 5).

The net N mineralisation for the feeds and a selection of the manure samples studied by Delve et al. (2001) is shown in Figure 6. The outputs from two simulations are compared, these being the outputs from the modified and unmodified versions of the model. The input data used for the modified model are set out in Table 1.

For most of the materials, the goodness of fit is substantially better for the modified than for the unmodified model. Using the analytical data to specify the fraction of C in each of the FPOOLS and the C:N ratio of FPOOL1, it was possible to choose

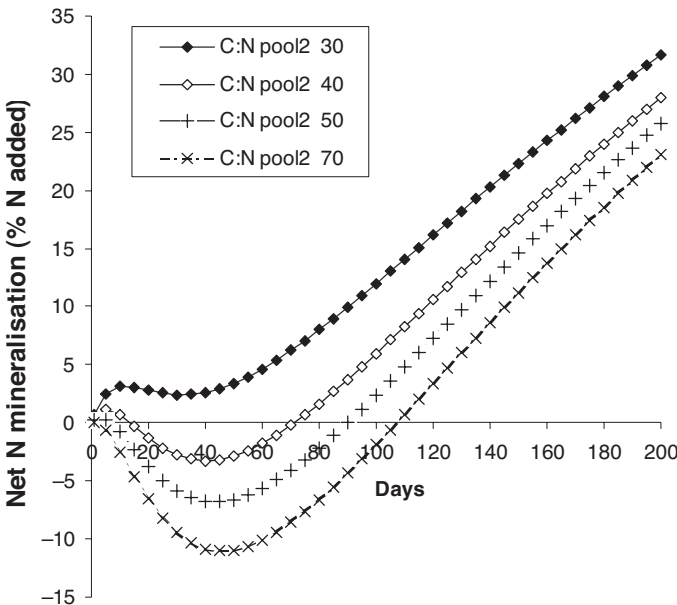


Figure 4. Effect of changing the quality of organic inputs by varying the C:N ratios of the FPOOLS. In this example, the inputs have fractional composition of 0.1:0.7:0.2, overall C:N ratio of 20 and C:N ratio of FPOOL1 of 10, with C:N of FPOOL2 as shown in the legend.

values for the C:N ratios of FPOOL2 and FPOOL3 to obtain satisfactory fits with the measured data.

In general, the fit is better for the manure samples than for the feeds, with the poorest fit for the poultry waste. The pattern of net mineralisation measured for the poultry waste, which had an overall C:N ratio of

17, is different from the other materials in that the change from immobilisation to mineralisation that occurred after about 50 days was not maintained, and further net immobilisation occurred later in the incubation. Delve et al. (2001) could not explain the behaviour of this material.

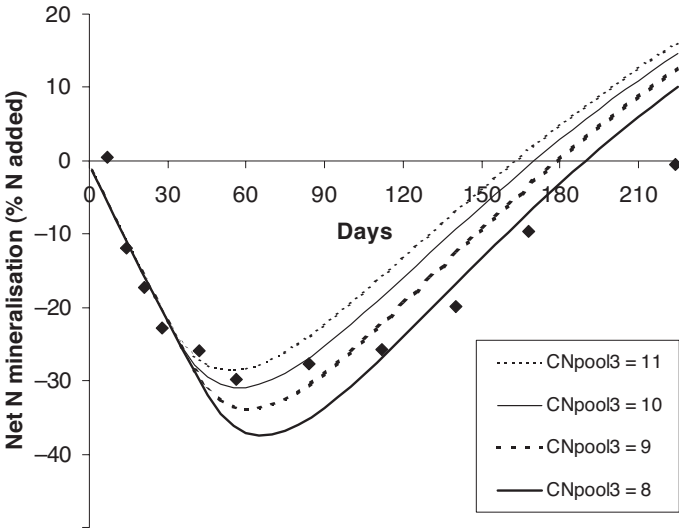


Figure 5. Illustration of how appropriate values for the C:N ratios of FPOOL2 and 3 were selected. In this example, the observed data for manure derived from the straw diet are compared with model output with different C:N ratios. Choice of a “best” value is a compromise between the maximum immobilisation and the longer-term mineralisation.

Table 1. Composition of organic materials (feeds and faecal samples) used for simulating the mineralisation study of Delve et al. (2001). Overall C:N ratio was measured; FPOOL1 based on measured C and N as water-soluble components; proportion of C in FPOOL3 based on measured ADL. C:N of FPOOL2 and 3 selected, subject to constraint that must be consistent with overall C:N, to give reasonable fit between simulated N mineralisation and measured data.

Sample	Overall C:N	Proportion of carbon in FPOOLS (%)			C:N of FPOOLS		
		Pool 1	Pool 2	Pool 3	Pool 1	Pool 2	Pool 3
<i>Calliandra</i>	13	12	74	14	9	44	3
<i>Macrotyloma</i>	22	16	74	10	17	67	4
Poultry waste	17	5	88.5	6.5	4.5	202	1.5
Barley straw ^a	86	6	84.5	9.5	24	103	103
<i>Calliandra</i> – manure (30%) ^b	22	4	74	22	16	40	9
<i>Macrotyloma</i> – manure (30%)	23	5.5	73.5	21	14	36	11
Poultry waste – manure (15%)	27	4.5	82	13.5	12	41	10
Barley straw – manure	27	9	71.5	19.5	20	66	9

^a Simulated N mineralisation was not sensitive to partitioning of N between pools 2 and 3.

^b Value in parentheses denotes proportion of supplement in diet.

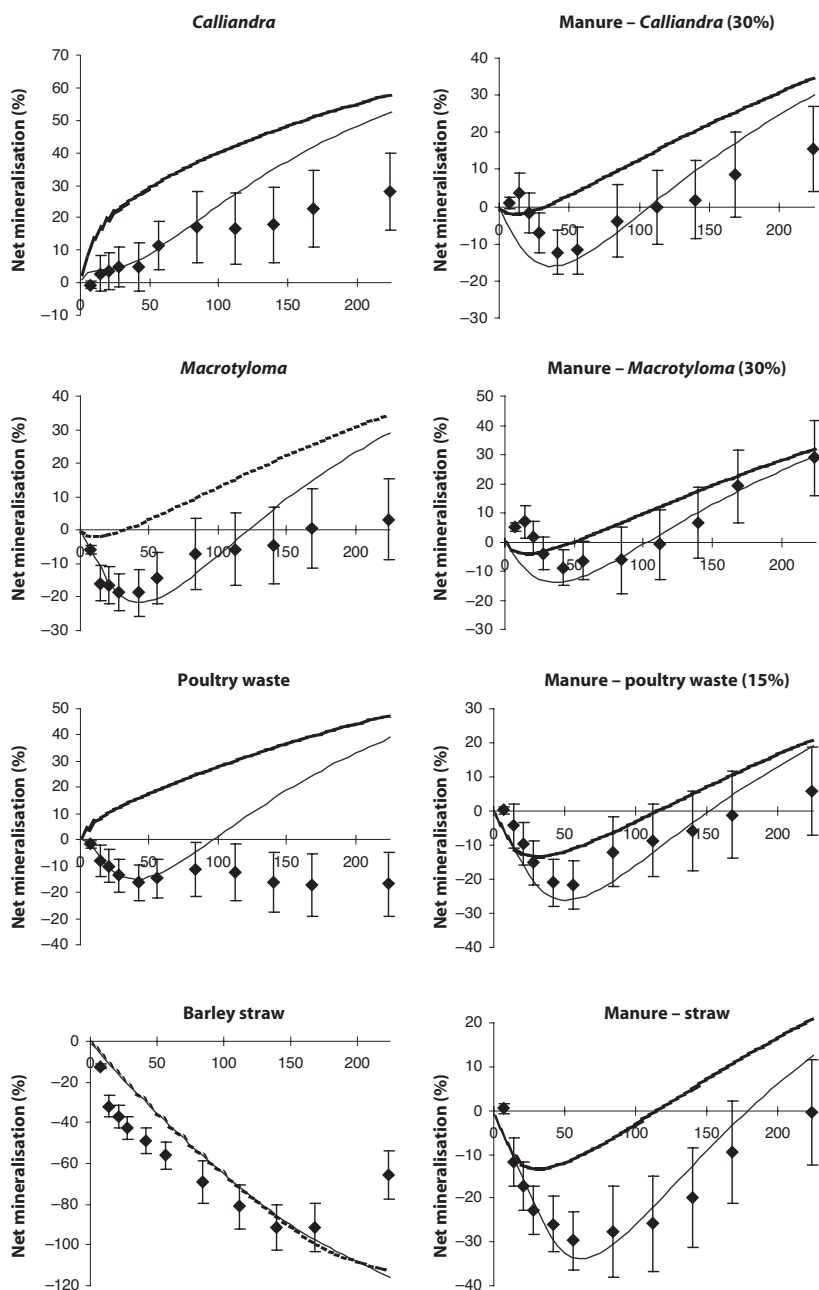


Figure 6. Net nitrogen mineralisation from feeds and faecal materials (data of Delve et al. 2001). Experimental data shown as symbols with bars representing \pm standard errors. The heavy broken line is for the model where all organic material is assumed to decompose with the same C:N ratio; the continuous line is for the model with different C:N ratio in each FPOOL. Parameters used to specify the different sources (proportion of C and C:N in the three FPOOLS) are set out in Table 1.

The simulation for the barley straw (C:N 86) predicts that immobilisation continues for at least 200 days. Because all mineral N initially present in the soil becomes immobilised in this treatment, the simulated immobilisation is determined by the rate of mineralisation of the control treatment and is not sensitive to how N is partitioned between FPOOLs 2 and 3 in the decomposing substrate.

Discussion

Models are capable of capturing the gross effect of C:N ratio on mineralisation/ immobilisation from plant residues (as illustrated in Figure 2). However, they are not able to represent the more complex pattern of mineralisation/immobilisation that has been reported from laboratory incubation studies of N release from manures with low C:N (e.g. Figure 1). To capture these patterns of N release, it is necessary to conceptualise the organic input as comprising discrete fractions that differ not only in their rates of decomposition but also in their chemical (i.e. C and N) composition.

The mineralisation data of Delve et al. (2001) (shown in Figure 6) and chemical composition of their materials (Table 1) indicate that the measured water-soluble component had a smaller C:N than the bulk materials. To simulate the observed mineralisation data it was necessary to assume that the materials had higher C:N in FPOOL2 than in FPOOL3.

What is rather simplistically called ‘manure’ is usually a complex mixture of faeces, urine, bedding material, feed refusals and soil! To add to the complexity, it may have undergone further composting and weathering with loss of some components. Thus, it is perhaps naïve to expect that the methods used to characterise the quality factors that determine N mineralisation from plant residues might also be applicable to manures, or that models which simulate N mineralisation from plant residues might also simulate N release from manures.

By simulation of hypothetical materials, we have shown that such a model can be parameterised to simulate the general pattern of N mineralisation that is observed for various organic sources. Nonetheless, it remains a challenge to know how appropriate parameters should be selected for a given source and/or how to derive the parameter values from other information that may be available as analytical data for supposed ‘quality factors’. Here we have used data

for C and N in the water-soluble components to specify FPOOL1, and the measured ADL to specify the C in FPOOL3. To obtain the goodness of fit shown in Figure 6 for the manures required C:N in FPOOL2 in the range 36–66, with corresponding C:N in FPOOL3 of 9–11 (Table 1).

For the feed materials (*Calliandra*, *Macrotyloma*, poultry waste), the predictions were not as good as those for the manure samples. To obtain a reasonable fit in the early stages of the mineralisation, a high C:N in FPOOL2 is required, but this results in very low values of C:N for FPOOL3 and over-prediction as the incubation period progresses beyond 100 days.

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References

- Constantinides, M. and Fownes, J.H. 1994. Nitrogen mineralization from leaves and litter of tropical plants; relationship to nitrogen, lignin and soluble polyphenol concentrations. *Soil Biology and Biochemistry*, 26, 49–55.
- Delve, R.J., Cadisch, G., Tanner, J.C., Thorpe, W., Thorne, P.J. and Giller, K.E. 2001. Implications of livestock feeding management on soil fertility in the smallholder farming systems of sub-Saharan Africa. *Agriculture, Ecosystems and Environment*, 84, 227–243.
- Giller, K.E. and Cadisch, G. 1997. Driven by nature: a sense of arrival or departure. In: Cadisch, G., and Giller, K.E., ed., *Driven by nature: plant litter quality and decomposition*. Wallingford, UK, CAB International, 393–399.
- Ma, L. and Shaffer, M.J. 2001. A review of carbon and nitrogen processes in nine U.S. soil nitrogen dynamics models. In: Shaffer, M.J., Ma, L. and Hansen, S., ed., *Modeling carbon and nitrogen dynamics for soil management*. Boca Raton, FL, Lewis Publishers, 55–102.
- McGechan, M.B. and Wu, L. 2001. A review of carbon and nitrogen processes in European soil nitrogen dynamics models. In: Shaffer, M.J., Ma, L. and Hansen, S., ed., *Modeling carbon and nitrogen dynamics for soil management*. Boca Raton, FL, Lewis Publishers, 103–171.
- Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G. and Giller, K.E. 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, Ecosystems and Environment*, 83, 27–42.

- Palm, C.A., Myers, R.J.K. and Nandwa, S.M. 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: Buresh, R.J., Sanchez, P.A., and Calhoun, F., ed., Replenishing soil fertility in Africa. Soil Science Society of America Special Publication No. 51, 93–217.
- Probert, M.E. and Dimes, J.P. 2004. Modelling release of nutrients from organic resources using APSIM. These proceedings.
- Probert, M.E., Dimes, J.P., Keating, B.A., Dalal, R.C. and Strong, W.M. 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agricultural Systems*, 56, 1–28.
- Stanford, G. and Smith, S.K. 1972. Nitrogen mineralization potentials of soils. *Soil Science Society of America Proceedings*, 36, 495–472.
- Tian, G., Kang, B.T. and Brussaard, L. 1992. Effects of chemical composition on N, Ca and Mg release during incubation of leaves from selected agroforestry and fallow plant species. *Biogeochemistry*, 16, 103–119.
- Van Soest, P.J., Conklin, N.L. and Horvath, P.J. 1987. Tannins in foods and feeds. In: *Cornell Nutrition Conference for Feed Manufacturers*. New York, Department of Animal Science and Avian Science, Cornell University, 115–122.

4.2

Evaluation of APSIM to Simulate Maize Response to Manure Inputs in Wet and Dry Regions of Zimbabwe

P. Chivenge,* J. Dimes,[†] N. Nhamo,[§] J.K. Nzuma[¶] and H.K. Murwira*

Abstract

This study evaluated the ability of APSIM to predict the response of maize to manure inputs as observed in on-farm experiments in Murewa (higher rainfall) and Tsholotsho (lower rainfall) communal areas of Zimbabwe. Three experiments were used in the study. The first experiment studied the initial and residual effects of pit and heap-stored manure on maize grain yields. The 3-year experiment was conducted on a granitic sand in Murewa, with a single application of manure in the first cropping season. APSIM failed to simulate the contrasting initial and residual yield trends observed for pitted and heaped manure. However, chemical characterisation of heaped and pitted manure was contrary to observed behaviour, and the residual effects of the manures may have been masked by the application of inorganic N. The second experiment, also in Murewa, examined combinations of manure with high N concentration and N fertiliser. The model successfully predicted maize grain yield response to the combinations and manure alone, but greatly over-predicted the yield for fertiliser alone. The third experiment examined maize biomass yield response to heap- and pit-stored manure in the drier Tsholotsho region, across several farms on sandy and clay soils. The model successfully predicted mean biomass yield trends for the sandy and clay soils, and higher yields on the clay than the sand. Simulation of the effects of increasing amounts of pit and heap manure (from 0 to 15 t ha⁻¹) was largely in agreement with the observed responses. Results of this study demonstrate the need for improved experimentation and measurements of manure quality in order to better understand crop response to applications of pit and heaped manure. This will provide, in turn, a sounder basis for further testing of the model's ability to predict the effectiveness of poor-quality manures.

Manure is used as the main source of nutrients for crop production in most communal areas of Zimbabwe (Mugwira and Mukurumbira 1984; Mugwira and Murwira 1997). This is more so in high rainfall

areas, where crop response is more certain, than in drier areas, where manure resources are often under-utilised (Ahmed et al. 1997). However, manure from communal grazing areas is nearly always of low quality (N < 1%) (Tanner and Mugwira 1984) and its low N content in particular is attributed to poor feed quality and losses during handling and storage (Probert et al. 1995).

Nzuma and Murwira (2000a) conducted a study to reduce N losses from manure through improved handling and storage practices. They compared the use of manure from the conventional heap-storage systems to pit-stored manure. The pit storage

* TSBF-CIAT, Box MP 228, Mt Pleasant, Harare, Zimbabwe <tsbfzim@zambezi.net>.

[†] ICRISAT, Box 776, Bulawayo, Zimbabwe <j.dimes@cgiar.org>.

[§] ICRAF-Zimbabwe Agroforestry Project, c/o AREX, Box CY594, Causeway, Harare, Zimbabwe <nnsprl@mweb.co.zw>.

[¶] Tobacco Research Board, Kutsaga Research Station, Box 1909, Harare, Zimbabwe.

systems reduced N losses, as was indicated by high total N and ammonium N concentrations in the pitted manure compared with heap-stored manure (Nzuma and Murwira 2000b). When applied to maize in a high-rainfall region, the pit-stored manure gave higher grain yields than heap-stored manure (Murwira 2003). The efficacy of high-quality manures has been further evaluated in field experiments that combined manure and inorganic N application and varied soil type and rates of application in semi-arid regions of Zimbabwe (Murwira et al. 2001).

Biophysical simulation models such as APSIM (McCown et al. 1996; Keating et al. 2003) and CERES–Maize (Jones and Kiniry 1986) have been used to predict crop response to inputs of inorganic N under African conditions. For example, Shamudzarira and Robertson (2002) used APSIM to simulate responses of maize to N fertiliser, and compared the output with observed data from a long-term experiment conducted at Makoholi Research Station in central Zimbabwe. Their results showed that the model predicted grain yield responses to a range of N rates (0, 20, 40, 80 kg N ha⁻¹) within one standard error of the observed in nearly all seasons. Importantly, the model was able to simulate the very low biomass and zero grain yield observed in the 1991–92 drought season (simulated biomass = 500 kg ha⁻¹, observed = 580 kg ha⁻¹). Such low yield levels are characteristic to most African farming systems, particularly in the semi-arid regions. With the addition of the APSIM–Manure module (Probert and Dimes 2004), APSIM acquired the capability to predict nutrient availability following the addition of organic as well as inorganic sources of N in smallholder farming systems. While this capability has been shown to assist in exploring various management options under African conditions (Carberry et al. 2002), there has been no evaluation of APSIM to simulate observed crop response to manure applications in the field.

In the study reported here, a series of manure experiments conducted in wet and dry regions of Zimbabwe was used to evaluate APSIM for simulating maize response to applications of manure with varying N content and availability. The intention was to better understand where APSIM–Manure could be usefully applied and to identify possible areas for improvement in the model.

Materials and Methods

Three experiments were used to evaluate APSIM's performance to predict maize response following applications of different quality manures. The first experiment studied the initial and residual effects of pit- and heap-stored manure on maize yield in a high rainfall region. It was conducted on a coarse grained, shallow granitic sand soil in Murewa, Zimbabwe.

Manure was taken from open kraals in July 1997 and stored as follows:

- Heap – straw: manure stored in uncovered heap without straw
- Heap + straw: manure plus added maize stover stored in uncovered heap
- Pit – straw: manure stored in a covered pit without straw
- Pit + straw: manure plus added maize stover stored in a covered pit

Manure from the different storage systems was removed in October 1997 and incorporated into field plots on an equal total N basis (60 kg N ha⁻¹) before sowing the first maize crop. Residual effects of the manure applications were evaluated in cropping seasons 1998–99 and 1999–2000. Basal P fertiliser was applied to all the treatments, including a control plot that had no manure. N fertiliser was applied to all plots that received manure, but not to the control, in two applications (20 + 20 kg N ha⁻¹ as ammonium nitrate, in all three cropping seasons. Medium duration maize (SC501) was grown as the test crop. There were three replications for treatment plots.

For the second experiment, manure from a commercial feedlot (%N = 2.7, %C = 19.2) was used to determine the effects of organic–mineral fertiliser combinations on maize yields in Murewa in 1997–98. Manure and ammonium nitrate (AN) were applied at a total N rate of 100 kg N ha⁻¹. All the manure was applied at planting, while fertiliser N was applied as split dressings at 4 and 8 weeks after crop emergence. The following combinations were tested:

1. Control (no N applied)
2. 100% AN : 0% manure
3. 75% AN : 25% manure
4. 50% AN : 50% manure
5. 25% AN : 75% manure
6. 0% AN : 100% manure

The third set of experiments was carried out in a semi-arid environment near Tsholotsho, Zimbabwe,

during the 2000–2001 cropping season. Farmer-managed manure (pit-stored and heaped-manure) was applied on clay (7 farms) and sandy (6 farms) soils at the rate of 3 t ha⁻¹, with three replicates at each farm. The effects of rate of manure application (0, 3, 6, 9, 12 and 15 t ha⁻¹) were also studied on one farm (sandy soil) with three replications. A short season maize variety (SC401) was used in Tsholotsho.

Simulations

To simulate experiments 1 and 2, daily temperature and radiation data from a nearby weather station (in Natural Region II which receives an annual rainfall of 800–1000mm; Vincent and Thomas 1961) were used in conjunction with daily rainfall measured at the site. Soil parameters for describing N and organic C content of soils were measured, while the soil water balance was estimated based on knowledge of the soil (N. Nhamo, unpublished data). Plant available water capacity (PAWC) to rooting depth (90 cm) was 73 mm, and percentage C in the surface layer was 0.7. For experiment 1, the amount of manure added to the soil varied between treatments according to the N contents (Table 1) to apply 60 kg N ha⁻¹. Initial soil water for simulations was assumed to be close to the lower limit (LL) of plant available water capacity and soil mineral N was set to approximately 10 kg N ha⁻¹. Experiment 1 was simulated without any re-sets for soil water and N in the residual seasons.

For Tsholotsho experiments, temperature and radiation data from a station representative of Natural Region IV was used in conjunction with rainfall data measured at the site. The soil descriptions used for simulating these experiments were:

clay soil	1.05 m deep, PAWC of 100 mm and 1.4% C in the surface layer:
sandy soil	1.0 m deep, PAWC of 57 mm and 0.4% C.

Initial mineral N for each soil (i.e. a sand and a clay) was chosen so that the simulated biomass yields for the control treatment was similar to the average of measured farmer yields on each soil type. The chemical data available for the manures from Tsholotsho farms (6 heap and 3 pit) show little difference in C and N content of heaped and pit-stored manure (data not shown); this contrasts with manures at Murewa (Table 1). Hence, the manure treatments in Tsholotsho were simulated using the same % C (10%) and only a small difference in N content (heaped 0.6% and pit-stored 0.75%).

For this study, the partitioning of manure carbon into the three pools comprising fresh organic matter (Probert and Dimes 2004) was in the ratio 0.3:0.3:0.4 for the pit-stored manure and 0.01:0.59:0.4 for heaped manure. These values imply that there is material in the pit-stored manure that decomposes and releases N more rapidly than the heaped manure.

Results

Manure storage experiment at Murewa

Manure characterisation

Table 1 shows the chemical characterisation for manures used in Experiment 1 at Murewa. Pit-stored manure had higher carbon, total N and cation concentrations and lower ash content than heaped manure. Despite its higher N concentration, the pit-stored manure had a higher C:N ratio, though all manures had C:N ratios considered conducive to net mineralisation of N (i.e. < 20). Addition of straw during storage had smaller effects on composition than the effect of method of storage.

Initial and residual maize responses

Rainfall in each of the three cropping seasons exceeded 1000 mm. In the first cropping season, pit-stored manure gave much higher grain yields than the control or heaped manure treatments (Figure 1a). In subsequent seasons, maize yields for this treat-

Table 1. Characterisation of manures from manure storage experiments in Murewa.

Treatment	C %	N %	P %	K %	Ca %	Mg %	Ash %	C:N ratio
Heap – straw	9.0	0.88	0.20	0.25	0.21	0.53	80.9	10.2
Heap + straw	11.9	0.96	0.13	0.26	0.11	0.21	76.5	12.3
Pit – straw	28.2	1.84	0.25	0.84	0.25	0.70	40.7	15.3
Pit + straw	30.0	1.54	0.28	0.76	0.26	0.57	55.6	19.5

ment declined. In contrast, heaped manure had low yields in the first season, and an increasing yield trend for the second and third seasons, to the extent that yields exceeded those for the pit treatment in the residual seasons. Cumulative yield for the three seasons was higher for pitted manure (7 t ha^{-1}) than for heaped (5.4 t ha^{-1}), and both were greater than for the control treatment, which produced 2.2 t ha^{-1} for the 3 years.

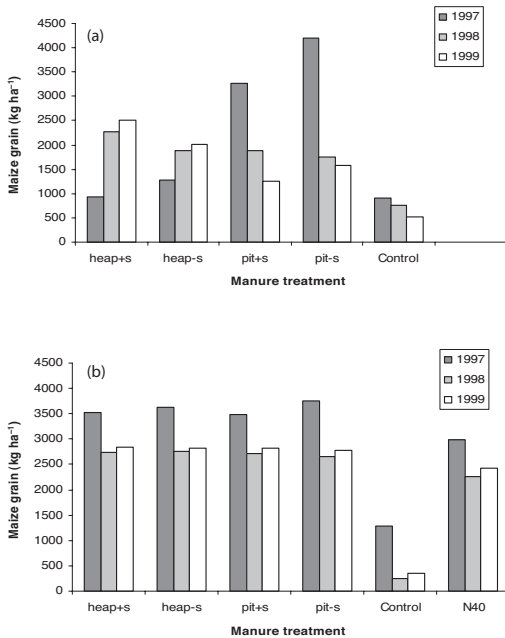


Figure 1. Initial and residual effects of heap- and pit-stored manure, with (+s) and without (–s) straw additions on maize grain yields at Musegedi farm in Murewa, Zimbabwe. a) Observed field responses; b) simulated responses.

The simulated yields for the control treatment that received no inputs of N were small in all three years and agreed reasonably well with the observed data (Figure 1b). However, the simulated responses to heaped and pitted manures were almost identical. Clearly, the model failed to simulate the contrasting release patterns observed for the pit-stored and heaped manure in the field. To explore the discrepancy, we tested the prediction for a treatment that received 40 kg N ha^{-1} as fertiliser but no manure (included in Figure 1b); it was predicted to yield higher than any of the observed manure treatments except pit-stored manure

in the first season. The model predicted that the yields with both manure and fertiliser would be slightly higher than for fertiliser alone.

Manure–fertiliser N combinations at Murewa

Grain yield response to various combinations of manure and fertiliser applying a total 100 kg N ha^{-1} to maize at Murewa are shown in Figure 2. Combinations gave higher maize yields than sole fertiliser or sole manure. The 100% manure and 100% fertiliser treatments gave almost identical maize yields, and these were more than double the yield of the control treatment that received no inputs of N.

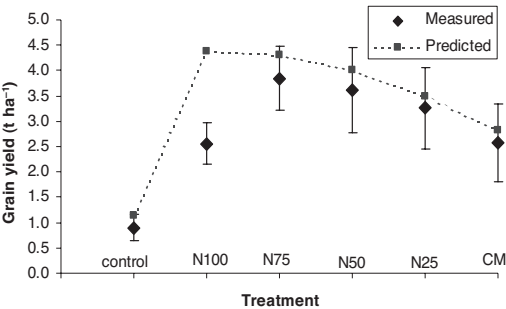


Figure 2. Measured and predicted effects of 100 kg N ha^{-1} applied as combinations of manure and fertiliser N on maize grain yield at Murewa in the 1997–1998 cropping season. (Control = no N inputs, N100 = 100 kg N ha^{-1} applied as fertiliser, CM = 100 kg N ha^{-1} applied as manure). Error bars denote standard deviations of measured means.

The model predictions agreed closely with the observed yields for the control and in response to the manure and fertiliser inputs, except for the 100% fertiliser treatment, for which there was a large over-prediction. The trend for yields to increase as the proportion of the N applied as fertiliser increased shows that the high-quality manure used in this experiment was a relatively less effective source of N than the fertiliser.

The reason for the poor prediction of the 100% fertiliser treatment is not known. One explanation could be that the manure inputs supplied some other limiting resource such as another nutrient (e.g. Ca, Mg, S or Zn) or had a liming effect. Such benefits of manure are not considered in the model.

Manure experiments at Tsholotsho

As a consequence of low rainfall, larger differences in maize growth were observed between soil type than between pit-stored and heap-stored manure in the Tsholotsho experiments. On both the clay and sandy soils, maize biomass was higher with manure inputs relative to the control, with pit-stored manure having the highest biomass yields overall, but these differences were although not statistically significant (Figure 3).

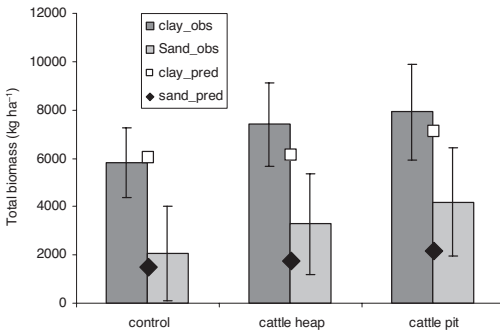


Figure 3. Observed and predicted maize response to heaped and pit-stored manure on clay (mean of 7 farms) and sandy (mean of 6 farms) soils near Tsholotsho in cropping season 2000–2001. Error bars denote standard deviations of measured means.

The model successfully predicted maize biomass yields within one standard deviation of the measured yields for the sandy and clay soils (Figure 3). The model also predicted a trend in maize biomass yields for the two soils, with the control treatment having the lowest maize yields and the pit manure treatment the highest.

For the experiment testing rates of manure on a sandy soil, highly variable maize responses were observed in the field (Figure 4). The model could predict the main trends, with maize yield increasing with increasing rates of application, and pit-stored manure having a higher yield trend than the heaped-manure. However, in this experiment, it should be noted that manure was applied on an equal mass basis, rather than equal N. Hence, differences in maize response between the two manure sources are exaggerated by the respective amounts of N added.

Discussion

The simulations did not always agree with the observed data. Unfortunately, reasons for the lack of conformity are not straightforward. Here we discuss matters that emerged in the testing of the model.

At the wetter location, the observed yields showed a larger response in the first season to the pit-stored manure than to heaped manure (Figure 1). While the pit-stored manure had higher N concentration, this should have been accounted for in the experimental

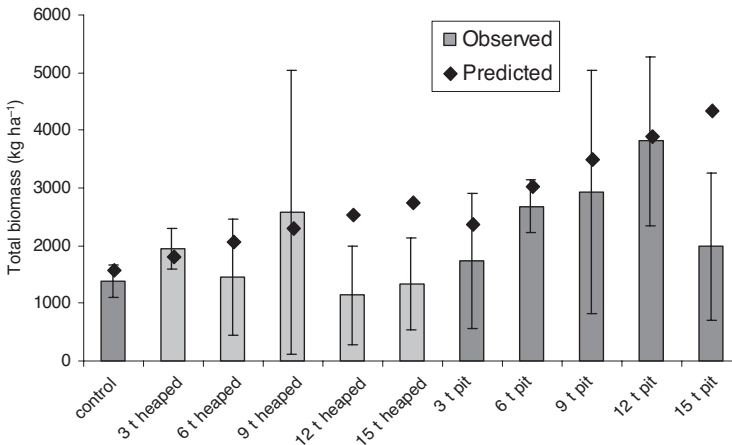


Figure 4. Observed and predicted effects of application rate (t ha^{-1}) of heaped and pitted manure on maize yields in Tsholotsho, in 2000–2001 cropping season. Error bars denote standard deviations of measured means.

design in that the manures were compared on an equal N basis. The expectation is that manure quality depends primarily on its C:N ratio and it is such concepts that are built into the model. In terms of C:N ratio, the pit-stored manures had higher values than the heap-stored manure so it would be expected to be a poorer source of N to the first crop. The model accurately predicted the low yields for the control treatment. The fertiliser N that was applied along with the manure treatments effectively masked any differences in the predicted yields for these treatments. It is unclear why the measured yields from the heaped manure should be so low. In the year of application there wasn't enough carbon added (680 kg C ha^{-1}) in the applied manure to immobilise the 40 kg N added as fertiliser. In the residual years, there is even less reason to expect the manure treatments to reduce the effect of the fertiliser input.

The simulations of the treatments of experiment 2 involving higher quality manure from a commercial feedlot were satisfactory, except for the treatment where fertiliser was the sole source of N. This treatment was seriously over-predicted. Above it was suggested that manure might have provided some benefit that is not considered by the model. Alternatively, one needs to invoke some mechanism that would result in reduced response to the 100% fertiliser treatment, though how this could be without similarly affecting the 75% fertiliser treatment is somewhat implausible.

The responses measured in experiment 3, particularly to the heap-stored manures, were small and variable (not statistically significant) (Figures 3 and 4). Thus, they are not well suited to providing insights into shortcomings of the model.

The attempts to model these experiments have highlighted several difficulties. The most obvious is that, where there is poor understanding of the measured responses, there can be little basis for judgment on the performance of the model. There is clearly scope for improving the design of experiments to test efficacy of manures (e.g. by not confounding the effects of manure and fertiliser); there is need to identify other possible benefits of manures besides N supply to crops; testing the performance of models would be aided if fuller information were available on initial soil conditions (soil water, mineral N) and it was possible to compare components of crop growth other than grain yield (e.g. total biomass and N uptake).

The results from experiment 1 show our inability to link the analyses of manures that are customarily made (e.g. Table 1) with their observed behaviour in the field. As a result of this study, new experimentation has begun in which the mass balances of C and N will be monitored during storage of manures in the dry (P. Masikate, unpublished data) and wet regions (P. Chivenge, unpublished data).

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References

- Ahmed, M.M., Rohrbach, D.D., Gono, L.T., Mazhangara, E.P., Mugwira, L., Masendeke, D.D. and Alibaba, S. 1997. Soil fertility management in communal areas of Zimbabwe: current practices, constraints and opportunities for change. Results of a diagnostic survey. ICRISAT Southern and Eastern Africa Region Working Paper No. 6.
- Carberry, P.S., Probert, M.E., Dimes, J.P., Keating, B.A. and McCown, R.L. 2002. Role of modelling in improving nutrient efficiency in cropping systems. *Plant and Soil*, 245, 193–203.
- Jones, C.A. and Kiniry, J.R., ed. 1986. CERES–Maize: a simulation model of maize growth and development. College Station, Texas A&M University Press, 194 p.
- Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy*, 18, 267–288.
- McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P. and Freebairn, D.M. 1996. APSIM: a novel software system for model development, model testing, and simulation in agricultural research. *Agricultural Systems*, 50, 255–271.
- Mugwira, L.M. and Mukurumbira, L.M. 1984. Comparative effectiveness of manures from the communal areas and commercial feedlots as plant nutrient sources. *Zimbabwe Agriculture Journal*, 81, 241–250.
- 1997. Use of cattle manure to improve soil fertility in Zimbabwe: past and current research and future research

- needs. In: A review of cattle manure in Zimbabwe. Soil Fertility Network Research Results Working Paper No. 2.
- Murwira, H.K. 2003. Managing Africa's soils: Approaches and challenges. In: Gichuru, M.P., Bationo, A., Bekunda, M.A., Goma, H.C., Mafongoya, P.L., Mugendi, D.N., Murwira, H.K., Mutiro, K., Nhamo, N. and Nzuma, J.K. 2001. Research results on improving use of cattle manure in Tsholotsho and Shurugwi in Zimbabwe. In: Twomlow, S.J. and Ncube, B., ed., Improving soil management options for women farmers in Malawi and Zimbabwe. Proceedings of workshop, 13–15 Sept. 2000, ICRISAT, Bulawayo, Zimbabwe.
- Murwira, H.K., Nandwa, S.M., Nyathi, P. and Swift, M.J., ed., Soil fertility management in Africa: a regional perspective. Nairobi, Academy Science Publishers, 293–306.
- Nzuma, J.K. and Murwira, H.K. 2000a. Improving the management of manure in Zimbabwe. Managing Africa's Soils, No. 15.
- 2000b. Effect of management on changes in manure nitrogen during storage. In: The biology and fertility of tropical soils. TSBF Report 1997–1998, 26–29.
- Probert, M.E. and Dimes, J.P. 2004. Modelling release of nutrients from organic resources using APSIM. These proceedings.
- Probert, M.E., Okalebo, J.R. and Jones, R.K. 1995. The use of manure on smallholders' farms in semi-arid eastern Kenya. *Experimental Agriculture*, 31, 371–381.
- Shamudzarira, Z. and Robertson, M.J. 2002. Simulating response of maize to nitrogen fertilizer in semi-arid Zimbabwe. *Experimental Agriculture*, 38, 79–96.
- Tanner, P.D. and Mugwira, L.M. 1984. Effectiveness of communal area manures as sources of nutrients for young maize plants. *Zimbabwe Agriculture Journal*, 81, 31–35.
- Vincent, V. and Thomas, R.G. 1961. An agricultural survey of southern Rhodesia. Part 1. Agro-ecological Survey. Salisbury, Government Printer.

4.3

A Capability in APSIM to Model Phosphorus Responses in Crops

M.E. Probert*

Abstract

Crop simulation models can be used to evaluate climatic risk and alternative management options, including the use of nitrogen fertilisers. However, they have not met the needs of researchers for low-input systems in tropical regions where organic inputs rather than fertilisers are often the only nutrient management option, and other nutrients besides nitrogen (particular phosphorus) frequently constrain crop growth.

This paper describes progress towards developing a capability to simulate response to P within the APSIM (Agricultural Production Systems Simulator) framework, and initial attempts to parameterise such a model to simulate the growth of maize crops grown in semi-arid eastern Kenya. The creation of this capability requires: (1) a new module (APSIM SoilP) that simulates the dynamics of P in soil and is able to account for effectiveness of alternative fertiliser management, e.g. water-soluble versus rock phosphate sources, and placement effects; (2) a link to the modules simulating the dynamics of carbon and nitrogen in soil organic matter, crop residues, etc. in order that the P present in such materials can be accounted for; (3) modification to crop modules to represent the P uptake process, estimation of the P stress in the crop, and consequent restrictions to the plant growth processes of photosynthesis, leaf expansion, phenology and grain filling.

To a large extent, the behaviour of P in the plant and in soil organic matter is modelled in a similar manner to nitrogen. However, that this can lead to a situation where predicted mineralisation of P from crop residues is contrary to experimental observations. It is suggested that the reason lies in the fact that C:P ratios are not common across the sub-fractions of organic matter, with a high proportion of the P being present in the water-soluble components.

The development and application of crop simulation models has focused on water and nitrogen as the main constraints to crop growth (Probert and Keating 2000). Such models have been useful for evaluating alternative management strategies and the effects of climatic conditions. However, their use assumes that other factors (e.g. nutrients other than N, pests, disease) are not limiting. In the case of nutrients, for high-input systems where fertiliser is used to correct nutrient deficiencies the assumption is acceptable. But in low-input systems, as occur in many tropical farming systems,

the assumption is untenable, and these models fail to meet the needs of researchers and extension workers (Palm et al. 1997).

Phosphorus is a limiting nutrient that frequently affects crop growth thereby reducing the usefulness of models. One situation where models have been less than adequate concerns use of scarce manure supplies, which are often the only input of nutrients to the cropping system, and can be a source of both N and P (McCown et al. 1992). It was in response to this particular need that efforts began towards developing a capability within APSIM (McCown et al. 1996; Keating et al. 2003; web site <www.apsim.info>) to simulate growth of crops that were constrained due to P deficiency.

* CSIRO Sustainable Ecosystems, 306 Carmody Road, St Lucia, Queensland 4067, Australia
<merv.probert@csiro.au>.

In order for this to be achieved, a new APSIM module (SoilP) was needed, to describe the dynamics of P in soil; modifications were needed to existing modules to describe the mineralisation of P from manures and other organic inputs; and modifications were needed in the various crop models to describe the P uptake process, together with the extent of P stress in the plant, and its effects on crop growth. This paper sets out how this has been achieved to develop a 'P-aware' APSIM maize module. We use 'P-aware' to distinguish a crop module that has the necessary enhancements to be constrained under low P conditions.

The experimental data set used to derive parameters for the model had been collected during an earlier ACIAR project, from experiments carried out in the Kenyan semi-arid tropics and described by Probert and Okalebo (1992). The testing of the model under a wider range of soils and climate is the subject of other papers in these proceedings (e.g. Kinyangi et al. 2004; Micheni et al. 2004).

Modelling Phosphorus in Cropping Systems

Phosphorus uptake by plants involves diffusion of phosphate to roots, and is increased by the presence of mycorrhizae. Models of diffusion to plant roots (e.g. Claassen and Barber 1976; Nye and Tinker 1977) show that root density is a controlling factor in P uptake. But models of the diffusion process are at a greater level of detail (in both time and space) than what is found in most crop models. Crop models typically assume that water and nitrogen are homogeneous throughout each soil layer with a dimension of centimetres, in marked contrast with the diffusion models where concentration gradients exist around individual roots with dimension of fractions of a millimetre.

More general system models, like EPIC (Jones et al. 1984) and CENTURY (Parton et al. 1988), have included P routines, but the generic crop routines in these models have limited ability to address crop management issues requiring accurate simulation of crop growth in response to weather, genotype, soil and management practices. They have not been widely used to explore management strategies involving P. It has been reported that the P routines in CENTURY were not able to describe the dynamics of P in tropical soils (Gijssman et al. 1996).

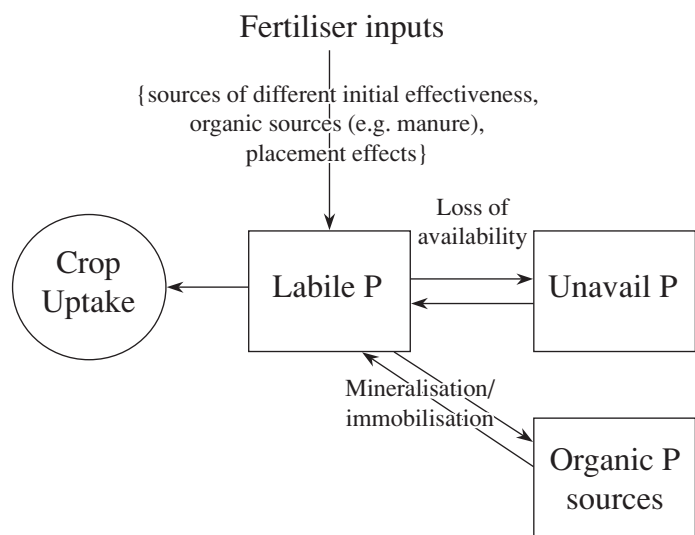
Management of soil P (especially in high-input agricultural systems) has focused on issues like whether to apply fertiliser, at what rate, evaluating placement and residual effects, and comparing relative effectiveness of water-soluble versus insoluble sources. Because P is immobile in soil (at least over the time scale of an annual crop) interactions with climate are of little importance. Unlike the management of N, there has been no need for a detailed crop model to evaluate alternative strategies for management of P. Models operating with a time-step of a growing season and an empirical relationship between yield and soil P status are adequate to gain insights into crop responsiveness to alternative fertiliser P sources and their residual effects (Probert 1985).

However, if there is a need for crop models to simulate response to manures and other organic sources in low-input systems, it is important that they respond to both N and P.

Crop models tend to perform best when there is a similar degree of detail for the various components of the overall model. At the time ACIAR project LW2/1999/003 commenced, it had not been demonstrated that this could be achieved for simulating a P constraint. It is noteworthy that the notion of including a P constraint into crop models has also been an activity for modellers using the DSSAT software. Their model has been published by Daroub et al. (2003).

The APSIM SoilP module

The central concept of the SoilP module is that it is possible to describe the availability of P in soil in terms of a labile P pool. Figure 1 illustrates the processes that are considered to affect the amount of labile P in soil. These are: inputs (fertilisers, manures etc.); crop uptake; transformation between available and organic forms of P; and transformation between available and unavailable forms of P. The model of this system (see the subroutine structure in Figure 1b) is really a statement of the P balance between the different forms of P present. Thus, the labile P in a given soil layer has units of kg ha^{-1} and responds quantitatively to inputs and removal. It cannot therefore be directly equated with any particular soil P test, though we shall return to the topic of how there is need to specify such a model in terms of soil P tests.



SoilP subroutine

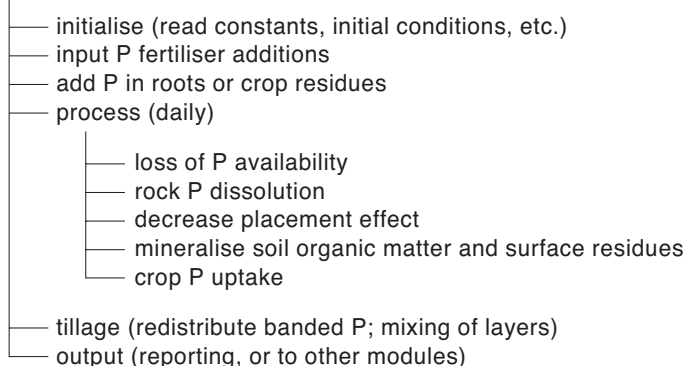


Figure 1. The APSIM SoilP module. The upper part of the figure shows in diagrammatic form the processes that are considered in the module. The lower part shows the simplified subroutine structure of the model where some actions are event based (e.g. initialisation, add fertiliser, tillage) whereas the ‘process’ activities occur on a daily time step.

Fertiliser inputs

SoilP has been designed to accommodate different forms of P fertiliser and also placement effects in fertiliser application. This is achieved by specifying fertiliser as either immediately available (e.g. water-soluble forms such as mono-ammonium phosphate) or as a non-water soluble source (e.g. rock phosphate) which needs to break down before P becomes

available, or some combination of the two. In the case of addition of an available form, if it is broadcast and mixed into soil its P content is immediately added to the soil labile P; but if it is banded, its P is accounted for separately so that it can be assigned a higher value than the rest of the labile P in terms of supplying P to a crop. Similarly, a rock phosphate source is accounted for separately and releases its P to the

labile P pool at a rate that is specified for a particular simulation run. To date, no effort has been made to make the rate of release of P from non-water soluble sources dependent on the source or soil properties.

Loss of availability

It is assumed that the transformations between labile P and unavailable P are first-order processes that are dependent on temperature. The relative rates of the forward and reverse processes (Jones et al. 1984) determine the magnitude of the unavailable pool relative to the labile P at steady-state conditions; it has been assumed that at steady state the unavailable pool is typically 10 times the labile pool. No attempt has been made to rationalise the sum of the soil P pools to measured total soil P.

Soil organic P

The APSIM SoilN module accounts for C and N in the various soil organic matter pools; the APSIM Residue module does likewise for the surface residues (see Probert and Dimes 2004). SoilP assumes that these pools also contain P. Decomposition of any pool (controlled by the SoilN or Residue modules) results in release of C, N and P in proportion to the composition of the pool. SoilP assumes that the C:P ratios of the soil BIOM and HUM pools are invariant (as is the case for the corresponding C:N ratios), but the C:P ratio of the surface residues and FOM can vary depending on the materials being added to the system. Decomposition of soil organic matter can thus result in mineralisation or immobilisation of P depending on the C:P ratios of the pools decomposing and being synthesised.

Crop uptake of P

SoilP calculates a potential daily supply of P from all soil layers. This involves (1) estimation of the effective P in a soil layer (the sum of labile P and placed P, with a premium being assigned to the latter); (2) conversion to a notional concentration in solution based on the P sorption characteristics of the soil; (3) summation across the soil profile weighted according to the presence of roots, soil water status of the layer, and layer thickness; and (4) application of a P uptake factor that can be crop or cultivar dependent. The P uptake factor, as used here, has similarities with the root absorbing power of Nye and Tinker (1977) in that it is the proportionality between P uptake and concentration in solution. Actual uptake is then the minimum of the potential supply and the demand calculated by the crop module. P uptake is apportioned between labile and placed P in the dif-

ferent layers in the proportion to which they contribute to the potential supply.

The notion of assigning a premium to placed P is analogous to what has been referred to as substitution, whereby one unit of placed P might be considered to substitute for, say, two units of soil P. The justification for relating P uptake to a notional concentration in solution follows from Probert and Moody (1998) who showed how P uptake can be related to a measure of P quantity combined with an index of P buffer capacity.

Simulating crop growth and development under P limiting conditions

The routines introduced into the maize module to restrict growth under P limiting conditions are similar to the corresponding N routines. The relative P concentration in the plant (or plant parts) is calculated with reference to defined optimal and minimal concentrations. This is then used to calculate P stress factors for photosynthesis, leaf expansion, phenology and grain filling, which are combined (law of minimum) with corresponding stress factors for water and nitrogen to modify crop growth.

Initial efforts to demonstrate that such a model might be feasible used P concentrations in the whole above-ground plant (see Figure 2) for calculating the P status of the plant. While this could work for a single crop, it is not compatible with simulating a sequence of crops where P in roots and residues must be considered. Accordingly, later efforts have endeavoured to partition P between the various plant components (leaf, stem, flower, grain, root) of the growing crop in a way similar to that in which N is modelled in APSIM crop modules. There is a dearth of information from which the appropriate critical P concentrations can be derived; current values are based on measurements on the short-duration cultivar Katumani Composite B (Probert and Okalebo, unpublished data) together with the published data of Jones (1983).

There are also few data on how P affects plant growth. Compared with the effects of nitrogen there seems to be a lack of information on leaf expansion, and only passing references to the fact that P deficiency delays flowering in maize (Probert and Okalebo 1992) and in sorghum (Sahrawat et al. 1995). Accordingly, the model currently assumes the dominant effect of P is expressed through a reduction in photosynthesis.

The plant demand for P is calculated from (a) the P requirement for today's growth (at the optimal P concentration), and (b) the overall P deficit of the crop, being the amount of P required to raise the whole of the plant mass to its optimal P concentration. Provided the soil supply (see above) is adequate, the model allows part (a) to be met. Further, in order that a plant can 'recover' from a P-deficient condition, the uptake is allowed to exceed the requirement for today's growth by a factor (a value of 1.5 is currently used (Jones et al. 1984)), thereby reducing the overall deficit. Because the predicted P supply from soil is strongly dependent on soil moisture, this approach to estimating uptake prevents the plant from rapidly meeting its P needs following a rainfall event.

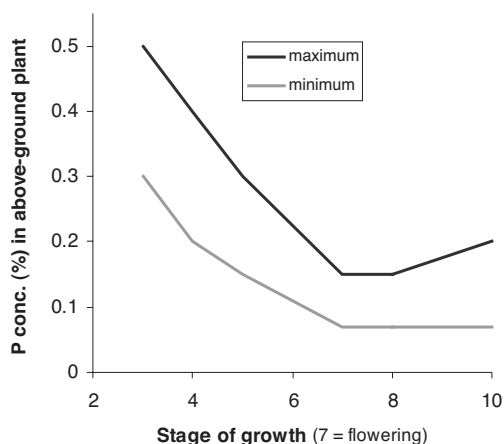


Figure 2. The P concentrations in maize used to define the crops P status. The minimum P concentrations are derived from the experimental data of Probert and Okalebo (1992); the maximum concentration from Jones (1983).

Parameterising the SoilP module

An example of a parameter file to initialise the APSIM SoilP module is shown in Table 1. In most circumstances it is envisaged that **banded_p** and **rock_p** would be zero in all layers (i.e. one would normally initialise the model before applying fertilisers); similarly in most unfertilised conditions it can be assumed that the labile P is in steady state with unavailable P (the default assumption if no values are provided for **unavailable_p**). Information is needed for the C:P ratio of roots and residues and also the rate

at which P will be released from **rock_p** (expressed on an annual basis).

The difficult business of specifying the soil with respect to its P status comes down to initialising the labile P pool and the soil's P sorption characteristics. For the latter the 'standard P requirement' is used, as defined by Beckwith (1965) and widely used by others (e.g. Fox and Kamprath 1970). It corresponds with the P sorbed at a final concentration of 0.2 mg L^{-1} . It has the advantage that it provides a scale for P sorption that is generally understood.

In most circumstances, it will be necessary to 'drive' the model using soil P test data to initialise the labile P pool. No effort has been made to include algorithms in the model code to specify how this should be done. Rather it is left to the discretion of the user. In experiences to date, we have used bicarbonate or resin extractable P. On low P sorbing soils it might be expected that these fractions will approximate the labile P, though more generally as P sorption increases it would be expected that the soil tests will extract a decreasing proportion of the soil's labile P.

Predictive performance

The data set that has been used to test the assumptions that underlie the P capability developed within the APSIM framework was collected on an Alfisol with low P sorption characteristics at Mutua Farm, near Katumani in eastern Kenya (Probert and Okalebo 1992). Bicarbonate extractable P (Olsen) in the surface 0–15 cm soil was 4 mg kg^{-1} . Briefly, maize (Katumani Composite B) was grown over two seasons (short rains 1989–1990; long rains 1990) with different inputs of P as single superphosphate and adequate N. Several harvests were made through the duration of the crop, and the plant biomass was separated into its components (leaf, stem, cobs and, at maturity, grain), dried and analysed for P and N.

The output from the model is compared with the measured data in Figure 3. What is shown is not implied to be an independent test of the model. However, it does indicate that the model was able to capture the main features of the measured data in terms of total dry matter and grain yield. Other data (not shown) showed reasonable agreement in leaf area and P concentration in the tissues.

A second experiment examined the effectiveness of different fertiliser sources of P (Figure 4). To demonstrate the potential of the model to simulate

Table 1. An example of a SoilP parameter file to initialise an APSIM simulation. The layer structure (number of layers, layer thickness) used in the simulation is defined by the soil water module; the additional input relates only to the P pools.

[all.soilp.parameters]					
layer number	1	2	3	4	
labile_p =	5	4	3	3	(mg/kg)
unavailable_p =	50	40	30	30	! optional
banded_p =	0	0	0	0	(kg/ha)
rock_p =	0	0	0	0	(kg/ha)
sorption =	110	150	200	200	! p sorbed at 0.2 mg/L
residue_cp = 250					
root_cp = 200					
rate_dissol_rock_p = 0.40 (L/yr)					

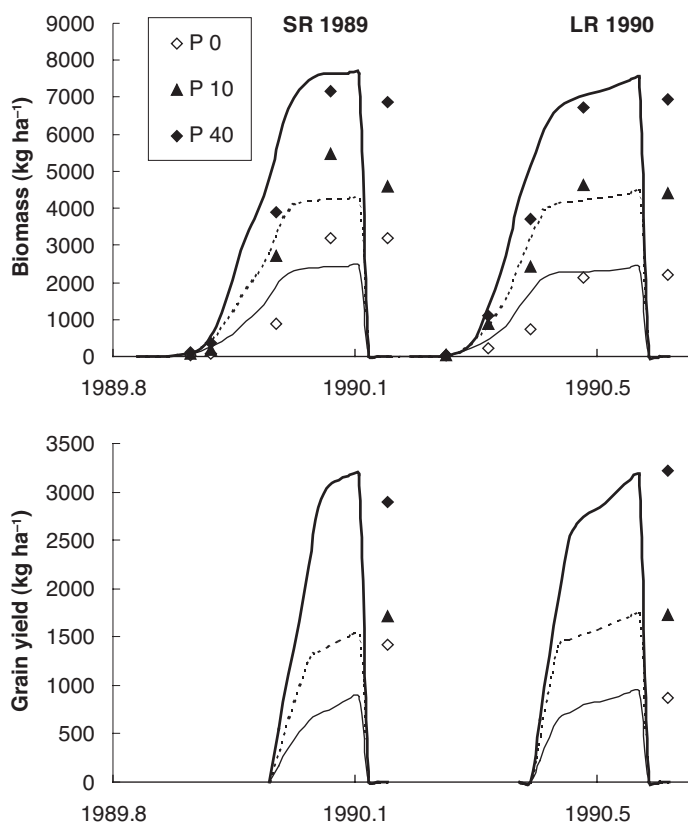


Figure 3. Comparison of measured and simulated yields of the maize crops grown at Mutua Farm, near Katumani with different rates of P as superphosphate applied as a band below the seed and 90 kg ha⁻¹ of N as calcium ammonium nitrate applied as three splits (Probert and Okalebo 1992). The observed data are shown as symbols, the predictions as continuous lines. Note that the crops were harvested several weeks later than physiological maturity as predicted by the model.

response to non-water-soluble sources, it was assumed that the Minjingu rock P had 20% of its P readily available and 80% unavailable; for the partially acidulated product, 60% was assumed available. No attempt was made to optimise values obtain a better fit. The simulated output shows that the model is able to predict a smaller response to P sources that are not immediately available. However, in this experiment the observed response to the partially acidulated product was similar to single superphosphate.

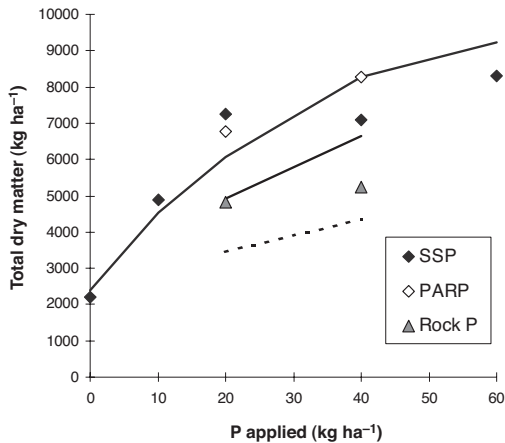


Figure 4. Simulation of total DM yield at maturity of maize fertilised with single superphosphate, partially acidulated (50%) rock phosphate, and Minjingu rock phosphate; all treatments received 90 kg ha⁻¹ of N as calcium ammonium nitrate. The observed data are shown as symbols, the predictions as continuous lines. The rock phosphate sources were only tested at rates of application of 20 and 40 kg P ha⁻¹. Experimental data from Probert and Okalebo (1992).

A comment on modelling the mineralisation of P from organic inputs

It is generally recognised that the mineralisation of N from organic sources depends largely on the C:N ratio of the substrate. This can be expressed succinctly (Whitmore and Handayanto 1997):

$$N_{\text{mineralised}} = C_{\text{decomposed}} [1/C:N_{\text{substrate}} - E/C:N_{\text{SOM}}]$$

where $C:N_{\text{SOM}}$ is the C:N ratio of the soil organic matter being synthesised; E is sometimes referred to

as the assimilation coefficient, which equates with the fraction of the decomposing carbon that is retained as soil organic matter and in APSIM SoilN is normally set at 0.4. If all the retained carbon is synthesised into the more labile soil carbon pool with a C:N ratio of 8, the C:N ratio of the substrate that determines whether net mineralisation or immobilisation occurs is 20. The essence of this relationship is the basis of the decomposition/mineralisation process in the APSIM SoilN module.

An assumption that the same principle would apply to the mineralisation of organic P leads to a relationship between the P mineralised and the C:P ratios of substrate and the soil organic matter being synthesised:

$$P_{\text{mineralised}} = C_{\text{decomposed}} [1/C:P_{\text{substrate}} - E/C:P_{\text{SOM}}]$$

From this equation, the P concentration determining net mineralisation/immobilisation can be calculated for different assumed C:P ratio of the soil organic matter (Table 2).

Table 2. Predicted phosphorus content of plant residues (expressed as C:P ratio and P concentration in dry matter) that would determine whether initial mineralisation or immobilisation of P occurs for different assumed values of the C:P ratio of the soil organic matter being formed.

C:P of organic matter	C:P of residues	P concentration (%) ^a
20	50	0.80
40	100	0.40
67	167	0.24
100	250	0.16
200	500	0.08

^a Assuming 40% carbon in plant dry matter

Palm et al. (1999) suggest a critical P concentration of 0.24% below which immobilisation of P would occur, while Nguluu et al. (1996) reported that mineralisation of N from plant residues was reduced (presumably because the decomposition rate was limited by P) when P concentration in tissues dropped below 0.16%.

On the other hand, the C:P ratio of soil microbial biomass is generally in the range 10 to 35 (quoted by He et al. (1997)). For a Nitisol from Western Kenya, Nziguheba (2001) measured small changes in microbial C:P due to P inputs and through time, with an

overall average of 27. He et al. (1997) reported much larger variation in a soil under grassland, due to time of sampling and nutrient inputs (range 9–276), but it seems implausible that living organisms could vary so widely. For comparison, the C:N ratio of microbial biomass is higher for fungi (~12) than for bacteria (~8), but otherwise does not seem to vary much across diverse ecosystems.

Thus, there would seem to be some discrepancy between the mineralisation of P from plant residues and the soil microbial C:P ratio. At typical biomass C:P values, no crop residue with P concentration <0.4% would be expected to mineralise P. Why this does not happen can probably be explained by the fact that sub-fractions of the substrate have different C:P ratios (compare Probert et al. (2004) who suggest a similar explanation to account for the N mineralisation pattern from some manures). In the case of crop residues, the C:P ratio of the soluble fraction is much lower than that of the total dry matter. Nziguheba (2001, Table 1.2.1) reports soluble C:soluble P ranging from 12–50 for six organic inputs used as green manure, whereas total C:P was in the range 140–250. For most materials, at least 50% of total P was soluble. Similarly, Ngululu et al. (1996) reported approximately 75% of total P to be water extractable, even for materials that were grown under P limiting conditions.

In many situations where the model will be applied, the mineralisation of organic P is likely to be unimportant. But, clearly, any efforts to simulate the effectiveness as P sources of biomass transfer systems (as studied by Nziguheba (2001)) would need to be able to specify inputs of organic material that have sub-fractions with different C:P ratios.

Discussion

The development of a capability to model crop response to limited P supply requires code to describe the behaviour of P in both the soil and the plant. The approach adopted to create this capability in APSIM has similarities and conceptual differences from how the problem has been tackled in DSSAT (Daroub et al. 2003).

The most obvious differences are in how the understanding of the behaviour of soil P is represented. Daroub et al. (2003) seek to specify numerous soil inorganic and organic P pools in terms of measured soil fractions. The philosophy in the APSIM

approach has been that the organic P pools are identical to the C and N pools found elsewhere in the model. Thus, there will always be a linkage between mineralisation/immobilisation of N and P and decomposition of soil organic matter. Also, the conceptual labile P pool in the APSIM SoilP module has not been directly linked to any soil P test. In this manner we avoid the difficulty that labile P, as it is defined in the model, responds quantitatively to inputs and removal of P, whereas this is not the case with soil tests. Nevertheless, this is to admit that it is not yet clear how such a model can be initialised and/or validated against measured soil test data. It remains an open question as to what are the 'pros and cons' of the two approaches.

Here we have shown that the P-aware maize model can be specified to produce output that matches observations from a single site on an Alfisol. In particular, the desire has been to produce a tool that will perform sensibly with regards to issues like soluble versus non-water-soluble sources, placement effects, and soils with different P sorption characteristics. The challenges that are still to be faced are to show that the model with the same parameterisation is able to perform satisfactorily for different soils and environments, and ultimately can be parameterised for other crops. Other papers in these proceedings test this hypothesis on a wider range of soils.

The SoilP module has been developed with the aim that it will also respond sensibly to inputs of P in organic sources including manures, but validation against suitable data sets has not yet been undertaken. An omission from the model is that it does not explicitly deal with the effects of mycorrhizae on P nutrition of crops. However, it is expected that this will not be a limitation in the low-input farming systems where the model is likely to be used.

Acknowledgment

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References

- Beckwith, R.S. 1965. Sorbed phosphate at standard supernatant concentration as an estimate of the phosphate needs of soils. *Australian Journal of Experimental Agriculture and Animal Husbandry*, 5, 52–58.

- Claassen, N. and Barber, S.A. 1976. Simulation model for nutrient uptake from soil by growing plant root system (maize). *Agronomy Journal*, 68, 961–964.
- Daroub, S.H., Gerakis, A., Ritchie, J.T., Friesen, D.K. and Ryan, J. 2003. Development of a soil–plant phosphorus model for calcareous and weathered tropical soils. *Agricultural Systems*, 76, 1157–1181.
- Fox, R.L. and Kamprath, E.J. 1970. Phosphate sorption isotherms for evaluating the phosphate requirements of soils. *Soil Science Society of America Proceedings*, 34, 902–907.
- Gijsman, A.J., Oberson, A., Tiessen, H. and Friesen, D.K. 1996. Limited applicability of the CENTURY model to highly weathered tropical soils. *Agronomy Journal*, 88, 894–903.
- He, Z.L., Wu, J., O'Donnell, A.G. and Syers, J.K. 1997. Seasonal response in microbial biomass carbon, phosphorus and sulphur in soils under pasture. *Biology and Fertility of Soils*, 24, 421–428.
- Jones, C.A. 1983. A survey of the variability in tissue nitrogen and phosphorus concentrations in maize and grain sorghum. *Field Crops Research*, 6, 133–147.
- Jones, C.A., Cole, C.V., Sharpley, A.N. and Williams, J.R. 1984. A simplified soil and plant phosphorus model: I. Documentation. *Soil Science Society of America Journal*, 48, 800–805.
- Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy*, 18, 267–288.
- Kinyangi, J., Delve, R., and Probert, M.E. 2004. Testing the APSIM model with data from a phosphorus and nitrogen replenishment experiment on an Oxisol in western Kenya. In: Delve, R.J. and Probert, M.E., ed., 2004. Integrated nutrient management in tropical cropping systems: improved capabilities in modelling and recommendations. These proceedings.
- McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P. and Freebairn, D.M. 1996. APSIM: a novel software system for model development, model testing, and simulation in agricultural research. *Agricultural Systems*, 50, 255–271.
- McCown, R.L., Keating, B.A., Probert, M.E. and Jones, R.K. 1992. Strategies for sustainable crop production in semi-arid Africa. *Outlook on Agriculture*, 21, 21–31.
- Micheni, A.N., Kihanda, F.M., Probert, M.E. and Warren, G.P. 2004. Testing the APSIM model with experimental data from the long-term manure experiment at Machang'a (Embu), Kenya. These proceedings.
- Ngululu, S.N., Probert, M.E., Myers, R.J.K. and Waring, S.A. 1996. Effect of tissue phosphorus concentration on the mineralisation of nitrogen from stylo and cowpea residues. *Plant and Soil*, 191, 139–146.
- Nziguheba, G. 2001. Improving phosphorus availability and maize production through organic and inorganic amendments in phosphorus deficient soils in western Kenya. PhD Thesis No. 462, Katholieke Universiteit Leuven, Belgium.
- Nye, P.H. and Tinker, P.B. 1977. Solute movement in the soil–root system. Oxford, Blackwell Scientific Publications, 342 p.
- Palm, C.A., Myers, R.J.K. and Nandwa, S.M. 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: Buresh, R.J., Sanchez, P.A. and Calhoun, F., ed., Replenishing soil fertility in Africa. *Soil Science Society of America Special Publication No. 51*, 193–217.
- Palm, C.A., Nziguheba, G., Gachengo, C.N., Gacheru, E. and Rao, M.R. 1999. Organic materials as sources of phosphorus. *Agroforestry Forum*, 9, 30–33.
- Parton, W.J., Stewart, J.W.B. and Cole, C.V. 1988. Dynamics of C, N, P and S in grassland soils: a model. *Biogeochemistry*, 5, 109–131.
- Probert, M.E. 1985. A conceptual model for initial and residual responses to phosphorus fertilizers. *Fertilizer Research*, 6, 131–138.
- Probert, M.E. and Dimes, J.P. 2004. Modelling release of nutrients from organic resources using APSIM. These proceedings.
- Probert, M.E. and Keating, B.A. 2000. What soil constraints should be included in crop and forest models? *Agriculture, Ecosystems and Environment*, 82, 273–281.
- Probert, M.E. and Moody, P.W. 1998. Relating phosphorus quantity, intensity, and buffer capacity to phosphorus uptake. *Australian Journal of Soil Research*, 36, 389–393.
- Probert, M.E. and Okalebo, J.R. 1992. Effects of phosphorus on the growth and development of maize. In: Probert, M.E., ed., A search for strategies for sustainable dryland cropping in semi-arid Eastern Kenya. Proceedings of a symposium, Nairobi, Kenya, 10–11 December 1990. Canberra, ACIAR Proceedings No. 41, 55–62.
- Probert, M.E., Delve, R.J., Kimani, S.K., and Dimes, J.P. 2004. The APSIM Manure module: Improvements in predictability and application to laboratory studies. These proceedings.
- Sahrawat, K.L., Rego, T.J., Burford, J.R., Rahman, M.H., Rao, J.K. and Adam, A. 1995. Response of sorghum to fertilizer phosphorus and its residual value in a vertisol. *Fertilizer Research*, 41, 41–47.
- Whitmore, A.P. and Handayanto, E. 1997. Simulating the mineralization of N from crop residues in relation to residue quality. In: Cadisch, G. and Giller, K.E., ed., Driven by nature: plant litter quality and decomposition. Wallingford, UK, CAB International, 337–348.

4.4

Testing the APSIM Model with Data from a Phosphorus and Nitrogen Replenishment Experiment on an Oxisol in Western Kenya

J. Kinyangi,* R.J. Delve[†] and M.E. Probert[§]

Abstract

An experiment was conducted on an Oxisol near Maseno in western Kenya, to compare the growth of maize crops to inputs of two phosphorus sources. Commercial triple superphosphate (TSP) and Minjingu phosphate rock were applied either at a once-only rate of 250 kg P ha⁻¹ or as five annual inputs of 50 kg P ha⁻¹. The experiment was carried out over 10 cropping seasons between 1996 and 2000. An additional factor studied was the source of N, either as urea or tithonia biomass-N to supply 60 kg N ha⁻¹. Both N and P sources were applied only to the crops grown in the long rain season. The APSIM model has been tested against this data set. The effects of P treatments were large in the long rain season, but in the short rain season the inadequate supply of N greatly reduced growth and P effects. The yields of the maize crops were predicted well ($r^2 = 0.88$) with respect to both the P treatments (as TSP) and the N inputs (as urea). The predicted water, N and P stresses were informative in understanding the contrasting pattern of response observed in the two seasons. The simulation of this long-term experiment shows that the APSIM SoilP module is robust, in as much as it extends the testing of the model to a very different environment where there were both N and P stresses affecting plant growth, and on a very different soil type to where the concepts in the APSIM phosphorus routines were originally developed and tested.

Crop production on many soils in western Kenya is limited by both nitrogen (N) and phosphorus (P). The concept of recapitalisation of soil P has focused attention on the use of rock phosphate materials rather than commercial forms of processed fertilisers, and the feasibility of raising soil P through large, one-time application rather than a gradual increase with smaller, but regular inputs (Buresh et

al. 1997). Such strategies have been evaluated in long-term experiments in western Kenya.

Probert (2004) describes how a capability to simulate P limited maize crops has been developed within the APSIM modelling framework. The data used to derive the parameter set defining the P status of maize through its growth cycle were from experiments at Katumani in the semi-arid region of eastern Kenya, on soils with low P sorption. There is a need to test the applicability of the model under a much wider range of environments and on different soil types.

In this paper, we describe the testing of the APSIM P routines using an experiment that provides suitable data for testing some aspects of the model. The annual rainfall and soil type, especially with regards to its phosphorus sorption properties, are

* TSBF-CIAT, PO Box 30667, Nairobi, Kenya. Present Address: Cornell University, Ithaca, NY, USA
<jmk88@cornell.edu>.

[†] TSBF-CIAT, PO Box 6247, Kampala, Uganda
<r.delve@cgiar.org>.

[§] CSIRO Sustainable Ecosystems, 306 Carmody Road, St Lucia, Queensland 4067, Australia
<merv.probert@csiro.au>.

extreme contrasts to those on which the model was first developed.

The Experiment

Site description

A field experiment was conducted at Olwenyi, Ondele and Julius farms near Maseno in western Kenya (0°06' N, 34°34' E, 1420 m above sea level). The annual rainfall in the region is typically 1800–2000 mm, with bimodal distribution and two growing seasons; the long rain season between March and July (LR) and the short rain season between September and January (SR).

The soil type is a very fine isohyperthermic Kandudalfic Eutrudox (USDA 1992). It has few chemical or physical barriers to rooting in the top 4 m (Mekonen et al. 1997). Air-dried soil (0–15 cm) had a pH of 5.2 (1:2.5 soil:water suspension); organic carbon 18 g kg⁻¹; exchangeable acidity (1 M KCl) 1.0 cmol_c kg⁻¹; calcium 3.5 cmol_c kg⁻¹; magnesium 1.3 cmol_c kg⁻¹; potassium 0.12 cmol_c kg⁻¹; bicarbonate–EDTA extractable phosphorus 1.7 mg kg⁻¹. Clay, silt and sand contents were 35%, 20% and 45%, respectively. P sorption is very high; based on sorption isotherms 250 mg P kg⁻¹ of soil was required to raise soil solution P to 0.2 mg L⁻¹ for 0–15 cm soil.

Treatments

The experiment began in 1996. It was designed as a balanced factorial combination comparing a one-time application versus repeated annual additions of P, with two P sources (triple superphosphate (TSP) and Minjingu rock phosphate from Arusha, northern Tanzania) plus a control treatment that did not receive any P, and two nitrogen sources (urea and tithonia biomass to supply 60 kg N ha⁻¹). The annual P application was 50 kg ha⁻¹ applied in March–April before the LR crop, while the one-time application rate was 250 kg ha⁻¹ applied before the 1996 LR crop only. The P sources were broadcast and incorporated into the soil before planting. After 10 seasons, the total P applied was the same for the one-time and annual applications.

The N inputs as urea or tithonia biomass (3.3% N) were applied to only the LR crops. Urea was split-applied, one-third at sowing and two-thirds at 5 weeks after sowing. The tithonia was chopped and

incorporated into soil before planting maize in the LR season.

Management

Sole maize crop was planted at 0.75 × 0.25 m spacing using medium to short duration hybrid varieties. The LR crops were sown in March–April, the SR crops in August–September. During maize harvest, all stover was removed from the plots. Between crops, soil was ploughed to 15 cm depth.

Potassium deficiency was observed to seriously affect the yield of the first crop. In March 1997, all plots were split to accommodate an additional factor testing the effect of 1) no addition of K fertiliser, and 2) annual application of 60 kg K ha⁻¹ as KCl. In this paper, we consider only data from plots that received K, and yields are assumed to be unaffected by K deficiency.

The soil (0–15 cm) was sampled in 1996, 1997 and 2000 at the time of sowing the LR crop after all organic and inorganic fertiliser materials had been applied and incorporated into the soil. Samples were air-dried, sieved through 2 mm, and fractionated for soil P using a method that employs a series of increasingly aggressive extractants to remove labile inorganic and organic P (P_i and P_o) followed by more stable P_i and P_o forms. The method is modified from the procedure of Tiessen and Moir (1993), which in turn is based on the fractionation procedure of Hedley et al. (1982).

Simulations

The model was specified to simulate the experimental treatments involving TSP and urea. We used the genetic coefficients for the maize hybrid HB 511 for all seasons, these being available from other studies. For most crops, the predicted maturity of the crop agreed reasonably with the date of harvest. An exception was the LR crop in 2000 (sown 7–8 April), which the model predicted to be mature on 10 September, later than the sowing date (29–30 August) for the next SR crop. This was accommodated by delaying the sowing of the SR crop until 12 September.

The simulation runs were initialised on 15 March 1996, corresponding to the start of the experiment, with the soil properties set out in Table 1. A continuous simulation was run for the 10 seasons. The soil's plant available water capacity to the rooting

depth of 1.8 m was 155 mm. The soil organic carbon in the surface soil layer was the measured value. The soil labile P in the surface layer was based on the sum of resin and bicarbonate-P measured in the sequential fractionation of soil P. Both organic carbon and soil P were assumed to decrease with depth, while P sorption was assumed to be higher in the subsoil layers.

Results and Discussion

Observed maize yields

The overall effects of the treatments on the total above-ground dry matter (DM) yield for maize are summarised in Table 2. Maize grain yields showed responses that were similar to the total DM yields and these data are not presented.

There is a very large response to P in the LR seasons, but only small differences between the two P sources or the frequency of application of the P fertiliser. This is consistent with Minjingu rock phosphate being recognised as an effective source of P, especially on an acidic soil.

The yields of the SR crops were much lower than for the LR. The stresses predicted in the simulations indicate that this is predominantly a nitrogen effect,

because there were no N inputs to the SR crops (see Figure 3).

The apparent effects of the two N sources are complex. For the LR crops, the main effect of N source was not statistically significant ($p > 0.05$). The application of tithonia-N resulted in higher average DM yields, but this observation is due almost entirely to the 1996 LR crop. In the first year of the experiment, before the K treatments had commenced, the tithonia biomass (containing 56 kg ha⁻¹ of K) largely overcame the K limitation that occurred when urea was the N source. The annual input of tithonia biomass also contained 6 kg ha⁻¹ of P and this contributes to some of the difference between the two N sources in the absence of any P fertiliser. The SR crops, grown without additional inputs, show a residual effect from the tithonia-N compared with urea-N, maize DM yields being approximately 1 t ha⁻¹ higher where P was applied ($p < 0.01$).

Comparison of observed versus predicted yields

Figure 1 compares the observed effects of the three P treatments with the output from the simulation, showing the response to P in each of the cropping

Table 1. Soil properties used for specifying APSIM simulation of the Maseno experiment.

Layer	1	2	3	4	5	6	7
SoilWat parameters^a							
Layer thickness (mm)	150	150	300	300	300	300	300
BD (g cm ⁻³)	1.10	1.22	1.31	1.23	1.19	1.15	1.21
SAT	0.50	0.49	0.46	0.48	0.50	0.50	0.49
DUL	0.35	0.38	0.40	0.37	0.36	0.35	0.37
SWCON	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Maize parameter							
LLmaize	0.22	0.24	0.28	0.30	0.30	0.29	0.30
SoilN parameters							
organic C (%)	1.8	1.0	0.72	0.57	0.45	0.35	0.30
finert ^b	0.35	0.7	0.8	0.9	0.95	0.99	0.99
fbiom	0.02	0.015	0.01	0.01	0.01	0.01	0.01
SoilP parameters							
labile P (mg kg ⁻¹)	8.5	5	2	2	2	2	2
P sorption (mg kg ⁻¹) ^c	260	400	400	400	400	400	400

^a The soil water balance is described in terms of the volumetric water content at saturation (SAT), drained upper limit (DUL), and lower limit of extraction by the crop (LL); BD is soil bulk density; SWCON is the proportion of water in excess of DUL that drains in 1 day.

^b finert is the proportion of soil carbon assumed not to decompose; fbiom is the proportion of decomposable soil carbon in the more labile soil organic matter pool.

^c P sorbed at 0.2 mg L⁻¹ in solution.

Table 2. Effect of P treatments on maize biomass yields (t ha^{-1}) at Maseno for the two sources of nitrogen. Data averaged across the 5 years 1996–2000.

Phosphorus treatment	Long rain crops		Short rain crops	
	Urea	Tithonia	Urea	Tithonia
No added P	3.3	5.8	1.6	2.2
Annual addition (50 kg ha^{-1}) as TSP	9.6	10.3	2.2	3.1
Annual addition (50 kg ha^{-1}) as MPR	8.8	10.3	2.2	3.2
One time addition (250 kg ha^{-1}) as TSP	9.5	10.6	2.5	3.5
One time addition (250 kg ha^{-1}) as MPR	9.1	9.9	2.5	3.3
Analysis of variance:				
P treatment	$p < 0.001$		$p > 0.05$	
N source	$p > 0.05$		$p < 0.01$	
P treatment \times N source	$p > 0.05$		$p > 0.05$	

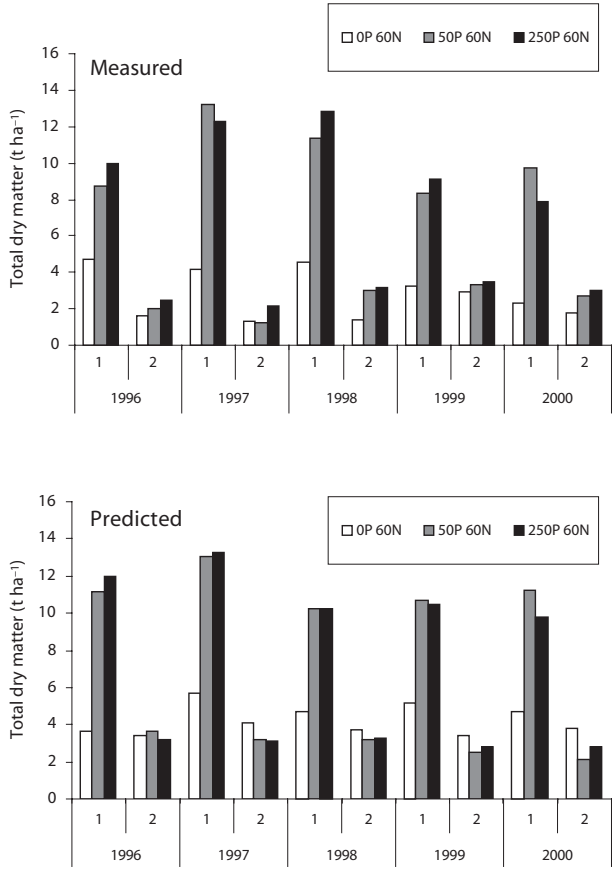


Figure 1. A comparison of the measured (upper pane) and simulated (lower pane) dry matter yields of maize through 10 seasons for the treatments receiving 60 kg ha^{-1} of N as urea and different inputs of P as TSP: none, 50 kg ha^{-1} annually, or 250 kg ha^{-1} as a single application before the 1996 crop. Note that for the measured data, the yields for the first crop in 1996 are for the treatments that received tithonia-biomass as the N source. For the later crops, the N source was urea, and potassium was also applied after 1997.

seasons. In Figure 2 the data are plotted in the more conventional ‘observed versus predicted’ manner.

The most marked feature of the pattern exhibited in Figure 1 is the difference in DM yields between the two seasons. This is captured well by the model. In the second (SR) season when no additional P and, more importantly, no N was applied, yields were very low (2–3 t ha⁻¹) and were little affected by P treatments. In the LR, the DM yields without P addition were around 4 t ha⁻¹ increasing to ~10 t ha⁻¹ where P was applied. There was reasonable agreement between the observed and fitted yields ($r^2 = 0.88$) with little indication of bias (Figure 2). However, the model provides no ability to discriminate between the treatments for the SR crops.

Where the P effects are not obscured because of limiting N, both the observed and predicted data show that, in the early years of the experiment, there was not much difference between the 50 and 250 kg ha⁻¹ rates, though with a tendency for the measured yields to respond beyond the 50 kg ha⁻¹ rate in 1996 and 1998 (Figure 1); but by the fifth year there is some suggestion that the annual application of 50 kg ha⁻¹ is giving larger yield than the single input of 250 kg ha⁻¹.

Insights provided by the model

Stresses on crop growth

In this experiment, there is little indication of year-to-year variation in crop growth, but it is evident that there are great differences between the two seasons and due to the treatments. The output from the model is helpful in understanding the cause of these effects.

In Figure 3 we show the predicted stresses on crop growth due to water, phosphorus and nitrogen. The experimental site enjoys high rainfall and the model predicts that, through the 10 crops, water stress was never limiting. For the no-P treatment, the simulation shows that P stress always dominates N stress, though for the SR crops after 1997 there are signs that N is also suboptimal. However, when P has been applied, the situation is reversed and N stress dominates. Particularly in the SR crops, N stress commences early and growth is severely restricted. Thus, the inference from the simulations is that the experiment was carried out under less than optimal N. Treatments with higher N inputs might well have accentuated the differences between the P treatments, especially in the SR crops.

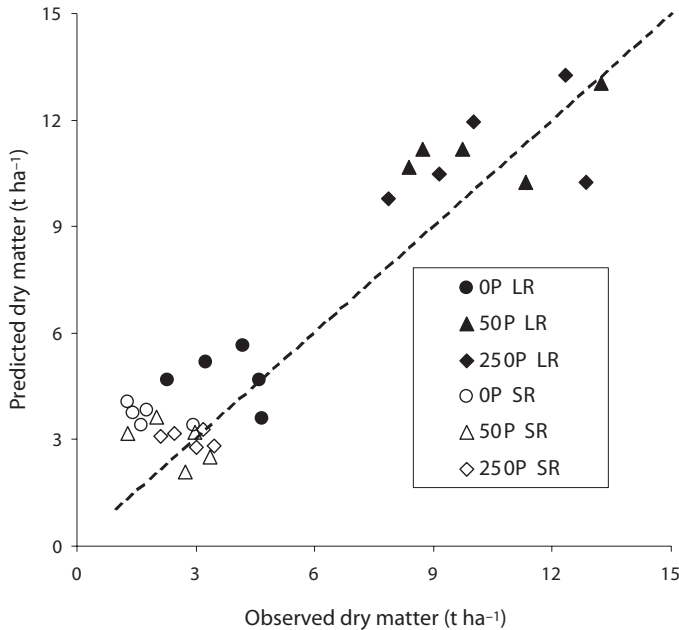


Figure 2. Plot of observed versus simulated maize dry matter yields in relation to the 1:1 line. The root-mean-square deviation between observed and predicted yields is 1.58 t ha⁻¹.

Figure 4 illustrates some aspects of the simulated water balance at the site. Over 25% of the rainfall is predicted to end up as drainage. Not much attention should be paid to the run-off values, because we deliberately parameterised the model to keep run-off low, based on the assertion that little run-off occurs on these soils. The large drainage reinforces that this is a very wet location where maize crops are not likely to be limited by water stress.

Another effect of the large drainage term is that it will effectively leach nitrate-N from the rooting zone. The lack of treatment effects in the second season is perhaps surprising, particularly where P-deficient crops have not fully exploited all of the applied N.

However, such behaviour is understandable in light of the predicted water balance. Table 2 shows that there is a greater residual effect from tithonia-biomass than from urea. The inference to be drawn from the water balance is that this occurs because more of the tithonia-N is present in organic form and so is protected against leaching, and will become available when it is re-mineralised in the second season.

Soil P

The simulated changes in labile P in the topsoil layer are shown in Figure 5. Only small changes are predicted to occur in the treatment without P addition; the small increase in labile P is due to minerali-

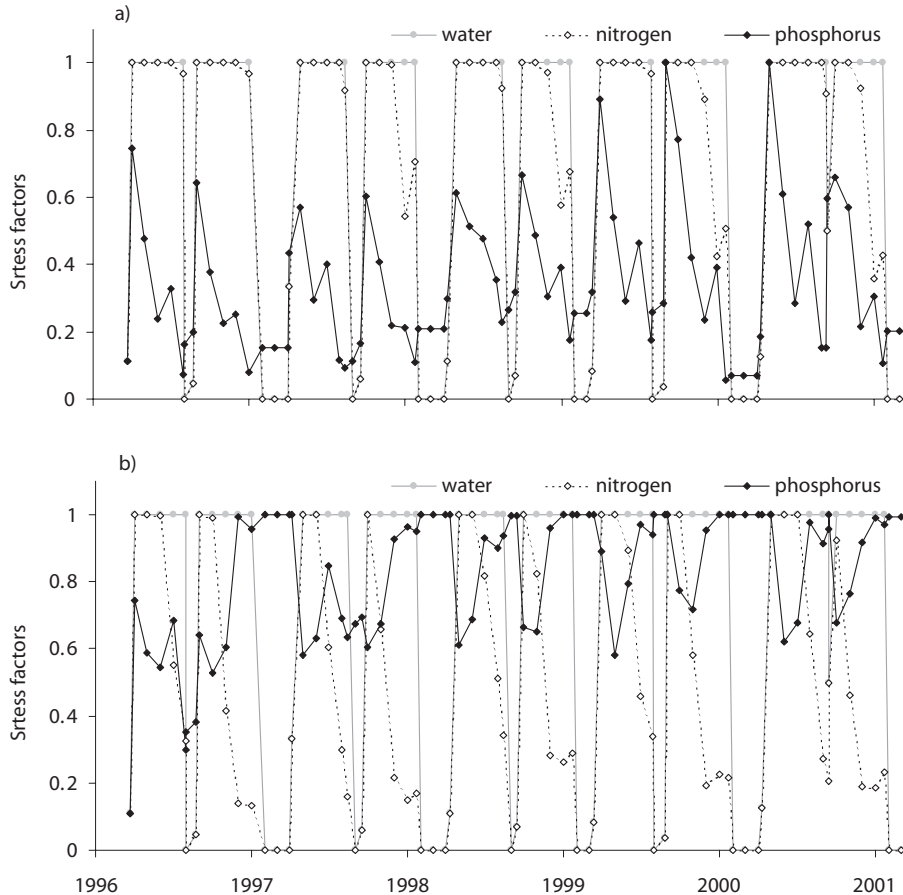


Figure 3. Illustration of the predicted stresses (1 – no stress, 0 – extreme stress) on the maize crops. The upper pane is for the treatment without applied P, the lower pane for the treatment with 50 kg ha⁻¹ of P applied annually. Nitrogen as urea (60 kg ha⁻¹) was applied to only the LR crops.

sation of soil organic matter, which is predicted to decline during the course of the experiment. It is to be noted that all above-ground crop residues were removed from the plots. The inputs of P fertiliser in 1996 result in the increase in soil P being five times larger for the one-time application. However, the processes presumed to be occurring in soil, notably the loss of availability with time, result in declining

labile P, so that by the end of the experiment the five annual applications results in higher labile P than for the one-time application. As mentioned above, some evidence to support this behaviour is found in the crop DM data.

Resin-P and bicarbonate extractable-P are generally considered to be the ‘available’ forms of P in soil. The measured data for the surface soil layer are

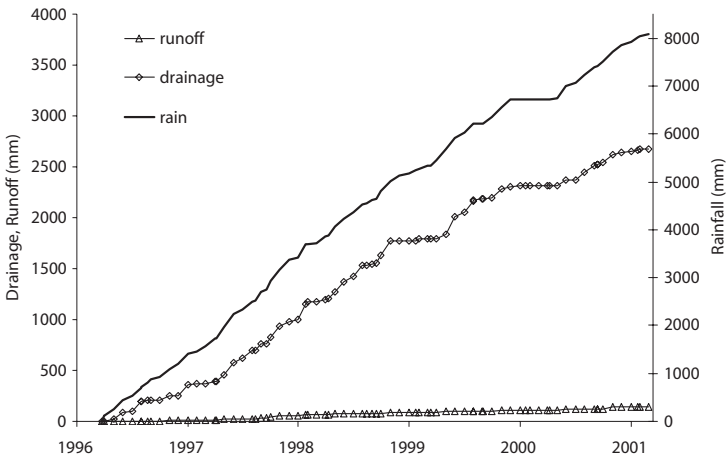


Figure 4. Cumulative rainfall and predicted drainage and run-off for the nil P treatment through the 10 seasons of the experiment. Note that rainfall is plotted on the right hand axis with a different scale to that used for drainage and run-off.

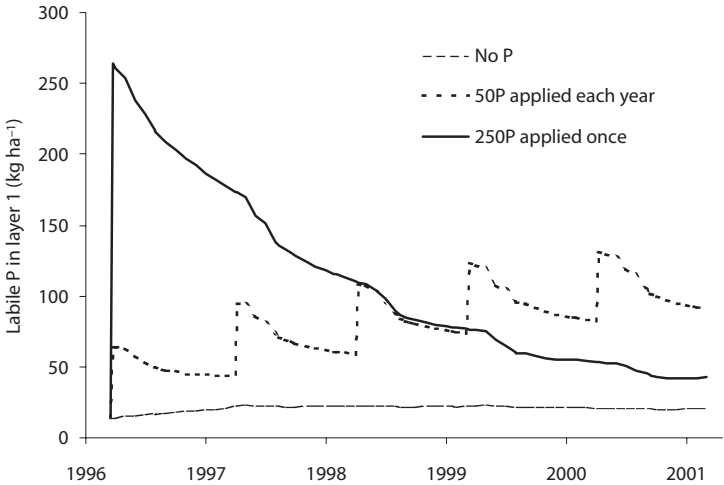


Figure 5. Simulated changes in labile P in the 0–15 cm layer of soil through the 10 crops for treatments that received different P treatment as specified in the legend.

Table 3. Measured soil P for the treatments receiving triple superphosphate (units: mg P kg⁻¹ soil). Resin- and bicarbonate extractable-P (inorganic) were determined successively on the same aliquot of soil. Values reported are averaged across the two N treatments.

Phosphorus treatment	Resin-P			Bicarb-P			Resin + Bicarb-P		
	1996	1997	2000	1996	1997	2000	1996	1997	2000
No added P	4	3	1	5	7	6	9	10	7
Annual addition (50 kg ha ⁻¹)	16	7	5	12	13	18	27	21	23
One time addition (250 kg ha ⁻¹)	28	8	4	19	22	19	47	30	23

summarised in Table 3. Conformity with the pattern of the model output is not good for either resin or bicarbonate P. However, when the two fractions are summed there is some semblance of agreement: the nil treatment changed little through time; a clear decline for the one-time application of P was measured; the pattern suggests that the soil P for the annual application will eventually exceed that for the one-time application, though it does appear that this treatment reached a plateau rather than exhibiting a regular increase as shown in the model output.

Other fractions of soil P that were measured are difficult to interpret and are not reported here. The organic-P fraction of the bicarbonate extract was unaffected by treatment or time of sampling; it averaged 26 mg P kg⁻¹ soil. Thus, for the treatment without P addition, a high proportion (~80%) of the bicarbonate extractable P was present as organic-P.

Conclusions

The Maseno experiment was carried out in a very different environment and on a very different soil to those on which the concepts in the APSIM phosphorus routines were originally developed and tested. Notably, this is a location with high rainfall where the model predicted that water stress did not affect crop growth, and the soil, an Oxisol, has high P-sorption characteristics. The parameter set used to simulate the behaviour of P in the soil and the P concentrations and uptake by maize was that based on crops grown on a low P-sorbing soil in a semi-arid environment. The model performed creditably in predicting the growth of maize crops for the different P treatments. A second aspect of this data set was that the N inputs (applied to only the LR crops) resulted in very different crop growth between the two seasons. The predicted water, P and N stresses were informative in helping to understand the reasons for the differences

in response to the N and P inputs in the two seasons. This is the first instance where the P version of the maize model has been tested under conditions where N stress was also a factor. Output from the model suggests that simulation of crop growth with two potential limiting nutrients was sensible.

Elsewhere Olsen P data have been used for initialising the labile P of the model. Here a fractionation procedure was used for the soil P data, and labile P has been equated to the sum of the resin and bicarbonate-P fractions. The soil P data were obtained for samples taken soon after the application of the fertilisers. There was poor agreement between the predicted changes in labile P and the soil P data.

Acknowledgments

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References

- Buresh, J.R., Smithson, P.C. and Hellums, D.T. 1997. Building soil phosphorus capital in Africa. In: Buresh, R.J., Sanchez, P.A., and Calhoun, F., ed., Replenishing soil fertility in Africa. Madison, WI, American Society of Agronomy and Soil Science Society of America Special Publication No. 51, 111–149.
- Hedley, M.J., Stewart, J.W.B. and Chauhan, B.S. 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society of America Journal*, 46, 970–976.
- Mekonen, K., Buresh, R.J. and Jama, B.A. 1997. Root and inorganic nitrogen distribution in sesbania fallow, natural fallow and maize. *Plant and Soil*, 188, 319–327.
- Probert, M.E. 2004. A capability in APSIM to model P responses in crops. These proceedings.

Tiessen, H. and Moir, J.O. 1993. Characterization of available P by sequential extraction. In: Carter, M.R., ed., Soil sampling and methods of analysis. Boca Raton, Florida, CRC Press, 75–86.

USDA (United States Department of Agriculture). 1992. Soil taxonomy. Washington, DC, USDA Agricultural Handbook No. 294.

4.5

Testing the APSIM Model with Experimental Data from the Long-term Manure Experiment at Machang'a (Embu), Kenya

A.N. Micheni,* F.M. Kihanda,* G.P. Warren[†] and M.E. Probert[§]

Abstract

A 27 season, long-term study (1989–2002) was conducted at Machang'a, near Embu in the semi-arid lands of eastern Kenya, to assess the effect of manure application on soil nutrient status and crop productivity. The experimental treatments comprised a control (no inputs); 5 and 10 t ha⁻¹ rates of high quality manure (26% C; 2.0% N; 0.48% P) from a single source and applied annually in October; residual manure treatments where manure application ceased from 1993; and a NP fertiliser treatment on previously unfertilised plots from 1993. The data from this experiment have been used to test the performance of the Agricultural Production Systems Simulator (APSIM) in predicting the crop dry matter yield, extractable soil phosphorus and soil organic carbon on a P-deficient soil. The experiment was simulated using the APSIM P-aware maize module, even though maize was not the test crop before the November 1999 season. Agreement between model predictions and measured data was generally satisfactory for all three of the variables tested.

The APSIM modelling framework described elsewhere in these proceedings now has a capability to simulate the dynamics of phosphorus in addition to nitrogen, and the effects of both nutrients on crop growth (Probert 2004). In order to validate that the model predictions are credible, there is a need to compare the model outputs against measured data. Unfortunately, few studies have been carried out in the tropics that provide suitable data sets for such purposes.

In this paper, we describe an experiment that does provide suitable data for testing the model, and to allow comparison of the observed data with model predictions.

The Experiment

Field site

The experimental site was at Machang'a, Mbeere District (0°47'S, 37°40'E; 1060 m above sea level), approximately 200 km northeast of Nairobi. The soil is a chromic Cambisol containing 56% sand, 13% silt and 31% clay, with pH (in water) 6.55 (Warren et al. 1997). These soils are deficient in nitrogen and phosphorus (Siderius and Muchena 1977; Warren et al. 1997). The site was cleared from native bush at the end of 1988 and cropping began in March 1989. There are two cropping seasons, which we identify by the month of peak rainfall; these are the 'November season' from October–January (in Kenya commonly referred to as the 'short rains') and the 'April season' from March–June (the 'long rains').

* Kenya Agricultural Research Institute, PO Box 27, Embu, Kenya <kariembu@alpha.co.ke>.

[†] Department of Soil Science, The University of Reading, PO Box 233, Reading, UK <g.p.warren@reading.ac.uk>.

[§] CSIRO Sustainable Ecosystems, 306 Carmody Road, St Lucia, Queensland 4067, Australia <merv.probert@csiro.au>.

Experimental design and treatments

The original design (Gibberd 1995) was a complete factorial of three cropping systems by three manure treatments (0, 5 and 10 t ha⁻¹), with the manure applied annually in October. In February 1993, all plots were sampled and it was found that the different crop rotations had not caused any significant effects on soil organic C, total N, extractable P or exchangeable cations (Warren et al. 1997). Subsequently, the rotation treatments were discontinued and new treatments introduced to study residual effects of manure and the effect of fertiliser applied to every crop (Table 1). Manure and fertiliser were broadcast and incorporated during cultivation before sowing (cultivation depth 0.15 m).

The manure was acquired from a single source (Goats and Sheep Project at Marimanti, Tharaka District) where flock management remained the same throughout the experiment. Average composition of the manure (dry matter basis) was 25.6% C, 2.04% N, 0.48% P (C:N = 12.7).

Crops and management

Before 1993, the cropping systems comprised rotations of sole legume and cereal crops and legume/cereal intercrops. The crops alternated between (i) sorghum (*Sorghum bicolor*) and cowpea (*Vigna unguiculata*), and (ii) pearl millet (*Pennisetum typhoides*) and green gram (*Vigna radiata*). After the experimental design was changed in 1993, the cropping system became sorghum/cowpea intercrop for the November season and millet/green gram intercrop for the April season, which closely follows local farming practice. Starting with the November 1999 season, all plots were cropped to maize (*Zea mays*, var. Katumani composite B) in both seasons. Sowing of all

crops was done at the start of the rains. Other agronomic practices were carried out at appropriate times using hand tools for cultivation and weeding. All plant materials except the grains were returned to the respective plots at the end of every season. The above-ground biomass was cut at ground level, residues chopped into small portions and incorporated into the soil during land preparation for the succeeding cropping seasons. Crop biophysical, soil nutrient characterisation and meteorological data were collected.

Soil sampling and analysis

Regular sampling of the soil (0–20 cm) began in 1993. Sampling was done either in February or September, before cultivation and incorporation of residues and manure. Soil was subsampled, air-dried, ground < 2 mm sieve and analysed for: extractable P (Olsen method; 0.5 M NaHCO₃, adjusted to pH 8.5); organic C by heating for 2 hours at 130–135° C with H₂SO₄ / H₃PO₄ / K₂Cr₂O₇ mixture (Anderson and Ingram 1993).

Simulations

The maize module is currently the only crop module available in APSIM that is 'P-aware', meaning that it has the necessary routines to constrain crop growth under P-limiting conditions (Probert 2004). We have therefore simulated the whole experimental period assuming that sole maize was planted every season (sowing dates 14 October and 18 March; 4 plants m⁻²). Manure was applied and incorporated on 2 October each year and fertiliser applied at sowing. Cultivations before sowing incorporated all residues from the previous crop.

Table 1. Soil fertility treatments used in the long-term experiment at Machang'a.

Treatment	1989–1992	1993–2001
Control	None	None
A1	5 t ha ⁻¹ y ⁻¹ manure ^a	5 t ha ⁻¹ y ⁻¹ manure
A2	10 t ha ⁻¹ y ⁻¹ manure	10 t ha ⁻¹ y ⁻¹ manure
B1	5 t ha ⁻¹ y ⁻¹ manure	None
B2	10 t ha ⁻¹ y ⁻¹ manure	None
F	None	NPK fertiliser (51, 12, 30 kg ha ⁻¹) every season ^b

^a Manure applied annually in October.

^b From November 1993; these rates provide same annual inputs of N and P as the 5 t ha⁻¹ manure treatment.

The simulations for each treatment were carried out as a single run, with all treatments initialised with identical inputs on 1 October 1989. Soil carbon in the surface 0–20 cm layer was based on the measured data in 1993, with an assumption that it declined in deeper layers (soil C deeper than 0.4 m was assumed not to mineralise). Soil labile P was initialised using the measured Olsen P data from the control treatment in 1993 and a factor of 2.5 to convert Olsen P (mg kg^{-1}) to labile P (see below for discussion of the relationship between labile P as conceptualised in the model and soil P test values).

The soil profile had been sampled to determine bulk density and gravimetric soil water when dry (to estimate crop lower limit, LL) and also when wet (to estimate drained upper limit, DUL). However, using these values in the simulation tended to over-predict crop yields. The DUL values were obtained following two weeks of wet weather with 40 mm rainfall on the day before sampling. It is surmised this may have over-estimated the soil's plant available water capacity (PAWC). For the simulations shown below, smaller values of DUL have been assumed,

with the rooting depth set to 0.8 m, resulting in PAWC of 92 mm. The soil parameters used for the simulation are set out in Table 2.

Results and Discussion

The mean annual rainfall during the experiment was 796 mm, while seasonal rainfall ranged from 100 to 1030 mm (Figure 1).

Crop yields

In presenting the crop data, emphasis is placed on the total above-ground DM yields since this procedure offers the best chance of minimising any effects of the actual crops grown, and whether grown as sole crops or intercrops. The measured and simulated yields are shown in Figure 2.

In most seasons, observed crop growth responded strongly to inputs of manure, though there were several seasons when yields were very poor for all treatments (April 1992, 1999, 2000; November 1998). There was little difference in yields between the 5 t ha⁻¹ and 10 t ha⁻¹ rates of manure.

Table 2. Soil properties used for initialisation of the simulation of the Machang's experiment.

Layer no.	1	2	3	4	5	6
SoilWat parameters^a						
Layer thickness (mm)	200	200	200	200	200	200
Bulk density (g cm^{-3})	1.28	1.27	1.31	1.31	1.31	1.31
SAT	0.42	0.42	0.43	0.43	0.43	0.43
DUL	0.25	0.27	0.27	0.27	0.26	0.26
LL15	0.13	0.14	0.15	0.16	0.16	0.16
Maize parameter						
LLmaize	0.13	0.14	0.15	0.18		
SoilN parameters						
organic C (%)	0.59	0.50	0.40	0.38	0.36	0.36
finert ^b	0.50	0.90	0.99	0.99	0.99	0.99
fbiom	0.02	0.015	0.01	0.01	0.01	0.01
nitrate-N (mg kg^{-1})	1.25	0.75	0.5	0.5	0.5	0.5
ammonium-N (mg kg^{-1})	0.8	0.35	0.2	0.2	0.2	0.2
SoilP parameters						
labile P (mg kg^{-1})	2.5	2.5	1.0	0.8	0.5	0.5
P sorption (mg kg^{-1}) ^c	94	200	200	200	200	200

^a The soil water balance is described in terms of the volumetric water content at saturation (SAT), drained upper limit (DUL), and lower limit of extraction by the crop (LL); BD is soil bulk density; SWCON is the proportion of water in excess of DUL that drains in 1 day.

^b finert is the proportion of soil carbon assumed not to decompose; fbiom is the proportion of decomposable soil carbon in the more labile soil organic matter pool.

^c P sorbed at 0.2 mg L⁻¹ in solution.

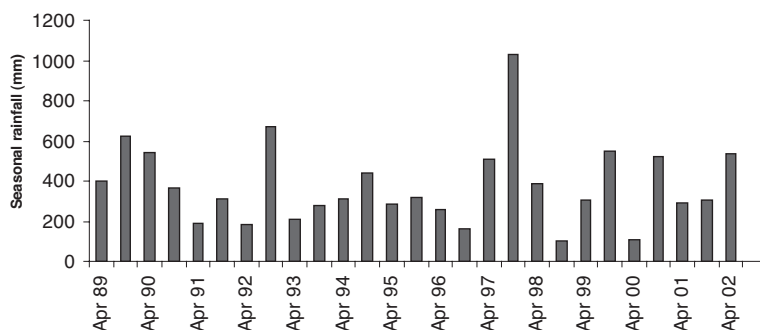


Figure 1. Total rainfall for the 'April' (March–June) and 'November' (October–January) seasons at the site during the experiment.

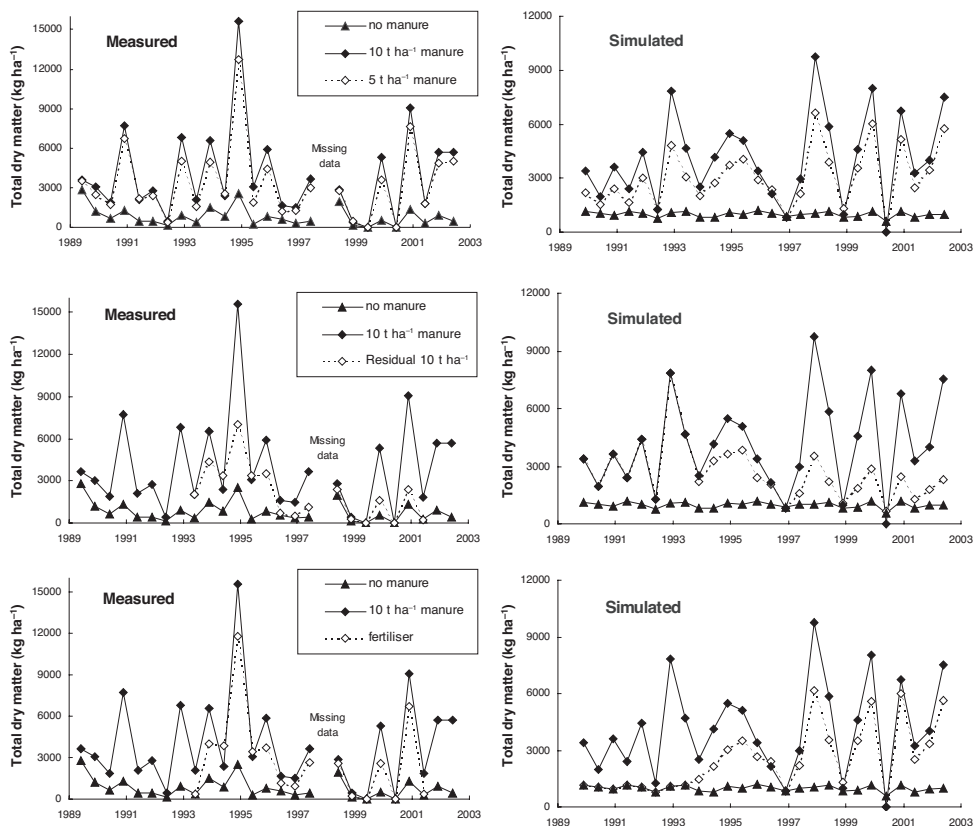


Figure 2. A comparison of the measured and predicted dry matter yields during the experiment. The measured data are in the left-hand panes, the corresponding simulated results in the right-hand panes. The top panes show the treatments that received 0, 5 or 10 t ha⁻¹ of manure; beneath are shown the effects of the 10 t ha⁻¹ residual treatment (application ceased from 1993) and the NP fertiliser treatment (begun 1993) with the 0 and 10 t ha⁻¹ of manure treatments repeated for scaling purposes.

After manure application ceased from 1993, the residual effect from manure declined and yields were only marginally better than the control in the later years of the experiment. Fertiliser application commencing from the November 1993 season increased yields to levels similar to those of the manure treatments.

This overall pattern in the observed yield data was captured reasonably well by the model. In particular, there was conformity in terms of: (i) the yields for the no-manure treatment were typically 1–2 t ha⁻¹ though, in contrast to the observed data, the simulated yields exhibited much less season-to-season variation and were never close to zero; (ii) yields with manure were 3–8 t ha⁻¹ with only small differences between the 5 and 10 t ha⁻¹ rates of manure; (iii) the declining effect from the residual manure treatment; (iv) the response to the fertiliser treatment; (v) crop failures in April 1992, 2000 and November 1996, 1998 seasons when yield for treatments with nutrient input was similar to the no-manure treatment. The largest discrepancy is for the November 1994 season when observed yields of sorghum for all treatments were unaccountably high. The model output permits examination of the stresses (water, N or P) that were limiting to growth.

For the control treatment, the dominant nutrient stress in all seasons was predicted to be due to P (data not shown).

The agreement between measured and predicted DM yields displayed in Figure 2 is despite the fact that the maize model is being used for the simulation when other crops were grown. From the November 1999 season this was no longer the case, with maize being grown. Figure 3 summarises the results for these crops. The correlation between observed and predicted yield is high and without any obvious bias.

Soil P

The frequent sampling and analysis for extractable P provides an opportunity to test another component of the model, namely the predicted changes in labile P through time and in response to inputs of P as fertiliser or manure. Conceptually, labile P as defined in the model does not equate directly to any soil P test (Probert 2004). However, it might be expected that, on a given soil, labile P would be proportional to some suitable soil test, so that the soil test values become the means of initialising the model and of testing the sensibleness of the output.

The simulated labile P (expressed as kg ha⁻¹) is compared with the measured Olsen P (mg kg⁻¹) in

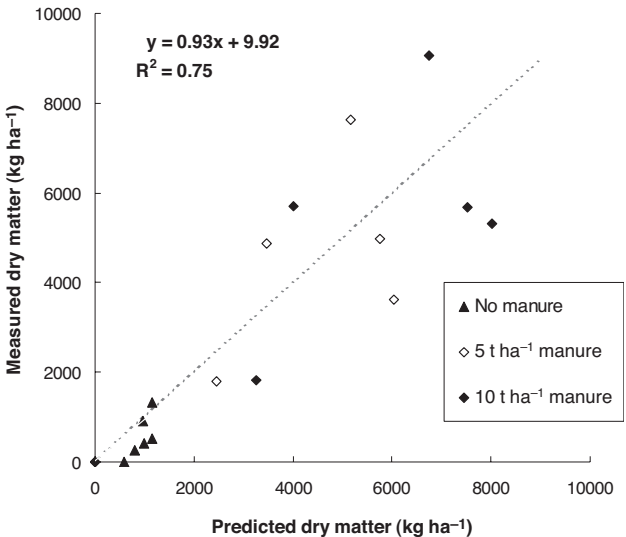


Figure 3. Comparison of measured and predicted dry matter yields of maize for seasons from November 1999. The dashed line is the 1:1 relationship. The fitted linear regression equation and correlation coefficient are given in the figure.

Figure 4. In these graphs, note that the proportionality between the two variates is the same for all of the treatments. For the control treatment, there is little change in P status during the experiment. The trends in the Olsen P data are well matched by the model for the 10 t ha⁻¹ manure treatment and the fertiliser treatment (though with much greater variability in the Olsen P data for the manure input). For the 5 t ha⁻¹ manure treatment the model over-predicts the Olsen P data, while for the residual treatment the measured Olsen P data decline more rapidly than the simulated labile P.

As presented in Figure 4, the factor between labile P and Olsen P, when adjusted for units, is approximately 2.5, which is the justification for how the labile P pool was initialised for the simulations.

Soil carbon

The simulated and measured soil organic C data are displayed in Figure 5. The agreement looks particularly good for the two treatments that differ most in soil C, and the model simulated well the difference that evolved between the control and 10 t ha⁻¹ manure treatment. For the other treatments the agreement is less impressive, though the direction of the trends is well captured by the model. The measured difference in soil C between the 5 and 10 t ha⁻¹ manure treatments was less than predicted. Also, the measured decline in soil C after manure application ceased was less rapid than predicted by the model, though there was close agreement at the end of the experimental period in 2002. For the fertiliser treatment, the model agreed with the measured data in that soil C increased compared with the control, but the increase was under-predicted. The change in soil C in the fertiliser treatment must occur as a result of greater crop growth and thus higher returns of crop residues and roots, since there are no direct inputs of C associated with this treatment.

Conclusions

The Machang'a experiment is a long-term experiment, on a P and N-responsive site. The experiment has studied the response of crop growth to inputs of nutrients as manure and fertiliser. Furthermore, it has documented the changes in the soil organic C and Olsen P as well as crop yields. The results of the experiment therefore provide a valuable data set against which several aspects of the APSIM model can be tested.

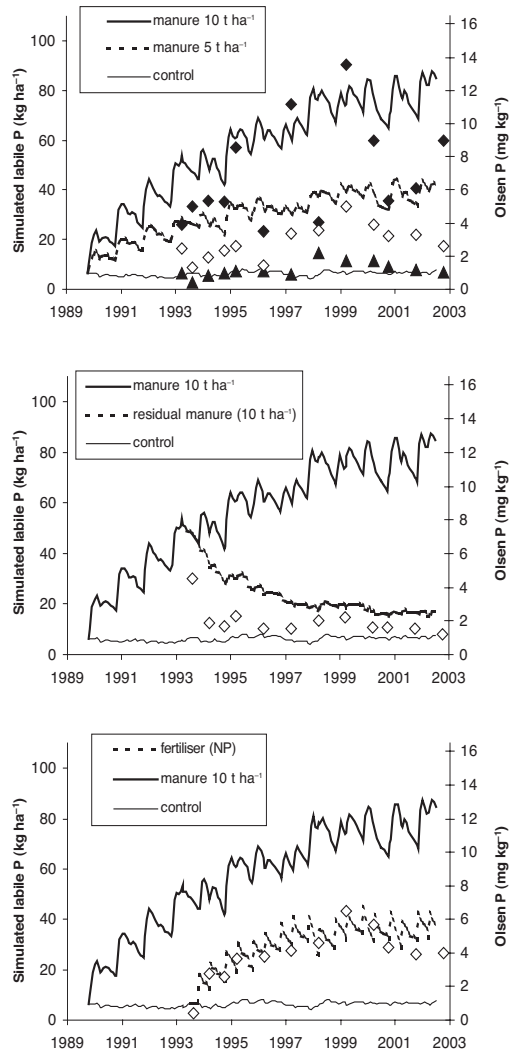


Figure 4. Comparison of simulated labile P (lines) in the surface 0–20 cm layer with the measured Olsen P data (symbols). Note that the two variates are plotted on different scales, but the proportionality between them is identical in the three panes. The top pane shows the 0 (▲), 5 (◇) and 10 (◆) t ha⁻¹ of manure treatments; the lower panes show the residual 10 t ha⁻¹ of manure treatment and the NP fertiliser treatments with the simulations for 0 and 10 t ha⁻¹ of manure treatments repeated for scaling purposes.

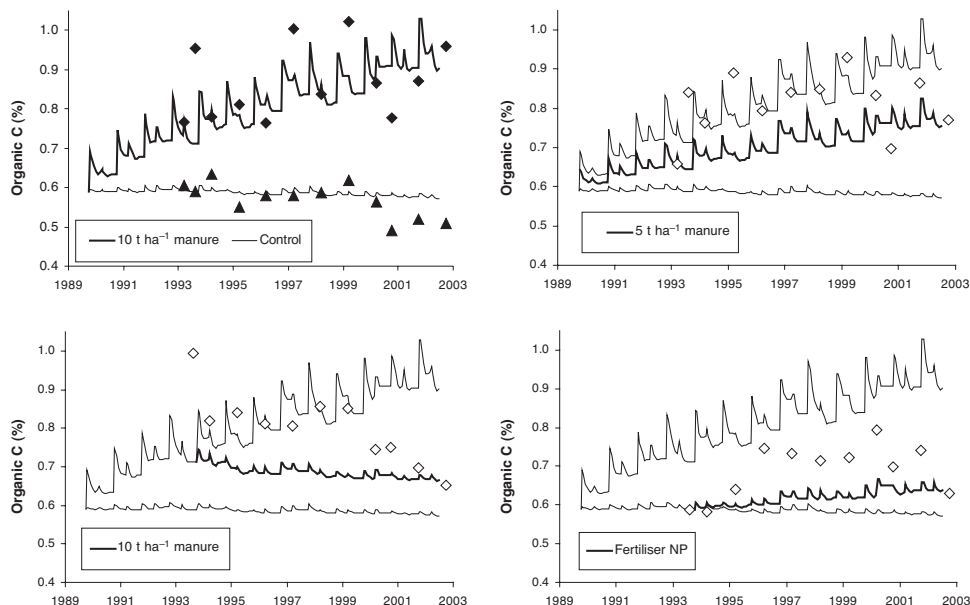


Figure 5. Comparison of simulated soil organic C (lines) in the surface 0–20 cm layer with the measured data (symbols). The top-left-hand pane shows the 0 and 10 t ha⁻¹ of manure treatments; in the other panes the simulated results for these treatments are repeated (for scaling purposes) together with the simulations and measured data for the 5 t ha⁻¹ of manure treatment, the residual 10 t ha⁻¹ of manure treatment, and the NP fertiliser treatment.

The manure source used in the experiment was from a single source throughout the experiment, and was of high quality and therefore may be expected to be a good source of N and P.

The model performance was tested in terms of:

1. *Dry matter yields.* To model the experiment, it was necessary to use the APSIM maize module as a surrogate for other crops that were grown in the early years of the experiment. In recognition of this, we have focused only on the dry matter production. It would be inappropriate to dwell on discrepancies between the observed and predicted yields; rather the focus should be on the ability of the model to capture the trends. The model captured reasonably well the patterns and trends due to treatments and seasons. For the most recent seasons, when maize was the test crop, there was close agreement between observed and predicted yields.

An issue that arises in the interpretation of the output of the model is whether P or water stress is the factor determining growth. For the seasons where there was no difference in yield between the different treatments, it seems probable that water was the lim-

iting factor. This is supported by the low rainfall in these seasons, as shown in Figure 1. However, in the model, P uptake is very dependent on soil water content, so that in these dry seasons the model predicts that P uptake is impaired and P stress becomes important for crop growth. Further testing of the model to explore this matter would require experimental data for a range of P treatments.

2. *Soil P.* The pattern of labile P simulated in the model was very similar to that of Olsen P. On this soil type, the proportionality between Olsen P and labile P (as simulated) was found to be approximately 2.5.

3. *Organic carbon.* The model predicted well the difference between the treatments with and without manure. Other aspects of the simulated soil C, such as the difference between the 5 and 10 t ha⁻¹ manure treatment, the decline of soil C in the residual manure treatment, and the magnitude of the increase in soil C when fertiliser was applied, were not so well predicted.

The conformity between simulated and measured data for the crop biomass and soil properties is

encouraging. A fuller test of the model's capability to simulate grain yields under P-limiting conditions requires P-aware versions of APSIM modules for the different crops.

Acknowledgments

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References

- Anderson, J.M. and Ingram, J.S.I. 1993. Tropical Soil biology and fertility: a handbook of methods. Wallingford, UK, CAB International.
- Gibberd, V. 1995. Yield responses of food crops to animal manure in semi-arid Kenya. *Tropical Science*, 35, 418–426.
- Probert, M.E. 2004. A capability in APSIM to model P responses in crops. These proceedings.
- Siderius, W. and Muchena, F.N. 1977. Soils and environment conditions of agricultural research stations in Kenya. Nairobi, Kenya, Ministry of Agriculture Miscellaneous Soil Paper No. M5.
- Warren, G.P., Muthamia, J. and Irungu, J.W. 1997. Soil fertility improvements under manuring in semi-arid Lower Embu and Tharaka-Nithi. In: Fungoh, P.O. and Mbadi, G.C.O., ed., 1997. Focus on agricultural research for sustainable development in a changing economic environment. Proceedings of the 5th KARI Scientific Conference, Nairobi, 14–16 October 1996. Nairobi, Kenya Agricultural Research Institute, 151–163.

4.6

Evaluation of APSIM to Simulate Plant Growth Response to Applications of Organic and Inorganic N and P on an Alfisol and Vertisol in India

J.P. Dimes* and S. Revanuru†

Abstract

Field experiments in India examined the response of sorghum and pigeonpea to inputs of low and high quality manures on N and P-responsive alfisol and vertisol soils. A special feature of the work was that inorganic fertiliser treatments were included to help quantify the cereal and legume responses to the N and P content of the manure. This paper provides a brief overview of the Indian experiments and results, and reports on the performance of APSIM to simulate aspects of the observed legume and cereal crop responses to N and P inputs, and the residual legume benefits to a following cereal. For this preliminary evaluation, the model performed poorly in simulating the observed P response of the cereal (sorghum) at low N levels. However, further modifications to input parameters for the P model, especially in relation to P supply and uptake for deeper soil layers, may improve the fit between observed and predicted results. In contrast, APSIM performed well in predicting the growth of pigeonpea well supplied with P, and the residual N benefits to a following cereal crop, including the response to additional inputs of N fertiliser.

Manures can contain appreciable amounts of P as well as N. In some instances, P is an additional, and sometimes greater, constraint to crop growth than N in low-input farming systems. With the generally low N content of manures found in smallholder farming systems (Motavalli and Anders 1991; Probert et al. 1995; Mugwira and Murwira 1997), questions arise as to whether a farmer would get a higher return from application of manure to a legume crop instead of a cereal, and to what degree is the residual N benefit of the legume to the following cereal crop enhanced by the legume responding to the applied manure?

Experimentation in India has examined these two questions for the case of low and high-quality manures applied to sorghum and pigeonpea crops grown on alfisol and vertisol soils (Revanuru 2002). A special feature of this work is that inorganic fertiliser treatments were included to help quantify the cereal and legume responses to the N and P content of the manure. Another is that monitoring of the experiments was quite extensive and many of the input parameters for simulation were known, especially for the soil and manure characterisation.

The data set was thought ideal for evaluating the performance of APSIM and its new modules, SoilP and Manure, to simulate the complex of climate, soil and plant interactions and effects on crop growth and yield. A complication, however, is that currently only the APSIM Maize module is able to respond to low soil P conditions to simulate P stress on plant growth (Probert 2004). Nevertheless, it was felt that

* Corresponding author. International Crops Research Institute for the Semi-Arid Tropics, PO Box 776, Bulawayo, Zimbabwe <j.dimes@cgiar.org>.

† International Crops Research Institute for Semi-Arid Tropics, Patancheru, India <s.revanuru@cgiar.org>.

the simulated total biomass response of APSIM Maize could be used as a surrogate for the observed sorghum responses. Within APSIM, the maize and sorghum models are based on a common crop template and share the same routines for interacting with the soil water and nutrient (N and P) modules to supply growth demand.

This paper provides a brief overview of the Indian experiments and results, and reports on the performance of APSIM to simulate aspects of the observed legume and cereal crop responses to N and P inputs, and the residual legume benefits to a following cereal crop.

Materials and Methods

Field experiments

Experiments were conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, in southern India (17.5°N, 78.3°E, 545 m above sea level) during the kharif (rainy) and rabi (dry) seasons of 1998. The experiments were conducted on two soils: an alfisol (Udic Rhodustalf) and a vertisol (Typic Pellustert).

Manure

Manure used in the experiments was collected from the bullock shed on the ICRISAT farm and from a local supplier in a nearby village. Manure was applied (11 June) to treatment plots on a fresh weight basis (10 t ha⁻¹). Dry weights and chemical characteristics of the manures applied are shown in Table 1. For the purpose of this paper, the two manures are referred to as high quality (HQM – narrow C:N, high P, from bullock shed) and low quality (LQM – wide C:N, low P, from village supplier).

Experimental design and treatments

Experiments investigated sorghum (*Sorghum bicolor*) and pigeonpea (*Cajanus cajan*) response to inputs of manure and fertiliser N and P on the two soils. For each crop, a split-plot design was implemented with soil type as main plots and nutrient treatments as sub-plots. For sorghum, there were six nutrient treatments: control, LQM, HQM, single superphosphate fertiliser at 20 kg P ha⁻¹ (P20), ammonium nitrate fertiliser at 80 kg N ha⁻¹ (N80), and N and P fertiliser at 80 kg N and 20 kg P ha⁻¹ (N×P) with six replicates. For pigeonpea there were four treatments: control, LQM, HQM and P20 with three replicates.

Management

Fallow pastures that preceded the experiments were incorporated in early May 1998. Extra-short duration pigeonpea, cultivar ICPL 88039, was planted (alfisol – 20 June, vertisol – 23 June) on 60 cm ridge spacing. Sorghum hybrid, CSH 9, was planted (alfisol – 20 June, vertisol – 23 June, both re-sown on 29 June) on similar ridges. Pigeonpea and sorghum plots were treated with pre-emergence herbicides and hand weeded twice during the season. During excessively wet conditions, pigeonpea plots were drenched to combat blight. Application of P fertiliser was banded at sowing, whereas application of N fertiliser was split; 40 kg N ha⁻¹ banded at sowing and 20 kg N ha⁻¹ side-banded at 30 and 60 days after sowing. Three irrigations were applied to help crop emergence and establishment.

Following harvest of grain and removal of stalks, kharif pigeonpea plots were planted with a medium duration sorghum variety, Maldandi-35-1 (9 November, both soils). The treatment plots were further subdivided into three sub-plots to accommodate three N levels (0, 40 and 80 kg N ha⁻¹) applied

Table 1. Nutrient content and application rates of manures applied to pigeonpea and sorghum at the start of the 1998 kharif season, at ICRISAT, Patancheru, India.

Manure type	%C	%N	%P	C:N	Dry weight applied (kg ha ⁻¹)	N applied kg ha ⁻¹	P applied kg ha ⁻¹	C applied kg ha ⁻¹
LQM ^a	25.3	0.7	0.3	35.0	2350	16.9	11.6	848.4
HQM	16.3	0.8	0.6	22.0	2870	21.7	17.3	469.1

^a LQM, low quality manure; HQM, high quality manure.

to the following sorghum crop. Application of N fertiliser was split; 40 kg N ha⁻¹ side-banded at 14 and 37 days after sowing. The rabi sorghum was irrigated throughout the crop cycle.

Measurements and analysis

Soil and manure samples were analysed for per cent organic carbon (OC) (Walkley and Black 1934), total N (Keeney and Nelson 1982), total P (Tandon et al. 1962), mineral N (Keeney and Nelson 1982) and extractable P (Olsen and Sommers 1982). Soils layers were sampled to 90 cm for the alfisol and 150 cm for the vertisol. Gravimetric water content of soil layers was monitored regularly throughout the kharif and rabi crop cycle for each experiment. Total plant biomass was harvested at maturity. Meteorological data were collected at the ICRISAT weather station. Treatment differences were analysed using ANOVA for a split-plot design.

Simulations

Soil descriptions

Soil parameters and initial conditions used to simulate experiments on the two soils are set out in Tables 2 and 3. Analysis of the gravimetric moisture determinations taken throughout the kharif and rabi crops provided estimates for the crop lower limit and the drained upper limit water contents in layers for each soil. Concentrations of OC, and NO₃-N and the amounts of soil water were measured. Bulk density and NH₄-N values were estimated. P sorption characteristics for surface layers were known (Sahrawat and Warren 1989), data for the other layers were estimates. Finert values (stable SOM not contributing to mineral N supply) have been set using %OC in the bottom layer as a guide and based on experience in setting this parameter (Probert et al. 1998b).

High atmospheric N contributions to the crop-soil budget have been reported for the Patancheru environment (up to 12 kg N ha⁻¹ year⁻¹ in rainfall (Murthy et al. 2000)), resulting in unexpectedly high biomass yields on the N impoverished soils. To increase the soil N supply and include the effects of N additions from the atmosphere, labile N (f_biom) in the soil surface layer was adjusted upwards until there was agreement between simulated and measured biomass yield for the control treatments. Simi-

larly, labile P values in Tables 2 and 3 were calibrated for the two soils, to give reasonable prediction of observed yields in the presence of adequate N.

Kharif sorghum (maize)

Simulation of the kharif experiment began on 11 June 1998, which coincided with application of the manure treatments. The applied manure was fully incorporated into the surface soil layer. A maize planting was simulated on 29 June (the re-sowing date for both soils, see Management above), with plant population set to 10 plants m⁻² (the observed plant stand at harvest, both soils). Crop parameters for maize cultivar Hybrid 614 were found to best approximate the duration of the kharif sorghum crop. Fertiliser applications were made on 21 June (P20 banded and 40N), 21 July (20N) and 3 Sept (20N). Irrigation was applied on 29 June (63 mm), 1 July (63 mm) and 13 July (50 mm). To assess model predictions, simulated maize biomass was compared with the observed total biomass of kharif sorghum.

Pigeonpea-sorghum (maize) sequence

Pigeonpea-maize sequences for the kharif-rabi seasons were simulated for each soil using the data in Tables 2 and 3, except in this case it was assumed that there was no P constraint. Simulations began on 11 June 11 and an extra short duration pigeonpea was planted on 20 June, with a population of 33 plants m⁻². After grain harvest, removal of pigeonpea stover was simulated on 4 November. Maize cultivar Hybrid 511 was planted on 9 November with a population of 13.8 plants m⁻² for the alfisol, and 14.7 for the vertisol. Three N fertiliser treatments for the rabi maize were simulated; 0, 40 and 80 kg N ha⁻¹, with fertiliser applied as per the experimental details described above for rabi sorghum. A total of 260 mm of irrigation was applied for the simulated rabi crop. To assess model predictions for pigeonpea, simulated biomass is compared to observed biomass from the P20 treatment (i.e. adequate P conditions). To assess simulation of maize response in the rabi following pigeonpea, simulated biomass is compared to observed biomass for rabi sorghum following pigeonpea receiving 20 kg P ha⁻¹ in the kharif season.

Table 2. Soil properties and initial conditions for simulation of the alfisol experiments at ICRISAT, Patancheru, India. C:N ratio for all layers was 8.6.

Layer no.	1	2	3	4	5
SoilWat parameters^a					
Layer thickness (mm)	150	150	300	300	300
Bulk density (g cm ⁻³)	1.50	1.45	1.40	1.40	1.40
SAT	0.36	0.40	0.42	0.42	0.42
DUL	0.21	0.21	0.23	0.23	0.24
LL15	0.09	0.09	0.11	0.14	0.18
Soil water	0.09	0.09	0.11	0.14	0.18
SoilN parameters					
Organic C (%)	0.57	0.42	0.31	0.24	0.18
Finert ^b	0.35	0.47	0.52	0.62	0.74
Fbiom	0.04	0.020	0.015	0.01	0.01
Nitrate-N (mg kg ⁻¹)	1.60	1.40	1.80	1.30	1.00
Ammonium-N (mg kg ⁻¹)	0.50	0.10	0.10	0.10	0.10
SoilP parameters					
Labile P (mg kg ⁻¹)	10	10	10	10	10
P sorption (mg kg ⁻¹) ^c	30	60	100	150	200

^a The soil water balance is described in terms of the volumetric water content at saturation (SAT), drained upper limit (DUL), and lower limit of extraction by the crop (LL).

^b Finert is the proportion of soil carbon assumed not to decompose; Fbiom is the proportion of decomposable soil carbon in the more labile soil organic matter pool.

^c P sorbed at 0.2 mg L⁻¹ in solution.

Table 3. Soil properties and initial conditions for simulation of the vertisol experiments at ICRISAT, Patancheru, India. C:N ratio for all layers was set at 12.

Layer no.	1	2	3	4	5	6
SoilWat parameters^a						
Layer thickness (mm)	150	150	300	300	300	300
Bulk density (g cm ⁻³)	1.00	1.10	1.20	1.20	1.20	1.20
SAT	0.55	0.54	0.50	0.50	0.50	0.50
DUL	0.37	0.37	0.42	0.42	0.46	0.46
LL15	0.17	0.23	0.29	0.32	0.37	0.41
Soil water	0.12	0.27	0.34	0.38	0.41	0.41
SoilN parameters						
Organic C (%)	0.57	0.47	0.43	0.37	0.19	0.17
Finert ^b	0.31	0.37	0.50	0.62	0.74	0.83
Fbiom	0.04	0.02	0.015	0.01	0.01	0.04
Nitrate-N (mg kg ⁻¹)	3.00	2.00	1.50	1.30	1.00	1.00
Ammonium-N (mg kg ⁻¹)	0.50	0.10	0.10	0.10	0.10	0.10
SoilP parameters						
Labile P (mg kg ⁻¹)	6.0	5.0	4.0	3.0	2.0	1.0
P sorption (mg kg ⁻¹) ^c	50	100	100	100	100	100

^a The soil water balance is described in terms of the volumetric water content at saturation (SAT), drained upper limit (DUL), and lower limit of extraction by the crop (LL).

^b Finert is the proportion of soil carbon assumed not to decompose; Fbiom is the proportion of decomposable soil carbon in the more labile soil organic matter pool.

^c sorbed at 0.2 mg L⁻¹ in solution.

Results

In-crop rainfall (980 mm) for the kharif (Figure 1) exceeded the long-term annual rainfall (899 mm) and waterlogging was observed in both soils for pigeonpea plots. There was little rainfall during the rabi crops, which were grown under irrigation.

Sorghum experiments

The simulated and observed biomass responses of kharif sorghum crops on alfisol and vertisol soils are shown in Figure 2. Observed biomass responses on the alfisol were significantly ($p < 0.05$) greater than those on the vertisol. For the alfisol, biomass yields for the manure and fertiliser treatments are signifi-

cantly ($p < 0.05$) higher than the control. In contrast, only the fertiliser treatments provided statistically significant responses on the vertisol. Results for both soils show a stronger response to N fertiliser (N80) than to P fertiliser ($p < 0.05$) and an increased N response ($p < 0.05$) in the presence of P (N \times P treatment).

The simulated trends in Figure 2 are less responsive, with almost no change in predicted yields for the application of manures or inorganic P on either soil. In fact, simulated biomass yields with addition of LQM are lower than that simulated for the control on each soil, indicating that the model simulated net immobilisation and a reduced N supply for crop growth with the addition of the LQM. Simulated

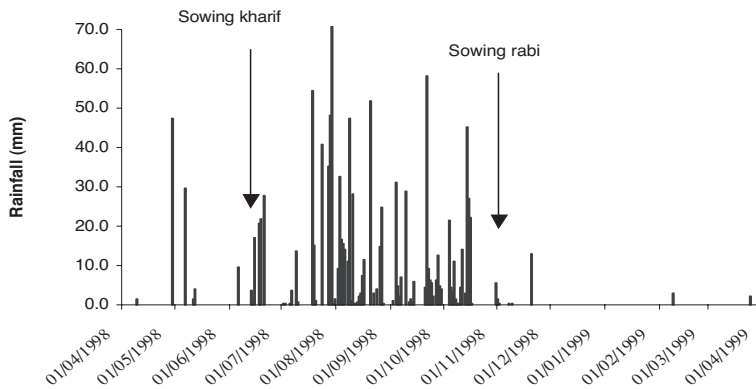


Figure 1. Rainfall during the kharif and rabi seasons in 1998 at Patancheru, India. Sowing of kharif and rabi crops shown by arrows.

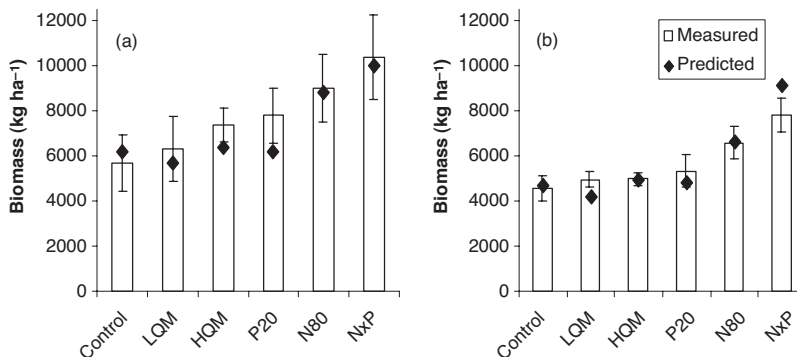


Figure 2. Measured (sorghum, bar) and simulated (maize, symbols) total crop biomass for kharif crops on (a) alfisol and (b) vertisol in response to low (LQM) and high (HQM) quality manure, fertiliser P (P20), fertiliser N (N80) and fertiliser N and P (N \times P). Error bars are standard deviations of treatment means.

responses to application of fertiliser N on both soils and N+P for the alfisol are close to the observed responses, but there is a large over-prediction for the N+P treatment on the vertisol. What the model was able to simulate reasonably well were the differences in biomass yields between soils.

Pigeonpea–Sorghum

Observed responses of pigeonpea to manures and fertiliser P in the kharif are shown in Figure 3. In the case of pigeonpea, biomass yields are significantly higher ($p < 0.05$) for the vertisol than for the alfisol. There are significant ($p < 0.05$) increases in biomass response of pigeonpea to the three nutrient treatments (LQM, HQM and P20) compared with the control, and between the nutrient treatments, indicating that pigeonpea responded to the different

levels of P input (12, 17 and 20 kg P ha⁻¹) and its availability.

As APSIM–Pigeonpea is not ‘P-aware’, simulated biomass can be compared only for the situation where P nutrition can be assumed adequate, in this case the P20 treatment. In Figure 3, simulated biomass of pigeonpea for the alfisol compares well with observed yield, but for the vertisol, the simulated yield is actually less than that for the alfisol, and substantially less than the observed. The Pigeonpea model used here (APSIM Version 1.61) has routines to simulate waterlogging stress on plant growth, and over-prediction of this stress seems to be responsible for simulation of the lower yield on the vertisol. For the vertisol, 87% of crop days are simulated to have profile water contents indicative of saturation, whereas for the alfisol it is less than 50% of days.

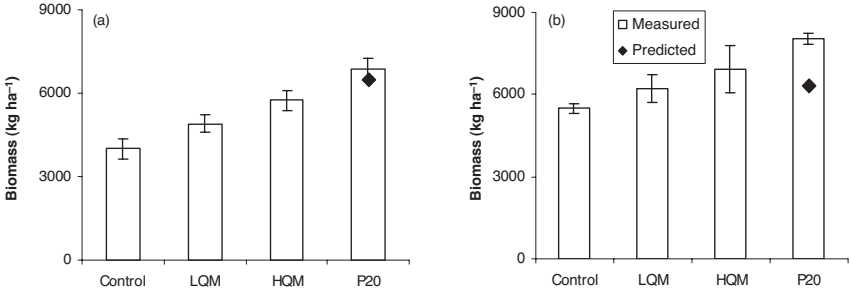


Figure 3. Measured (bar) and simulated (◆) total crop biomass for pigeonpea crops on (a) alfisol and (b) vertisol in response to low (LQM) and high (HQM) quality manure and fertiliser P (P20). Error bars are standard deviations of treatment means.

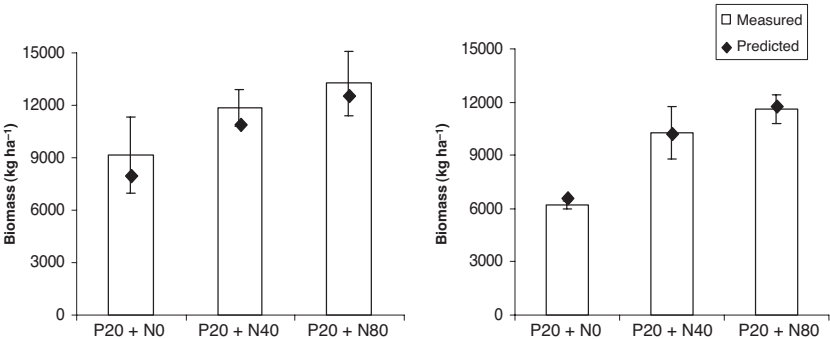


Figure 4. Measured (sorghum, bar) and simulated (maize, ◆) total crop biomass for rabi crops on (a) alfisol and (b) vertisol following kharif pigeonpea (fertilised with 20 kg P ha⁻¹). Rabi crops received zero (P20+N0), 40 (P20+N40) and 80 (P20+N80) kg N ha⁻¹. Error bars are standard deviations of treatment means.

The pigeonpea–maize sequence provides an assessment of how well the systems model is able to simulate the combined effects of organic and inorganic N supply. Figure 4 shows the observed and predicted biomass yield of the rabi cereal crops planted following pigeonpea (fertilised with P20) and receiving three rates of N fertiliser. From the observed responses to fertiliser N, it is clear that the preceding pigeonpea was unable to supply all of the rabi crop N requirements on either soil.

The model was able to predict very closely the observed biomass responses for the respective soils along with the response to N fertiliser inputs on each soil (Figure 4). It should be noted that, for both the simulated and observed rabi crops, all above-ground biomass from the preceding pigeonpea was removed, and the carryover of N from the kharif legume is via the pigeonpea root system and detached leaf material. Hence, results in Figure 4 suggest that the system model is able to simulate these residual organic N benefits, and interaction with inorganic N, with a high degree of accuracy.

Discussion

The measured yield responses for the legume and cereal crops in these experiments clearly indicate P and N responsive soils. However, the results of simulation of the observed P responses and interaction with N supply in the kharif cereal crop were disappointing, showing no sensitivity to inputs of organic or inorganic P at low N levels (i.e. LQM, HQM and P20 treatments). Application of APSIM to simulate the Indian data is one of the earliest attempts at using the new P capabilities on an independent data set. Results achieved here undoubtedly reflect a measure of inexperience with parameterising this new model.

Probert (2004) has suggested that the difficulty in parameterising the model is largely associated with specifying the P status in terms of P sorption and labile P in each soil layer. Further exploratory modifications to input parameters are no doubt warranted, especially in terms of the proportionality factor between measured Olsen P and labile P (Micheni et al. 2004) and how this may need to vary between soils, and perhaps with soil depth. Another parameter that may warrant attention is the P uptake factor that Probert (2004) suggests is crop and cultivar dependent. In this analysis, the *p_supply_factor* was set to 3.

However, the main concern with the model is the insensitivity of plant response to P inputs at the low N levels. Part of this problem is perhaps attributable to the calibration process used for labile P. For the kharif crop responses used in this study, moisture stress, at least due to deficits, can be discounted. Hence, the results suggest further testing of the model is required for conditions where both N and P are limiting plant growth. The ideal data set would have crop growth response to each element quantified in the presence of adequate levels of the other, in addition to limiting levels of both. This would help eliminate some of the calibration problems encountered in this current study.

The APSIM–Pigeonpea model (Robertson et al. 2001) is also relatively untested against observed growth responses in the field. While the P effects on pigeonpea growth in these experiments cannot be considered at this time, simulation of the P20 treatment for the two soils provided some useful insights. Clearly, the waterlogging stress routines in Pigeonpea and the soil drainage parameters for the vertisol warrants closer consideration. The close agreement between observed and predicted biomass at zero N for the rabi cereal crop (Figure 4) suggests that the model captures very well the key components contributing to enhanced soil N supply following a legume, in this case simulation of leaf senescence and detachment and residual root biomass of the pigeonpea.

In the past, APSIM has been shown to perform well in simulating mineral N supply following organic inputs (Probert et al. 1998b) and crop response to inorganic and organic N, including legume–cereal rotations (Probert et al. 1998a; Shamudzarira et al. 2000). Simulation of the pigeonpea–maize sequence in this study has extended evaluation to a tropical legume species and for two of the important soil types in semi-arid agricultural systems. The study has also highlighted the need to extend the P stress routines to other cereal and legume crops commonly grown by smallholder farmers in the tropics.

References

- Keeney, D.R. and Nelson, D.W. 1982. Nitrogen inorganic forms. In: Page, A.L., Miller, R.H. and Keeney, D.R. ed., *Methods of soil analysis – Part 2 Chemical and microbiological properties*. Madison, Wisconsin, USA, American Society of Agronomy, 651–658.

- Micheni, A.N., Kihanda, F.M., Warren, G.P., and Probert, M.E. 2004. Testing the APSIM model with experimental data from the long-term manure experiment at Machang'a (Embu). These proceedings.
- Motavalli, P.P. and Anders M.M. 1991. Management of farmyard manure in India's semi-arid tropics: farmer perceptions and practice. Patancheru, India, ICRISAT, Progress report, Resource management programme, 106 p.
- Mugwira, L.M. and Murwira, H.K. 1997. Use of cattle manure to improve soil fertility in Zimbabwe: past and current research and future research needs. Soil Fertility Network Research Results Working Paper No. 2, May 1997, 33 p. Soil Fertility Network for Maize-based Cropping Systems in Malawi and Zimbabwe.
- Murthy, K.V.S., Sahrawat, K.L. and Pardhasaradhim G. 2000. Plant nutrient contribution by rainfall in the highly industrialized and polluted Patancheru area in Andhra Pradesh. *Journal of Indian Society of Soil Science*, 48, 803–808.
- Olsen, S.R. and Sommers, L.E. 1982. Phosphorus. In: Page, A.L., Miller, R.H. and Keeney, D.R., ed., *Methods of soil analysis – Part 2 Chemical and microbiological properties*. Madison, Wisconsin, USA, American Society of Agronomy, 421–422.
- Probert, M.E. 2004. A capability in APSIM to model P responses in crops. These proceedings.
- Probert, M.E., Carberry, P.S., McCown, R.L. and Turpin, J.E. 1998a. Simulation of legume–cereal systems using APSIM. *Australian Journal of Agricultural Research*, 49, 317–328.
- Probert, M.E., Dimes, J.P., Keating, B.A., Dalal, R.C. and Strong, W.M. 1998b. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agricultural Systems*, 56, 1–28.
- Probert, M.E., Okalebo, J.R., and Jones, R.K. 1995. The use of manure on smallholders' farms in semi-arid eastern Kenya. *Experimental Agriculture*, 31, 371–381.
- Revanuru, S. 2002. Simulation of the effects of manure quality, soil type, and climate on N and P supply to sorghum and pigeonpea in semi-arid tropical India. Ph.D thesis, Acharya N G Agricultural University, Rajendranagar, Hyderabad, 300 p.
- Robertson, M.J., Carberry, P.S., Silim, S., Chauhan, Y.S., Ranganathan, R. and O'Leary, G.J. 2001. Predicting growth and development of pigeonpea: a simulation model. *Field Crops Research*, 71, 195–210.
- Sahrawat, K.L. and Warren, G.P. 1989. Sorption and labelled phosphate by a Vertisol and an Alfisol of the semi-arid zone of India. *Fertilizer Research*, 20, 17–25.
- Shamudzarira, Z., Waddington, S., Robertson, M.J., Keating, B.A., Mushayi, P., Chiduza, C. and Grace, P. 2000. Simulating N fertilizer response in low-input farming systems. 1. Fertilizer recovery and crop response. Mexico, D.F., CIMMYT Series 00/05.
- Tandon, H.L.S., Cescas, M.P. and Tyner, E.H. 1962. An acid free vanadate–molybdate reagent for the determination of total phosphorus in soils. *Soil Science Society America Proceedings*, 32, 48–51.
- Walkley, A.J. and Black, I.A. 1934. Estimation of soil organic carbon by the chromic acid titration method. *Soil Science*, 37, 29–38.

4.7

Soil Phosphorus Dynamics, Acquisition and Cycling in Crop–Pasture–Fallow Systems in Low Fertility Tropical Soils: a Review from Latin America

I.M. Rao,* E. Barrios,* E. Amézquita,* D.K. Friesen,[†] R. Thomas,[§]
A. Oberson[¶] and B.R. Singh**

Abstract

Knowledge of the phosphorus (P) dynamics in the soil–plant system, and especially of the short- and long-term fate of P fertiliser in relation to different management practices, is essential for the sustainable management of tropical agroecosystems. A series of field trials was conducted in the tropical savannas and Andean hillsides in Colombia to follow the dynamics of P under different management systems. In tropical savannas in the Llanos of Colombia, in cereal–legume rotations (maize–soybean or rice–cowpea) and ley pasture systems, measurements of soil P fractions indicated that applied P moves preferentially into labile inorganic P pools, and then only slowly via biomass production and microbes into organic P pools under both introduced pastures and crop rotations. Field studies conducted to quantify the residual effectiveness of P fertiliser inputs in crop rotations in terms of both crop growth response and labile P pool sizes, indicated that soluble P applications to oxisols of Colombia remain available for periods that are much longer than expected for ‘high P-fixing’ soils, such as the oxisols of Brazilian Cerrados. In Andean hillsides of Colombia, the impact of short-term planted fallows to restore soil fertility in N and P-deficient soils by enhancing nutrient recycling through the provision of organic matter, was investigated. Results indicated that the fractionation of soil organic matter and soil P could be more effective for detecting the impact of planted fallows on improving soil fertility than the conventional soil analysis methods. Litterbag field studies contributed to characterisation of the rate of decomposition and nutrient release from green manures and organic materials that could serve as biofertilisers. The data sets from these field and greenhouse studies are valuable for further testing and validation of APSIM.

Phosphorus (P) deficiency is a widespread nutrient constraint to crop production on tropical and sub-tropical soils and it affects an area estimated at over 2×10^9 hectares (Fairhurst et al. 1999). However, for most resource-poor farmers in developing countries, correcting soil P deficiency with large applications of

P fertiliser is not a viable option. Furthermore, the inexpensive rock phosphate reserves remaining in the world could be depleted in as little as 60–80 years (Runge-Metzger 1995). Therefore, sustainable P management in agriculture requires additional information on the mechanisms in plants that enhance P

* Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT), CIAT, A. A. 6713, Cali, Colombia <i.rao@cgiar.org>.

[†] IFDC–CIMMYT, P.O. Box 25171, Nairobi, Kenya <d.freisen@cgiar.org>.

[§] ICARDA, P. O. Box 5466, Aleppo, Syria <r.thomas@cgiar.org>.

[¶] Swiss Federal Institute of Technology (ETH), Zurich, Switzerland <astrid.oberson@ipw.agrl.ethz.ch>.

** Agricultural University of Norway, PO Box 5028, Aas, Norway <balram.singh@ijvf.nlh.no>.

acquisition in order to make plants more efficient at acquiring P, development of P efficient germplasm, and advanced crop management schemes that increase soil P availability (Rao et al. 1999a; Vance 2001).

Knowledge of the P dynamics in the soil–plant system, and especially of the short and long-term fate of P fertiliser in relation to different management practices, is essential for the sustainable management of tropical agro-ecosystems. Sequential chemical extraction procedures have been and still are widely used to divide extractable soil P into different inorganic and organic fractions (Hedley et al. 1982). The underlying assumption in these approaches is that readily available soil P is removed first with mild extractants, while less available or plant-unavailable P can be extracted only with stronger acids and alkali.

Several studies have related these different P fractions in tropical soils to plant growth (Crews 1996; Friesen et al. 1997; Guo and Yost 1998; Oberson et al. 1999, 2001; Phiri et al. 2001a, b; Lehmann et al. 2001; Bühler et al. 2002). The results obtained in these studies suggest that, in tropical soils, the amounts of P in the different pools measured by sequential P extraction procedures, and the fluxes of P between pools, are controlled both by physico-chemical factors such as sorption and desorption and by biological reactions such as immobilisation and mineralisation. However, the importance of these processes for different land-use systems, such as monocropping, pasture or intercropping, remains largely unknown.

CIAT researchers, in collaboration with their partners, conducted a series of field trials in the tropical savannas and Andean hillsides in Colombia. The main objectives of these studies were: (i) to quantify the soil and plant processes associated with changes in primary biomass productivity in typical systems and ‘best bet’ options to develop indicators of soil quality and degradation; (ii) to quantify and understand nutrient dynamics in systems to improve cycling and minimise losses; and (iii) to quantify factors that influence and determine the rates of processes to calibrate, modify, or develop simulation models for overcoming site specificity and testing alternative scenarios. We describe here the progress in quantifying soil P dynamics, acquisition and cycling under different management systems in tropical savannas and hillsides agro-ecosystems.

Tropical Savannas Agroecosystem — Llanos of Colombia

The neotropical savannas occupy 243 million hectares in South America and are one of the most rapidly expanding agricultural frontiers in the world (Thomas and Ayarza 1999), with oxisols predominating. Intensification of agricultural production in this ecosystem requires acid soil (aluminium) tolerant crop germplasm, soil fertility improvement and management of highly vulnerable physical properties (Amézquita 1998). Grain legumes, green manures, intercrops and leys are possible system components that could increase the stability of systems involving annual crops (Karlen et al. 1994). Soil P dynamics, acquisition and cycling were quantified in crop rotations and ley pasture systems (Friesen et al. 1997). Comparison of rooting patterns of crop and forage components indicated that introduced legume-based pastures are more deep-rooted than crops, and acquire considerable amounts of P despite a lower level of available P in the surface soil. Greenhouse studies indicated that forage legumes are more efficient in acquiring P per unit root length (Rao et al. 1997). Comparative studies of a forage grass (*Brachiaria dictyoneura* CIAT 6133) and a legume (*Arachis pintoi* CIAT 17434) demonstrated that the legume could acquire P from relatively less-available P forms from oxisols of Colombia (Rao et al. 1999b). Field studies on root distribution of maize showed that most of the roots are in top 20 cm of soil depth. These differences in rooting strategies have important implications for P acquisition efficiency in relation to available soil P in different crop and pasture systems (Table 1). Application of higher amounts of lime did not improve subsoil-rooting ability of maize but contributed to greater nutrient acquisition. This knowledge is useful to match the plant components to overcome edaphic constraints and to model plant responses to P supply in soil.

Observed differences in crop–forage residue decomposition and P release rates suggest that managing the interaction of these residues with soil could reduce P fixation. Measurements of soil P fractions indicated that applied P moves preferentially into labile inorganic P pools, and then only slowly via biomass production and microbes into organic P pools under both introduced pastures and crop rotations (Friesen et al. 1997). In cultivated soils, much higher P fertiliser doses significantly increase available inorganic P contents with lesser impact on

organic P pool sizes. Agricultural land-use systems replacing native savanna on oxisols affect the partitioning of P among inorganic and organic P fractions (Table 2). The amount and turnover of P that is held in the soil microbial biomass is increased when native savanna is replaced by improved pasture while it was lowered when soils are cultivated and cropped continuously (Oberson et al. 2001). Based on these studies alternative strategies for cropping low P oxisols, involving strategic application of lower amounts of P fertiliser to crops and planting of grass–legume pastures, would promote P cycling and efficient use of P inputs.

Legume-based pastures (16 years old) maintained higher organic and available P levels than the grass alone or native pastures (Oberson et al. 2001). Greater turnover of roots and above-ground litter in legume-based pastures could provide for steadier organic inputs and therefore higher P cycling and availability. Failure of P to enter organic P pools is thought to indicate a degrading system due to low level of P cycling. If that is true, work done so far in the Llanos of Colombia indicates that legume-based pastures could be considered as important land-use options to stimulate P cycling, reduce P fixation and minimise soil degradation in tropical savannas.

Field studies were conducted to quantify the residual effectiveness of P fertiliser inputs in cereal–grain legume rotations (maize–soybean or rice–cowpea) in terms of both crop growth response and labile P pool sizes in an oxisol in the Llanos of Colombia (CIAT 1996; D. K. Friesen, unpublished data). The results showed that soluble P applications to oxisols of Colombia remain available for periods that are much longer than expected for ‘high P-fixing’ soils, such as the oxisols of Brazilian Cer-

rados. For determining the available P in low-P supplying oxisol, we compared an acid ammonium oxalate extraction method with Bray-II extraction, resin and bicarbonate extraction, and extraction with iron-impregnated paper strips (Guo and Yost 1998; CIAT 2001). This comparative study of P extraction methods indicated that use of either oxalate-P or resin-P + bicarbonate-P pools of Hedley sequential fractionation scheme are better suited to determine soil P availability in oxisols that receive strategic applications of lower amounts of fertiliser P.

Crop simulation models are increasingly used to estimate crop yields as affected by nutrients and water inputs as well as management practices and climatic conditions. A group of models, CERES for cereal simulation growth and CROPGRO for legume simulation, has been used successfully around the world for various purposes. A computer model for the simulation of P in soil and plant relations has been developed and added to the two above crop simulation models to enhance their capabilities, especially in tropical areas where P deficiencies are common. We tested these models using data on maize, soybeans and upland rice grown under acidic tropical conditions in the Colombian savannas (CIAT 2000; S. Daroub, unpublished data). The sensitivity analysis done on the model showed that it is responsive to different rates of P fertiliser applications as well as to initial conditions of labile P. Several growth parameters responded to P additions. Some of the growth parameters from the model that do not seem to be affected by P fertilisation are: flowering and maturity dates, panicle number and leaf number. This early work lead to the inclusion of P routines in DSSAT (Daroub et al. 2003).

Table 1. Differences among crop and pasture systems in accessible phosphorus (P) recovery in relation to available soil P (0–20 cm soil depth).

System	Bray-II available P (mg kg ⁻¹)	Total root length (km m ⁻²)	Specific root length (m g ⁻¹)	Total P uptake (kg ha ⁻¹)	Accessible P recovery ^a (%)
Native savanna pasture	1.6	5.8	122	4	74
Introduced grass/legumes pasture ^b	3.5	7.2	75	14	94
Maize monoculture ^c	19.8	4.8	106	18	24

^a Total P uptake per unit available P in rhizosphere soil (assuming an effective rhizosphere diameter of 5 mm).

^b *Brachiaria humidicola* CIAT 679/*Stylosanthes capitata* CIAT 10280 + *Centrosema acutifolium* CIAT 5277 + *Arachis pintoi* CIAT 17434.

^c *Zea mays* cv. Sikuaní

Table 2. Distribution of phosphorus (P) in various fractions in fertilised land-use systems (continuous rice, grass-legume pasture) 5 years after establishment on native savanna as assessed from sequential extraction. Relative changes (% increase) describe the percentage of total P increase in fertilised systems over native savanna that was found in a given fraction (for formula see footnote †). Adapted from Oberson et al. (2001).

Treatment	Resin		NaHCO ₃		NaOH		HCl	Resid	Sum	
	P _i	P _o	P _i	P _o	P _i	P _o	P _i	P _t	P _{tt}	P _o ¶
<i>Savanna</i>										
Mean (mg kg ⁻¹)	2.6a	11.3a	27.4a	45.3	35.6a	23.9	60.6	212a	69a	81.9
<i>Grass-legume</i>										
Mean (mg kg ⁻¹)	4.8b	14.6b	45.5b	51.0	46.5b	30.3	62.2	263b	103b	97.8
% increase	4.3	5.4	35.5	11.3	21.4	12.6	3.2	101	66.6	31.1
<i>Continuous rice</i>										
Mean (mg kg ⁻¹)	14.3c	20.2c	17.1b	111.0c	54.3b	36.2	65.6	363c	200c	98.0
% increase	7.7	10.7	3.8	-1.7	12.3	8.1	3.3	100	85.8	10.6
F-test	***	***	***	ns	*	ns	ns	***	***	ns

Means of four field replicates samples per treatment. Means within a column followed by the same letter are not significantly different ($p = 0.05$) by Tukey's multiple range test. F-test: *** $p < 0.001$, ** $p = 0.001-0.01$, * $p = 0.01-0.05$, ns = not significant.

† Increase (%) = (size of fraction in fertilised treatment - size of fraction in SAV) / (Sum P_i fertilised treatment - Sum P_i SAV) * 100

‡ Sum P_t = Resin P_i + NaHCO₃ P_i + NaOH P_i + HCl P_i + Resid P_t = Sum P_i + Sum P_o

§ Sum P_i = Resin P_i + NaHCO₃ P_i + NaOH P_i + HCl P_i

¶ Sum P_o = NaHCO₃ P_o + NaOH P_o + HCl P_o

A need identified during this simulation work was for a P rate and fractionation experiment in the Llanos designed specifically for testing P routines in simulation modelling. This four-year experiment, established in 2001, is a balanced P experiment, with a one-off addition of 80 and 160 kg P ha⁻¹, compared with annual applications of 5, 10, 20 and 40 kg P ha⁻¹. Crop yields from a maize–bean rotation and soil P fractionation will be used to further test the SoilP routine in APSIM and P routines in other simulation models. This work is ongoing and simulation modelling using APSIM will continue during 2004–2005.

The main lessons learned from the work in tropical savannas can be summarised as follows: 1) P from fertilisers and P released from organic residues flows preferentially into labile inorganic pools, but much more slowly into more stable pools; 2) P flows rapidly through, and does not accumulate in, organic pools in the short-term; and 3) crop and forage cultivars differ in their ability to acquire and utilise P, and these differences can be exploited to improve P input use efficiency in crop–livestock systems of the tropics.

Andean Hillsides Agroecosystem – Cauca, Colombia

Hillsides of tropical America cover about 96 million hectares (Jones 1993) and have important roles as reserves of biodiversity and source of water for

areas downslope (Whitmore 1997). Agriculture in this region is often characterised by farming systems under which soils are degrading through erosion and loss of nutrients (Amézquita et al. 1998). Maintenance of the natural resource base in the hillsides is thus vital not only to ensure the future livelihood of resource-poor farmers, but also to prevent their migration to urban centres where social problems are already endemic. Agriculture in the Andean hillsides of Colombia is practised on steep slopes, on soils that are acidic, rich in allophane with a very high capacity to fix P, and prone to severe erosion, particularly on farms of the poorest farmers (Ashby 1985; Reining 1992).

Traditional agricultural systems in the Andean hillsides of Colombia are based on slash-and-burn shifting cultivation with 3–5 years of cropping and then abandonment to fallow vegetation because of low crop yields (Knapp et al. 1996). Local farmers recognise soil nutrient depletion and estimate that it takes more than 6 years for complete soil fertility recovery by natural fallows. Planted fallows are an appropriate technological entry point because of their low risk for the farmer, relatively low cost, and potential to generate additional products (i.e. fuelwood) that bring immediate benefit while improving soil fertility (Barrios et al. 2004).

The volcanic-ash soils in Colombian hillsides generally contain high amounts of soil organic matter (SOM) but nutrient cycling through SOM in these

Table 3. Decomposition and nutrient release differences among green manures and organic materials. Results are from a 20-week litterbag field study in hillsides of Cauca, Colombia. Adapted from Cobo et al. (2002b).

Plant species ^a	Decomposition rate (<i>kD</i> , d ⁻¹)	N release rate (<i>kN</i> , d ⁻¹)	P release rate (<i>kP</i> , d ⁻¹)	Total N release (kg ha ⁻¹)	Total P release (kg ha ⁻¹)
CAN	0.019	0.045	0.033	116	8.0
CRA	0.009	0.026	0.015	90	3.5
IND	0.034	0.061	0.024	130	5.7
MDEE	0.019	0.048	0.044	144	11.4
MPBR	0.022	0.045	0.032	131	8.9
MPIT	0.020	0.039	0.029	110	7.7
MPTL	0.021	0.042	0.030	116	7.9
TTH	0.037	0.044	0.022	124	7.6
INDm	0.015	0.054	0.028	91	4.5
INDs	0.005	0.040	0.063	41	3.5
MPITm	0.017	0.028	0.032	83	6.5
MPITs	0.008	0.011	0.044	28	4.7

^a CAN = *Canavalia brasiliensis* (leaves); CRA = *Cratylia argentea* (leaves); IND = *Indigofera constricta* (leaves); MDEE = *Mucuna deerengianum* (leaves); MPIT = *Mucuna puriens* var. IITA-Benin (leaves); MPTL = *M. puriens* var. Tanzania (leaves); MPBR = *M. puriens* var. Brunin (leaves); TTH = *Tithonia diversifolia* (leaves); INDm = *I. constricta* (stems + leaves); INDs = *I. constricta* (stems); MPITm = *M. puriens* var. IITA-Benin (stems + leaves); N = nitrogen; P = phosphorus.

soils is limited because most of it is chemically protected, which limits the rate of its decomposition (Phiri et al. 2001b). Short-term planted fallows on these P-fixing soils could restore soil fertility by enhancing nutrient recycling through the provision of organic matter to increase N supply and decrease P fixation (Barrios and Cobo 2004). Field and greenhouse studies were conducted to assess the magnitude and timing of nutrient release and to establish relationships with chemical characteristics (quality) of five green manures and four organic materials as a means of defining selection criteria for use as biofer-

tilisers (Cobo et al. 2002a). Results indicated significant diversity in decomposition and nutrient-release patterns (Table 3) and highlighted the value of screening new farming system components to achieve efficient nutrient cycling and minimal environmental impact. Greenhouse studies on nitrogen mineralisation and crop uptake from surface-applied leaves of green manure species indicated that green manures that decomposed and released N slowly resulted in high N uptake when they were used at pre-sowing in a tropical volcanic-ash soil (Cobo et al. 2002b).

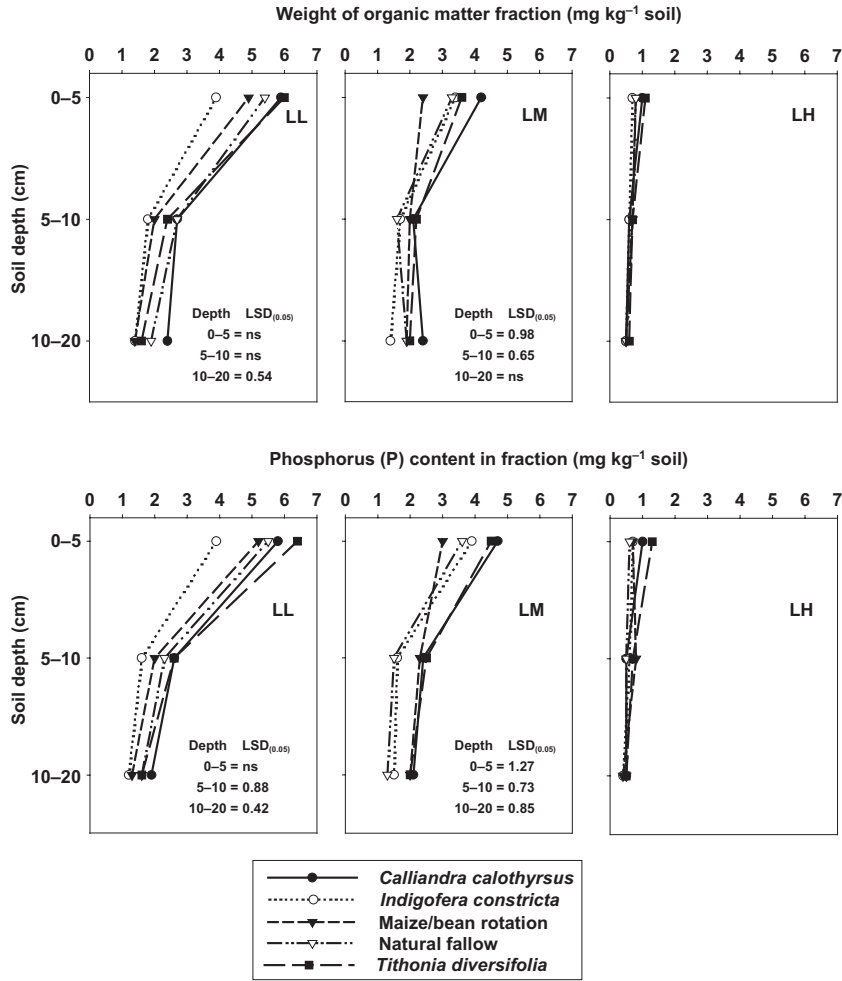


Figure 1. Soil profile weight distribution of light (LL), intermediate (LM), and heavy (LH) fractions of soil organic matter and their phosphorus (P) contents as affected by different fallows and the crop rotation system. LSD values are presented only when the differences among treatments are significant Adapted from Phiri et al. (2001b).

Studies on the impact of improved fallows on soil fertility indicated that a *Tithonia diversifolia* slash/mulch system has the greatest potential to improve soil fertility (Barrios et al. 2004; Barrios and Cobo 2004). Nevertheless, such a system may not be suitable for areas with seasonal drought as it is not very tolerant of extended dry periods. The *Calliandra calothyrsus* slash/mulch fallow system proved to be the most resilient as it produced similar amounts of biomass independent of initial level of soil fertility and was thus a candidate for wider testing as a potential source of nutrient additions to the soil and to generate fuelwood for resource-poor rural communities. The slower rates of decomposition in *C. calothyrsus*, compared with *Indigofera constricta* and *T. diversifolia*, indicated that the benefits provided may be longer lasting. The *I. constricta* slash/mulch fallow, on the other hand, was less adapted to low soil fertility and this may limit its potential for extended use.

The *T. diversifolia* slash/mulch fallow showed the greatest potential to improve SOM, nutrient availability, and P cycling, because of its ability to accumulate high amounts of biomass and nutrients (Phiri et al. 2001b; Barrios and Cobo 2004; Barrios et al. 2004). The amount of P in the light (LL) and medium (LM) fractions of SOM was greater with *T. diversifolia* fallow than the other two planted fallows (Figure 1) and it correlated well with the amount of 'readily available' P in the soil (Phiri et al. 2001b). It is suggested that the amount of P in the LL and LM fractions of SOM could serve as sensitive indicators of 'readily available' and 'readily mineralisable' soil-P pools, respectively, in P-fixing volcanic-ash soils. These results also indicated that fractionation of SOM and soil P could be more effective than the conventional soil analysis methods in detecting the impact of planted fallows on improving soil fertility.

The main lessons learned from the work in Andean hillsides can be summarised as follows: 1) the *Tithonia* slash/mulch fallow system appear to be the best option to contribute to the rapid restoration of soil fertility by increasing the plant available P pool in soil; and 2) a *Calliandra* fallow system could improve soil fertility and also provide good quality firewood for cooking for resource-poor farmers.

The Way Forward

Strategic P inputs are an essential component to increased and sustained agricultural production in

low-P soils. Strategic P applications based on soil P availability, soil P fixation, crop P uptake and reduced crop P requirements could gradually increase the level of available P in the soil. Consequently, the frequency and amounts of P applications required to sustain production will decrease with time. Combined with strategic P inputs, P-efficient germplasm will contribute to agricultural sustainability by: (i) reducing the need to improve soil P status to higher levels to achieve similar productivity, a strategy which is also more demanding regarding maintenance levels of P; and (ii) increasing the efficiency of use of the applied P, which is a non-renewable resource. Moreover, P-efficient crops would bring the economic rates of applied P within reach of smallholder farmers who might otherwise not use fertilisers.

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References

- Amézquita, E. 1998. Propiedades físicas de los suelos de los Llanos Orientales y sus requerimientos de labranza. In: Romero G., Aristizábal D., Jaramillo C. ed., *Memorias Encuentro Nacional de Labranza de Conservación*. 28–30, April 1998, Villavicencio-Meta, Colombia. Editora Guadalupe, Ltda., Bogota, Colombia, 145–174.

- Amézquita, E., Ashby, J., Knapp, E.K., Thomas, R., Müller-Sámann, K., Ravnborg, H., Beltran, J., Sanz, J.I., Rao, I.M. and Barrios, E. 1998. CIAT's strategic research for sustainable land management on the steep hillsides of Latin America. In: Penning de Vries, F.W.T., Agus, F., and Kerr, J., ed., *Soil erosion at multiple scales: principles and methods for assessing causes and impacts*. Wallingford, UK, CAB International, 121–132.
- Ashby, J. 1985. The social ecology of soil erosion in a Colombian farming system. *Rural Sociology*, 50, 377–396.
- Barrios, E., Cobo, J.G., Rao, I.M., Thomas, R.J., Amézquita, E. and Jiménez, J.J. 2004. Fallow management for soil fertility recovery in tropical Andean agroecosystems in Colombia. *Agriculture, Ecosystems and Environment*, in press.
- Barrios, E. and Cobo, J.G. 2004. Plant growth, biomass production and nutrient accumulation by slash/mulch agroforestry systems in tropical hillsides of Colombia. *Agroforestry Systems*, in press.
- Bühler, S., Oberson, A., Rao, I.M., Friesen, D.K. and Frossard, E. 2002. Sequential phosphorus extraction of a ³³P-labeled oxisol under contrasting agricultural systems. *Soil Science Society of America Journal*, 66, 868–877.
- CIAT (International Center for Tropical Agriculture) 1996. Annual report. Soils and plant nutrition unit. Project # 10. Productive and regenerative agricultural systems for marginal and degraded soils of tropical Latin America. Cali, Colombia, CIAT, 93 p.
- 2000. Annual report. Project PE-2: Overcoming soil degradation through productivity enhancement. Cali, Colombia, CIAT, 154 p.
- Annual report. Project PE-2: Overcoming soil degradation through productivity enhancement. Cali, Colombia, CIAT, 151 p.
- Cobo, J.G., Barrios, E., Kass, D.C. and Thomas, R.J. 2002a. Decomposition and nutrient release by green manures in a tropical hillside agroecosystem. *Plant and Soil*, 240, 331–342.
- 2002b. Nitrogen mineralization and crop uptake from surface-applied leaves of green manure species on a tropical volcanic-ash soil. *Biology and Fertility of Soils*, 36, 87–92.
- Crews, T.E. 1996. The supply of phosphorus from native, inorganic phosphorus pools in continuously cultivated Mexican agroecosystems. *Agriculture, Ecosystems and Environment*, 57, 197–208.
- Daroub, S.H., Gerakis, A., Ritchie, J.T., Friesen, D.K. and Ryan, J. 2003. Development of a soil–plant phosphorus model for calcareous and weathered tropical soils. *Agricultural Systems*, 76, 1157–1181.
- Fairhurst, T., Lefroy, R., Mutert, E. and Batjes, N. 1999. The importance, distribution and causes of phosphorus deficiency as a constraint to crop production in the tropics. *Agroforestry Forum*, 9, 2–8.
- Friesen, D.K., Rao, I.M., Thomas, R.J., Oberson, A. and Sanz, J.I. 1997. Phosphorus acquisition and cycling in crop and pasture systems in low fertility tropical soils. *Plant and Soil*, 196, 289–294.
- Guo, F. and Yost, R. 1998. Partitioning soil phosphorus into three discrete pools of differing availability. *Soil Science*, 163, 822–833.
- Hedley, M.J., Stewart, J.W.B. and Chauhan, B.S. 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society of America Proceedings*, 46, 970–976.
- Jones, P. 1993. *Hillsides: Definition and Classification*. CIAT, Cali, Colombia. 7 p.
- Karlen, D.L., Varvel, G.E., Bullock, D.G. and Cruse, R.M. 1994. Crop rotations for the 21st Century. *Advances in Agronomy*, 53, 1–45.
- Knapp, B., Ashby, J.A. and Ravnborg, H.M. 1996. Natural resources management research in practice: the CIAT Hillsides Agroecosystem Program. In: Preuss, H.-J.A., ed., *Agricultural research and sustainable management of natural resources*. Munster-Hamburg, Germany, LIT Verlag, 161–172.
- Lehmann, J., Cravo, M.S., Macedo, J.L.V., Moreira, A. and Schroth, G. 2001. Phosphorus management for perennial crops in central Amazonian upland soils. *Plant and Soil*, 237, 309–319.
- Oberson, A., Friesen, D.K., Tiessen, H., Morel, C. and Stahel, W. 1999. Phosphorus status and cycling in native savanna and improved pastures on an acid low-P Colombian soil. *Nutrient Cycling in Agroecosystems*, 55, 77–88.
- Oberson, A., Friesen, D.K., Rao, I.M., Bühler, S. and Frossard, E. 2001. Phosphorus transformations in an oxisol under contrasting land-use systems: the role of the soil microbial biomass. *Plant and Soil*, 237, 197–210.
- Phiri, S., Amézquita, E., Rao, I.M. and Singh, B.R. 2001a. Disc harrowing intensity and its impact on soil properties and plant growth of agropastoral systems in the Llanos of Colombia. *Soil and Tillage Research*, 62, 131–143.
- Phiri, S., Barrios, E., Rao, I.M. and Singh, B.R. 2001b. Changes in soil organic matter and phosphorus fractions under planted fallows and a crop rotation on a Colombian volcanic-ash soil. *Plant and Soil*, 231, 211–223.
- Rao, I.M., Borrero, V., Ricaurte, J., Garcia, R. and Ayarza, M.A. 1997. Adaptive attributes of tropical forage species to acid soils III. Differences in phosphorus acquisition and utilization as influenced by varying phosphorus supply and soil type. *Journal of Plant Nutrition*, 20, 155–180.
- Rao, I.M., Friesen, D.K. and Osaki, M. 1999a. Plant adaptation to phosphorus-limited tropical soils. In: Pessarakli, M., ed., *Handbook of plant and crop stress*. New York, USA, Marcel Dekker, 61–96.

- Rao, I.M., Borrero, V., Ricaurte, J. and Garcia, R. 1999b. Adaptive attributes of tropical forage species to acid soils. V. Differences in phosphorus acquisition from inorganic and organic phosphorus sources. *Journal of Plant Nutrition*, 22, 1175–1196.
- Reining, L. 1992. Erosion in Andean hillside farming: characterization and reduction of soil erosion by water in small scale cassava cropping systems in the southern central cordillera of Colombia. *Hohenheim Tropical Agricultural series No. 1*. Weikersheim, Margraf Scientific Books, 219 p.
- Runger-Metzger, A. 1995. Closing the cycle: obstacles to efficient P management for improved global security. In: Tiessen, H., ed., *Phosphorus in the global environment*. Chichester, U.K., John Wiley & Sons Ltd, 27–42.
- Thomas, R.J. and Ayarza M.A., ed., 1999. Sustainable land management for the Oxisols of the Latin American Savannas: dynamics of soil organic matter and indicators of soil quality. Cali, Colombia, International Center for Tropical Agriculture (CIAT), 231 p.
- Vance, C.P. 2001. Symbiotic nitrogen fixation and phosphorus acquisition. *Plant nutrition in a world of declining renewable resources*. *Plant Physiology*, 127, 390–397.
- Whitmore, T.C. 1997. Tropical forest disturbance, disappearance, and species loss. In: Laurance, W.F., and Bierregaard, R.O., ed., *Tropical forest remnants: ecology, management and conservation of fragmented communities*. Chicago, USA, The University of Chicago Press, 3–12.

Improved Capabilities in Modelling and Recommendations: Summary

R.J. Delve,* M.E. Probert† and J.P. Dimes§

The purpose of the project 'Integrated nutrient management in tropical cropping systems: improved capabilities in modelling and recommendations' (ACIAR Project no. LWR2/1999/03) was to test and enhance a modelling capability that can be applied to farming systems where both organic and inorganic sources of nutrients are used. In tropical regions, organic materials are often more important for maintenance of soil fertility than fertilisers, yet current fertiliser recommendations and most crop models are unable to take account of the organic inputs and the different qualities of these organic inputs used by farmers.

When the project commenced, simulation modelling had a limited ability to predict the effects on soil processes and crop growth of organic sources that differed in 'quality'. APSIM was chosen because it had draft modules to describe the release of nutrients (both nitrogen and phosphorus) from manures (Manure module) and the dynamics of P in soil (SoilP module), and it contained routines to limit crop growth under conditions of water, N and P stress. At the start of the project, these modules were largely untested. The project tested, and where necessary improved, the APSIM Manure and SoilP modules, so that they can be applied to the management of soil fertility, especially in low-input systems in the tropics.

Developments in Improving APSIM Manure and SoilP Modules

Resource-poor farmers regularly make decisions on the use of scarce nutrient sources in crop–livestock production systems. The decisions made generally reflect farmer experience (of expected returns) and livelihood preferences. However, for resource-poor farmers, 'experience' is often limited by the feasibility and capability of the farmer to experiment with alternative management practices. In the case of allocating animal manure for crop production, this decision is usually taken with limited knowledge of the impact of the potential of alternative uses on plant production and soil and water resources. A deeper understanding of the comparative values and usefulness of manures and other locally available resources and sources of P would help fill such knowledge gaps, offering the possibility for increased production and efficiency of mixed crop–livestock systems. While efforts are required to expand our knowledge of the biophysical aspects of alternative uses of organic nutrient sources, similar efforts are also required on the socioeconomic driving forces behind farmers' decision-making.

Cross-method analysis of plant quality

N content or C:N ratio are the primary indicators of decomposition and N release across a range of plant materials of different quality. However, other parameters (such as lignin and polyphenolics) are needed to explain the variation observed in N mineralisation studies.

Measurements for assessing plant resource quality include an extensive array of proximate analyses (lignin, acid-detergent fibre (ADF), total soluble

* Tropical Soil Biology and Fertility Institute of International Centre for Tropical Agriculture, PO Box 6247, Kampala, Uganda <r.delve@cgiar.org>.

† CSIRO Sustainable Ecosystems, 306 Carmody Road, St Lucia, Queensland 4067, Australia <merv.probert@csiro.au>.

§ International Crops Research Institute for Semi-Arid Tropics, PO Box 776, Bulawayo, Zimbabwe <j.dimes@cgiar.org>.

polyphenolics, and a variety of condensed tannins). Decomposition is determined by the combination of these different factors. Indirect methods that can serve as 'integrative measures' of resource quality are discussed in Section 3 of these proceedings. These include aerobic decomposition, near infrared reflectometry (NIR) and in vitro dry matter digestibility. Results from these integrative methods correlated well with mineralisation rates estimated in the traditional leaching tube experiment and have the potential to predict this laboratory estimation of resource quality.

From this cross-method analysis, the minimum data set to assess organic resource quality consists of N, lignin, and soluble polyphenol content. This finding is consistent with conclusions from earlier efforts. Considerations of cost and speed also need to be compared where more than one method is available. Aerobic incubations are one of the cheapest but slowest methods, whereas NIR is the fastest. Although NIR instrumentation is expensive to set up, for routine analysis of many samples it could become cost effective. Construction of spectral calibration libraries in centralised laboratory facilities would greatly increase the efficiency of NIRS use for routine organic resource characterisation in laboratories and dramatically reduce the costs of such analyses.

Modifying and testing the APSIM Manure module

Existing laboratory incubation experiments and SWNM network trials in East and southern Africa situated in diverse agro-ecological zones and soil types were used to test the manure module (see Section 4). The field experiments used manures of differing quality and combined organic and inorganic sources of N. These trials provided data on the short and long-term effects on nitrogen availability, soil organic matter and crop production — information that is necessary for testing APSIM and to provide the insights needed for making any modifications to APSIM.

Initially, as in other models of soil organic matter turnover, the model assumed that the soil organic matter pools (BIOM and HUM) have C:N ratios that are unchanging during the decomposition process. Additions of fresh organic matter (FOM) are considered to comprise three pools (FPOOLS): the carbohydrate-like, cellulose-like and lignin-like fractions.

Each FPOOL has its own rate of decomposition, which is modified by factors to allow for effects of soil temperature and soil moisture. Although the three fractions have different rates of decomposition, they did not have different compositions in terms of C and N content. During this project we concluded that, to simulate release of N from diverse sources of manure, the model could match observed short-term release patterns only if the pools had different C:N ratios. This insight came from the results of laboratory studies that showed variable N-release patterns depending on the C:N ratio of the soluble fraction of the manures (Probert et al., these proceedings). The APSIM Manure module has been modified so that the pools can now be specified to have different C:N ratios. This enabled the effects of different qualities of organic resources on N-mineralisation patterns to be simulated in accordance with observed responses, especially during periods immediately following manure application.

Modifying and testing APSIM's phosphorus routines

The SoilP and modified maize modules that existed when the project commenced explored the feasibility that it might be possible to include P-stress as a limitation to growth in APSIM crop models. During this project, as it became clear that that was indeed feasible, two significant advances were made.

Firstly, the P status of the crop had been considered only on a whole plant basis. This is not consistent with how N is modelled in the APSIM crop modules; in particular, it is far from ideal when a sequence of crops is to be simulated (for example, how to handle P in residues at harvest?). The development was to simulate the partitioning of P to different plant components (leaf, stem, flower, grain, root) throughout the life of the crop. A consequence of this development is that the data requirements for specifying the P dynamics in the crop are much greater, because P concentrations in the various plant components need to be described. A new parameter set (specifying P concentrations and stresses) was created for maize (based on results from an earlier experiment at Katu-mani — ACIAR Project no. 8326).

The second improvement was in the P-uptake routine. In the prototype, this was directly related to the amount of labile P in a soil layer. Current understanding suggests it ought to be related to the P concentration in solution at the root interface. A new

routine was introduced into the code and 'tuned' to the Katumani experiment. Testing against other data sets (particularly that from Maseno on a very different soil with much higher P sorption characteristics, and from Machang's) showed that the new uptake routine and parameter set was transferable. Having shown that the model could simulate P-deficient maize, the P routines were put into an APSIM crop template so that, in principle, any model using the template can be P-aware, provided the necessary parameter set exists to define P concentration in the plant and the effects of P stress on the plant growth processes.

The initialisation of the APSIM SoilP module requires inputs for labile P and P sorption on a soil layer basis. In this project, labile P has been identified with bicarbonate extractable P (Olsen P), though further testing on a wider range of soils is needed. It is unlikely that there is a 1:1 fit between the conceptual labile P of the model and any soil P test. The measure of 'P sorption' used is the amount of P sorbed at 0.2 mg L⁻¹.

For model-testing purposes, the only additional crop variables beyond those needed to validate the N and water routines would be P concentrations in plant components and P uptake. The parameter set required to make a crop model 'P-aware' comprises values for the maximum, minimum and senesced P concentration in the different plant components through the growth cycle of the crop, together with factors specifying how P stress affects photosynthesis, leaf expansion and phenology.

Unfortunately, during the project, no data set from Latin America, Africa or Asia contained all the required data to thoroughly evaluate the model. Ideally, for testing the ability of the SoilP module to simulate effects of P on crop growth, one would want to look at crop growth (yields, phenology, leaf area, nutrient uptake), soil water and rooting depth, mineral N in soil, soil P test values and, in a long-term experiment, soil organic matter. To address this, ongoing fieldwork in Latin America will be used for further testing of the model.

None of the data sets explicitly addressed the effectiveness of P in organic sources. In the model, mineralisation of P is simulated in a similar manner to N and will be determined by the C:P ratios of the substrate and the soil organic matter being synthesised. Using typical values for C:P in soil microbial biomass of 10–35, leads to the inference that net P mineralisation from an organic source would require

a C:P of less than 100 (i.e. a P concentration of greater than 0.4% in tissue). This does not conform with published data. The cause of the disparity is again thought to lie in the C:P ratio not remaining constant during decomposition. For P, the water-soluble fraction has a much lower C:P ratio than the total C:P. Therefore, in the enhanced SoilP module the release of plant-available P from organic inputs depends on the FPools having different C:P ratios.

Testing of APSIM with long-term tropical data sets

Long-term experiments covering a range of soil types were identified by project collaborators in East and West Africa, Latin America, and Southeast Asia, and were used to test the new APSIM modules for predicting nutrient release and plant growth under field conditions. Results show that the model performed well across a wide range of applications, from simulation of N and P supply to crops where P constraints were more severe than N, to long-term P and C dynamics, and for crop responses to different rates and qualities of manures, responses to inorganic and manure combinations, and residual benefits of manure.

Using the long-term data for the Machang's experiment, the model was shown to accurately predict crop responses to inputs of manure or fertiliser, while the predicted dynamics of labile P in soil were similar to the measured Olsen P data. Of course, none of these simulations was perfect, and discrepancies between observed and predicted data were reported. Notably for the Maseno data set, where soil P was determined irregularly (and soon after fertiliser application), the agreement between observed and predicted values was poor. In some cases, the lack of fit between model and observed data will arise from limitations in the modelling capability, e.g. there are effects of manures other than N and P that cannot be modelled. In other cases, the discrepancies are due to our poor understanding of the observed responses, which limits our interpretation.

Generally, experiments, especially long-term ones, are not established with model validation or development in mind. This project used existing long-term experiments from East and West Africa, Latin America, and Southeast Asia and, of course, found some shortcomings in the available data. While this did not hamper model development, it has prevented the evaluation of model performance from

being as thorough as one might like. Accordingly, new experimentation was established during this project in Latin America, to overcome these data constraints and for further testing of APSIM.

Extension to other crops

The 'P-aware' maize model was a major breakthrough in our thinking of how to explicitly reflect soil P dynamics and especially P limitations in crop simulations. There is a clear need to apply the new capability to other crops. During this project, field-work was initiated to conduct experiments that would permit parameter sets to be assembled. This work was co-funded from other projects. The crops being studied are cowpea and millet (funded by IFDC in West Africa), pigeonpea, groundnut and sorghum (funded by DFID and ICRISAT in India), and canola (funded by CSIRO in Australia).

Many of the soils in Africa and Latin America are P-fixing and/or P deficient, and these projects are now contributing further modelling capability for P dynamics in these farming systems. The SoilP module developed and evaluated within this project has provided the opportunity for these other projects to proceed, and this is a major outcome and one measure of the project's success.

Future Activities Needed in Developing APSIM

The ACIAR-funded project LWR2/1999/03 developed a unique capability in simulation modelling by introducing the ability to have crops respond to P constraints and to model N and P dynamics following addition of manures of different quality. There remains a need to test these routines against a wider suite of data sets, especially for a wider range of cropping systems and soil types.

The external review team made several recommendations about follow-up activities with project partners. In the short and medium terms, these were to:

1. generate a few high-quality contrasting data sets for validation
2. refine and publish the data collection protocols for others to use
3. start working with end users including farmers to utilise model outputs.

A two-year project extension has since been funded by ACIAR to address the first two recommendations and, at the same time, strengthen the skills of current APSIM users in the project. The major components of this extension are as follows:

1. The N and P capabilities of the APSIM Manure and SoilP modules are being further tested against existing data sets in Latin America and Southeast Asia. Field studies established during the project were designed to provide a comprehensive data set for testing of the SoilP module and the P routines in the maize module. These studies are still in progress.
2. As part of the testing activities above, researchers from Latin America and Southeast Asia would be exposed to the use of the APSIM model and how it might be applied in the carrying out of their research activities and in extending, to the farming community, the results of their research. Training in the use of APSIM for the partners would be a component of this activity.
3. The data collection protocols for manure characterisation are being refined and published, so future researchers collect data that are appropriate to Manure module use. Also, the minimum data set protocols for APSIM are being updated.