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# What soil constraints should be included in crop and forest models?

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**Abstract**

Models of agro-ecosystems provide means of prediction beyond the bounds of experience or experimentation. Extrapolation may involve simulation of the expected behaviour for different climate and/or soil conditions, perhaps with alternative management, or for a longer time scale than observed experimentally. The issues to be addressed include those concerned with crop growth and profitability, effects on the soil resource, and consequences for the environment.

The extent to which the model output is credible depends on how well the model represents those aspects of the system that are important for a particular application. In principle, any model can be enhanced to deal with additional factors, but more complex models become increasingly hungry for inputs, and increasingly difficult to test against actual data. There are judgements to be made as to whether the demands of model building/testing can be justified.

The choice of what soil constraints should be included in models will depend on what the model is to be used for and the understanding of the processes that the model purports to represent. The dynamics of water and nitrogen are the soil features commonly represented in crop/forest models. Based particularly on experiences with the APSIM modelling framework, the paper reports developments aimed at dealing with erosion, soil structure, salinisation, acidification, and phosphorus as limitations to plant growth.

Modelling the consequences of global change on crops and forests involves issues of productivity, climatic variability, "greenhouse" effects and sustainability. Discussion focuses on whether current models need to be enhanced by including other constraints in order to address such issues. 

*Keywords:* Modelling; Global change; Soil constraints; APSIM

## 1. Introduction

Many of the important issues that confront the world today (like global change and sustainability of agro-ecological systems) involve extrapolation beyond the bounds of experience or experimentation. There are expectations that models of agro-ecosystems can provide the means of extrapolation. To be useful the models must be credible, and they must represent the processes that are known, or are supposed to be important in determining the behaviour of the system. It must also be recognised that any model is only a simplification of the real world. Accordingly there will be judgements about what processes and constraints need to be considered and how they are to be represented in the model.

The choice of what to include or omit will depend primarily on what the model is to be used for. Thornley (1997) has outlined three reasons for building mod-

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els: in order to make predictions; because we want to understand how something works; and to provide a means of studying complexity and elucidating how sub-systems interact. At a conference focusing on the consequences of global change, there is little doubt that models are seen especially as a means of making predictions that go well beyond our capability for measurement or experiment. However, the confidence that can be placed on the predictions must come from an understanding of how the system behaves including interactions between sub-systems. So, model building and application are always likely to include aspects of all of Thornley's reasons.

Other factors important in determining what is included in a model, and the level of detail that is adopted in the modelling approach, are the information that is available to parameterise, specify and drive the model, and the interests of the model builders.

Crop and forest models have a variety of uses that place very different demands on a model and especially on what soil constraints need to be considered. At one extreme the interest might be in a single crop, possibly under non-limiting conditions of water and nutrients: in such a case there is no requirement for the model to feature any soil constraint. At the other extreme, the system could be as complex as one's imagination allows, embodying a cascading set of potential constraints, any one of which might become limiting under particular circumstances.

The aim of this paper is not to make detailed comparisons between particular models. A broad brush is applied to identify what soil issues models are able to deal with, and to indicate where there is need for models to be enhanced (by inclusion of other soil constraints) so that they might have the capability to address the issues of the real world. The paper draws particularly on the experiences of users of the APSIM modelling framework (McCown et al., 1996), e.g., of how models are being developed in order to address emerging needs.

## 2. Soil constraints in crop and forest models

The type of model being considered is one that is capable of simulating growth of crops and forests in response to diverse management practices when driven by climatic inputs. Such models have been described as dynamic, deterministic and mechanistic. They are dynamic because they include time in the model specification; deterministic because given one set of inputs they produce only one set of outputs; mechanistic in the sense that they are based on assumptions about the mechanisms of the processes represented. The availability of climatic data, and the need to capture the effects of management and weather on growth, means that such models typically operate with a daily time-step. Also, they are almost invariably one-dimensional (1D), simulating the system at a point (that can be considered to represent a single plot or a field under uniform management).

Most crop/forest models claim to deal with water and nitrogen (N). This is not surprising because it is aspects of the water and N supply to plants that are most amenable to adjustment or control by management. However, to get at the processes represented, one must examine in more detail what is being implied when it is said that a model "deals with water (or N)".

Table 1 sets out some of the matters that need to be considered in modelling soil water. There are many processes involved: infiltration, runoff, redistribution within the profile, drainage, evaporation, transpiration, freezing, melting of snow. Understanding of how the system behaves leads to another level of detail — this is the reductionist's view of the system. Using the redistribution of water in the soil profile as an example, one might list issues such as the presence of macropores, the notion of mobile vs. immobile water, whether the soil has a water table. With the issues that

Table 1
Schema illustrating the hierarchy of issues that need to be considered when modelling soil water

| | |
|---|---|
| Modelling approaches | Cascading "bucket"<br>Solution of Richards' equation |
| Processes | Infiltration/runoff<br>Redistribution within profile<br>Drainage<br>Evaporation<br>Transpiration<br>Freezing<br>Snow melt |
| Issues (relevant to redistribution of water) | Saturated/unsaturated flow<br>Macropores<br>Mobile/immobile water<br>Water table |

are of importance for the other processes, these make up a spectrum of factors that are possible candidates for inclusion in any model of soil water.

In the case of soil water, there are two modelling approaches that are commonly used, either the cascading "bucket" approach or a solution of Richards' equation (often combined with the convection–dispersion equation to model solute movement). Some soil water issues can be represented better by the more rigorous approach involving the simultaneous solution of the flux equations describing the sources and sinks and the redistribution of water in the whole profile. Examples are the ability to specify alternative boundary conditions at the base of the profile, and to handle effects of surface sealing. However, many of the processes involved in modelling soil water can be adequately dealt with using either approach. A comprehensive study comparing the two approaches found both to be capable of giving good descriptions of soil water content and solute movement (Verburg, 1996).

The detail that is included in a model to represent the behaviour of soil water will be selective from the possible range of options that could be included. To take an obvious (and trivial) example — a model developed by workers in the tropics is not likely to have routines that focus on freezing or melting of snow! The inclusion of code to represent a particular process does not imply that all aspects of the process are adequately represented. Consider the ability to deal with a water table. A capability to accurately predict the presence of a water table does not determine the fate of the water by lateral flow. Furthermore a model that has plant growth routines to modify root function and growth under conditions of limited water supply may not have routines that enable the plant to respond to the water-logged condition when a water table occurs.

Similar considerations apply with regard to modelling N in soil. The dynamics of N in soil are linked with soil organic matter. The processes involved include mineralisation of soil organic matter, decomposition of crop residues and roots, nitrification, denitrification, volatile loss as ammonia, leaching of nitrate, and crop uptake. The interests of the modellers can strongly influence what is deemed to be important in the model. Using denitrification as an example, the requirements for an agronomic application, where partitioning of losses into the component gases ($N_2$, $N_2O$, NO) would not be of concern, can be contrasted with an application where accurate prediction of greenhouse gas emissions, notably $N_2O$, would be of prime importance.

Geographical location of the model builders may be a contributing factor to the variety of functions that have been used to describe temperature effects on mineralisation (e.g., Rodrigo et al., 1997). The different functions are likely to have been tested largely under the range of soils and climatic conditions that are most applicable to the model builder/developer. Transferring a model to other environments is not always straightforward.

While water and N constraints are generally addressed in crop and forest models, the approach used and model specification can vary considerably in response to modelling purpose, geographic focus, and the interests and expertise of the model builders.

## 3. What soil constraints are missing from models?

Constraints, other than water and N, which could be limiting for plant growth are less often included in models. Several reasons can be suggested why any particular constraint is not included: (i) it is not considered sufficiently important; (ii) it is not well-enough understood; (iii) the matter of balance and feedback in the model.

Because many factors can affect plant growth under particular circumstances, it does not follow that there is need for them all to be included in models. A dynamic modelling approach may be helpful in addressing some issues: when such opportunities are identified, there are likely to be endeavours towards developing capabilities in the model for dealing with the crucial processes.

In discussing soil constraints that might be needed for a model to deal adequately with particular situations, we will draw on the experiences of colleagues using the APSIM system model (McCown et al., 1996). The N aspects of this model are similar to what exists in many others models and have been described by Probert et al. (1998), whilst modules are available to describe the water balance using either the "bucket" approach or a solution of Richards' equation. The constraints to be considered are soil erosion, soil structure, salinisation, soil acidification, and phosphorus supply and utilisation. They provide examples that direct attention to whether the processes themselves and the link between the soil and vegetation are understood sufficiently to be represented in models.

### 3.1. Soil erosion

The model PERFECT (Littleboy et al., 1989) was developed especially to model the consequences of erosion on the vertisols of southern Queensland. The APSIM erosion module retains this functionality from PERFECT. Aspects of erosion that are captured by the model are: (i) the decreasing depth of soil, and thus plant available water capacity, as a consequence of soil loss; (ii) the loss of organic matter rich surface soil reduces the soil's ability to supply N to crops. Nelson et al. (1998) used APSIM's capability to model erosion to study the consequences of erosion in a hedgerow farming system.

### 3.2. Soil structure

It is rare for soil structure to be explicitly included in crop and forest models, though it can clearly be important in determining system performance in some situations. There are several potential effects ranging from consequences of compaction on root exploration or water movement, surface sealing affecting infiltration, to how ped structure influences gaseous diffusion and the creation of anaerobic micro-sites that are of importance to denitrification.

Some APSIM crop modules can be specified to simulate the effects of compaction layers (plough pans) on the downward proliferation of root systems. Asseng et al. (1998) were able to simulate the effect of deep ripping on the growth of wheat by changing the root hospitality factor for the affected soil layers.

An APSIM module (SURFACE) has been developed (Silburn and Connolly, 1995) which predicts surface seal conductivity through time depending on tillage, rainfall intensity, cover and roughness. This module has been used in research studying the effects of pasture phases on soil structure in a cropping rotation.

### 3.3. Salinisation

Where high salt concentrations exist in soil that inhibit root growth the effect can sometimes be accommodated by restricting rooting depth or through the use of root hospitality factors. However, this is inadequate for capturing the temporal effects of soil salinisation. Moreover, the nature of soil salinisation has a spatial dimension whereby drainage at one location may create rising water tables and increasing salinity elsewhere.

Most 1D models with routines for redistribution of water and movement of solutes have the capability of addressing some of the issues involved in salinisation. In APSIM, there is capability to track the movement of non-reactive solutes, such as chloride, in the soil profile. The redistribution of solute is determined by the flux of water as predicted by the water balance routines, either using a mixing algorithm to move solute between soil layers (Probert et al., 1998) or a numerical solution of the convective–dispersion equation (Verburg et al., 1996). Such models have been used to study chloride accumulation in soil when irrigated with effluent (Snow et al., 1999).

Secondary salinisation is occurring in large areas of southern Australia as water escaping below the rooting zone of crops moves salt around the landscape. The 1D crop models considered here can predict some of the driving forces at work, but they do not address the spatial consequences at a catchment or landscape scale. An approach to scaling up is to use the outputs from the point models (which have the sensitivity to cope with the climatic effects on crop growth thereby influencing the components of the water balance) as inputs for other models that can integrate over a catchment (Paydar et al., 1999; Ringrose-Voase et al., 1999).

### 3.4. Soil acidification

There is interest in Australia in models that can be used in research into management practices to prevent or ameliorate soil acidification. Helyar and Porter (1989) showed how the balance of hydrogen ions in the soil–plant system can be calculated and related to changes in soil pH. As originally proposed, the only flux that could not be measured was the leaching of nitrate. This could be calculated by difference by assuming that any acidification not accounted for by other processes is due to nitrate leaching. However, all the additions and removals of nitrate and ammonium on a soil layer basis can be predicted in soil–plant models. The APSIM SoilpH module uses the simulation of N and carbon (C) to predict changes in soil pH (Hochman et al., 1998). In its current version, APSIM SoilpH requires inputs of the ash alkalinity of the plants being grown, whilst changes in the soil's pH buffering capacity are not treated rigorously (Verburg et al., 1998).

The model provides a representation of the acidification of soil, and how pH changes are distributed through the profile, as a consequence of the imbalance in uptake of cations and anions, the leaching of nitrate and changes in soil organic matter content. It is a tool that can be used for exploring strategies for reducing the effect and for examining the effectiveness of remedial actions (e.g., liming).

However, an ability to simulate soil pH does not of itself provide a means of simulating long-term effects of soil acidification in the whole system. The link that is missing is the feedback between the soil pH and plant growth. Plants do not respond directly to pH. Rather, effects of soil acidity are manifested through toxicities of aluminium or manganese, or deficiency of calcium. Whilst soil pH might be simulated, the model is ignorant of these other factors. There is interest in developing a generalised response of crop growth to low pH, but it seems unlikely that the model will be elaborated to permit crops to respond to the specific limiting factors (aluminium, manganese, calcium).

Besides influencing plant production, soil pH also affects the turnover of soil organic matter (Paul and Clark, 1989). Soil processes such as mineralisation, nitrification and urea hydrolysis are pH dependent. Whilst models do include routines to represent the effects of pH on the dynamics of soil C and N, the ability of such a model to capture the consequences of soil acidification on N mineralisation or C balance in soil does not seem to have been studied.

The prospect of a systems model that is capable of capturing the effects of soil acidification raises a problem in how uptake of N by plants is modelled. Many crop models only consider the uptake of nitrate. For most situations this is adequate because ammonium is rapidly nitrified in soil. However, in acid soils nitrification is inhibited and models of plant growth will need to account for the uptake of both nitrate and ammonium. Whilst nitrate is present in the solution phase, ammonium is largely held on the cation exchange sites of the soil. A mechanistic approach to ammonium uptake is likely to require rather different treatment to how nitrate uptake is simulated.

### 3.5. *Phosphorus*

Phosphorus (P) 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., Nye and Tinker, 1977) show that root density is a controlling factor in P uptake. The models required are at a greater level of detail than what is present in most crop and forest models. More general system models, like EPIC (Jones et al., 1984) and CENTURY (Parton et al., 1988), have included P routines but these have not been widely used to explore management strategies involving P. It has been reported that the P routines in CENTURY are not able to describe the dynamics of P in tropical soils (Gijsman et al., 1996).

Management of soil P (especially in high input agricultural systems) has been concerned with issues like whether to apply fertiliser, at what rate, evaluating placement and residual effects, and comparing relative effectiveness of soluble vs. non-soluble sources. Because P is practically 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. In fact there are few prospects for improving management of P beyond recommendations for amount and method of application of fertiliser. Models operating with a time-step of a growing season and 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).

This is not the case for low input systems. Improvement in food security requires that traditional fertility maintenance practices be augmented with external inputs of nutrients (e.g., McCown et al., 1992). Many soils on which subsistence crops are grown are deficient in both N and P. Fertiliser is little used because it is (too) expensive and responses are uncertain depending on variable rainfall. The manure that is available is generally of poor quality, but may provide a better source of P than of N (Probert et al., 1995). Integrated nutrient management, involving the combined use of organic and inorganic sources of nutrients, is being promoted as the sustainable means of managing soil fertility in the tropics. Palm et al. (1997) have pointed out that there is little predictive ability to guide recommendations for the combined use of different sources of nutrients.

If models are to be useful for simulating the nutritional effects of manures and other organic sources in low input systems, they will need to cope with the supply of both N and P. This has led to the development of the APSIM modules SOILP (describing the transformations of P in soil) and MANURE (handling the release of N and P from manures). The crop modules also require modification so that crop growth becomes dependent on P supply from the soil. These models are being tested in a project that is concerned with improving capability in modelling and recommendations for integrated nutrient management (Cheryl Palm, unpublished).

### *3.6. Other nutrients*

Sulphur (S), together with C, N and P, is a constituent of soil organic matter. CENTURY (Parton et al., 1988) simulates the dynamics of all four elements in the organic and inorganic parts of the soil system. Sulphur is also included in a model of nutrient uptake by pastures (McCaskill and Blair, 1990). Incidences of S deficiency are becoming more widespread due to reductions in gaseous emissions from industrial sources. However, this has not yet resulted in development and application of crop models that include S as a constraint.

Disorders of other nutrients are less widespread than for N and P, and it would seem are sufficiently infrequent and not of wide enough interest to justify their inclusion in crop/forest models. Simpler relationships are often available to interpret soil or plant analyses in terms of possible nutrient disorders for plant growth and fertiliser recommendations. Furthermore there is likely to be a lack of understanding on which to base crop routines in models relating growth and phenology to nutrient stresses other than N and P. Even for P there are few data available for a wide range of crops that are suitable for developing the necessary relationships.

## 4. Modelling the consequences of global change

The discussion above has attempted to show that the constraints included in models are dependent largely on the overall context of why the modelling is being done. In this section, the appropriateness of current modelling capabilities is addressed in relation to "global change".

From the programme for the conference "Food and Forestry: Global Change and Global Challenges", four topics involving global change have been identified where there are obvious benefits to be obtained from application of a dynamic modelling approach. In Table 2 these are listed together with some of the key issues. Further, suggestions are made of what enhancements may be needed in models beyond the ability to deal with soil water and N as limiting factors for plant growth.

### *4.1. Productivity*

Global change, resulting from anthropogenic activities, involves increased concentration of $CO_2$ in the atmosphere, increases in temperature, and modified rainfall patterns. The productivity issues related to soil constraints on crop growth largely concern the soil water balance and the effects of temperature on soil organic matter and plant residue transformations. To the extent that increased atmospheric $CO_2$ results in increased net primary production, there are questions about whether nutrients will become limiting (especially in forest systems) and/or whether there will be a higher requirement for inputs of fertilisers. However, the nutritional effects are secondary to the main effects of climate change (rainfall and temperature) which will influence the productivity of agricultural systems, and in extreme situations may alter the suitability of crops for a given location.

Changes in the soil water balance as a result of climate change could have deleterious effects on the environment. An increased drainage component will have potential consequences for leaching of solutes, and ultimately result in problems such as high nitrate concentrations in groundwaters, eutrophication of waterways, dryland salinisation or soil acidification. An increased runoff component can be expected to result in increased erosion and sedimentation problems.

Models of crops or forests that focus only on how climate changes will affect growth and productivity may not adequately deal with the environmental aspects. Some of the issues are discussed further under Section 4.4.

Table 2
Soil constraints (other than water and nitrogen) which need consideration when modelling impacts of global change on crop and forestry systems

| Topic | Issues | Soil related factors |
|---|---|---|
| Productivity | Elevated $CO_2$ | Erosion |
| | Increased temperature | Salinisation |
| | Modified rainfall pattern | Soil acidification |
| | Consequences for environment | (Limiting nutrients) |
| Climate variability | Tactical management | |
| | Benefits of climate forecasting | |
| “Greenhouse” | Carbon sequestration | Gaseous losses of N (denitrification) |
| | Emissions of $CO_2$, $N_2O$, $CH_4$ | Limiting nutrients |
| | Effects of land use change | Scale issues: availability of data; type of model needed |
| Sustainability | Nutrient mining | Multi-nutrient limitations (especially P in low input systems) |
| | Depletion of soil organic matter | Decomposition of organic inputs |
| | Erosion | Erosion |
| | Salinisation | Soil acidification |
| | Soil acidification | |

### 4.2. *Climatic variability*

Models are important tools for evaluating tactical management strategies to cope with the vagaries of climate and the benefit of climate forecasts. Water and N are the two limiting factors that are most under control of management. Accordingly models that deal with water and N in an adequate manner are well suited for these activities.

### 4.3. *“Greenhouse” effects*

The issues include the emission of greenhouse gases ($CO_2$, $N_2O$, $CH_4$), sequestration of C in the plant/soil system, and the effects of land use change. There is considerable uncertainty over the ability of current models to simulate denitrification and to partition losses into the component gases. Understanding of the denitrification process suggests that it perhaps needs a more detailed treatment than can be handled by a 1D model with a daily time-step (Smith, 1980).

Smith et al. (1997) assessed the performance of a range of models in simulating the dynamics of soil organic C. However, not many of the models they studied predicted the inputs of C to the system from the growing plants. They concluded that some form of coupling between the soil organic models and plant growth models is needed if whole ecosystems are to be simulated. Also some models limit the description of soil organic C to a single surface layer. It seems unlikely that this is adequate for prediction of C sequestration. However, there is a scarcity of data on long-term changes in soil organic matter in soil profiles under different managements that could be used for testing of models. Furthermore, the below ground inputs of C into soil from crops and trees are only poorly understood. Vegetation responses to higher atmospheric concentration of $CO_2$ introduce another element of uncertainty.

Prediction of greenhouse effects involves matters of scale that do not arise when considering productivity or climate variability. Firstly, there is the time scale. The sequestration of C over a long period of time will depend on net primary production. Whether other factors are, or become, constraints will be important to the outcome. Secondly in estimating C emissions or stocks, the output is needed on a regional, national or global scale. For models that are able to describe plant/soil behaviour at a point or field scale there is a mismatch in terms of data availability and computation time. One response to this will be in the choice of the type of model and acceptance of some trade-off between use of more generic, less data hungry models against ability to handle the detailed processes, interactions and management intervention.

### 4.4. Sustainability

There are several land degradation issues that are not particularly linked to global change, but which are at the core of sustainable development of agricultural and forestry systems. The question that arises in the context of global change is whether a change in climate (higher temperature, altered rainfall pattern) would cause systems to become less sustainable. Many current crop and forest models are not well equipped to tackle these issues.

Nutrient mining, due to removal of nutrients in products exceeding inputs, is especially important in low input systems. In many instances there will be deficiencies of nutrients other than N. Phosphorus deficiency is widespread over large areas of highly weathered soils of the tropics. Nutrient inputs to these systems are likely to be as organic sources (crop residues, composts and manures). For models to be an effective means of researching these systems they will need to include aspects of the quality factors that affect the release of nutrients from these organic inputs and the availability to crops of both N and P.

Erosion contributes to declining nutrient content of soil as well as reducing the soil's capacity to store water. It is a factor that contributes to the sustainability of many farming systems. Models used for investigating strategies for more sustainable systems will require capability to simulate erosion.

Soil acidification has become a factor that now limits productivity and choice of crop in much of southern Australia. The underlying cause is leakage of nitrate below the rooting depth of the crops. Much of this N has been fixed by legumes. Models that can predict soil acidification and crop response to acid soils will provide a tool to explore management strategies for these degraded situations. They would also enable the evaluation of strategies to ensure that other systems do not become degraded by acidification.

## 5. Conclusions

It has been argued in this paper that the issues to be addressed by application of crop and forest models determines which soil constraints need to be represented in the models. Water and N are the two soil factors that are most subject to management of crop and forest systems and are similarly important in the context of global change. These factors are generally included in existing crop/forest models. However, models for global change research will also need to address a range of other soil processes and constraints that are important to the productivity of crops and forests and the sustainability of agro-ecosystems. Erosion, soil acidification and salinisation, and other limiting nutrients (notably P) are identified as constraints that will be important in some situations.

The focus has been on soil constraints that influence plant growth. At a field scale, the dynamic 1D models are at a sufficient level of detail to predict the effects of soil factors on plants, and of plants on soil properties. Challenges that confront modellers of the effects of global change include the need to bring together the models that exist for individual crops, forests and soil processes, in order to address whole system issues and how to scale up to catchments or landscapes. In linking such models together it will be important to achieve balance in the level of detail with which different parts of the system are described and appropriate feedbacks between the sub-systems. Comparisons of model performance invariably show that bigger, more complex models are not necessarily better (e.g., de Willigen, 1991; Smith et al., 1997).

## References

Asseng, S., Keating, B.A., Gregory, P.J., Bowden, J.W., Turner, N.C., Fillery, I.R.P., Palta, J.A., Abrecht, D.G., 1998. Performance of the APSIM wheat model in western Australia. Field Crops Res. 57, 163–179.

de Willigen, P., 1991. Nitrogen turnover in the soil–crop system; comparison of fourteen simulation models. Fert. Res. 27, 141–149.

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.

Helyar, K.R., Porter, W.M., 1989. Soil acidification, its measurement and the processes involved. In: Robson, A.D. (Ed.), Soil Acidity and Plant Growth. Academic Press, Marrickville, pp. 61–101.

Hochman, Z., Braithwaite, S., Probert, M.E., Verburg, K., Helyar, K.R., 1998. SOILpH — a new APSIM module for management of soil acidification. In: Michalk, D.L., Pratley, J.E. (Eds.), Agronomy — Growing a Greener Future. Proceedings of the Ninth Australian Agronomy Conference, Wagga Wagga, pp. 709–712.

Jones, C.A., Cole, C.V., Sharpley, A.N., Williams, J.R., 1984. A simplified soil and plant phosphorus model: I. Documentation. Soil Sci. Soc. Am. J. 48, 800–805.

Littleboy, M., Silburn, D.M., Freebairn, D.M., Woodruff, D.R., Hammer, G.L., 1989. PERFECT — a computer simulation model of productivity erosion runoff functions to evaluate conservation techniques. Queensland Department of Primary Industries, Bulletin QB89005.

McCaskill, M.R., Blair, G.J., 1990. A model of S, P and N uptake by a perennial pasture. 1. Model construction. Fert. Res. 22, 161–172.

McCown, R.L., Keating, B.A., Probert, M.E., Jones, R.K., 1992. Strategies for sustainable crop production in semi-arid Africa. Outlook Agric. 21, 21–31.

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. Syst. 50, 255–271.

Nelson, R.A., Dimes, J.P., Paningbatan, E.P., Silburn, D.M., 1998. Erosion/productivity modelling of maize farming in the Philippine uplands. I. Parameterising the agricultural production systems simulator. Agric. Syst. 58, 129–146.

Nye, P.H., Tinker, P.B., 1977. Solute Movement in the Soil–Root System. Blackwell Scientific Publications, Oxford.

Palm, C.A., Myers, R.J.K., 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., Calhoun, F. (Eds.), Replenishing Soil Fertility in Africa. SSSA Special Publication No. 51, pp. 193–217.

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.

Paul, E.A., Clark, F.E., 1989. Soil Microbiology and Biochemistry. Academic Press, Orlando, FL.

Paydar, Z., Huth, N.I., Ringrose-Voase, A.J., Young, R.R., Bernardi, A.L., Keating, B.A., Cresswell, H.P., Holland, J.F., Daniels, I., 1999. Modelling deep drainage under different land use systems. 1. Verification and systems comparison. In: Oxley, L., Scrimgeour, F. (Eds.), Proceedings of the International Congress on Modelling and Simulation, Vol. 1. University of Waikato, Hamilton, New Zealand, pp. 37–42.

Probert, M.E., 1985. A conceptual model for initial and residual responses to phosphorus fertilizers. Fert. Res. 6, 131–138.

Probert, M.E., Okalebo, J.R., Jones, R.K., 1995. The use of manure on small-holders' farms in semi-arid eastern Kenya. Exp. Agric. 31, 371–381.

Probert, M.E., Dimes, J.P., Keating, B.A., Dalal, R.C., Strong, W.M., 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agric. Syst. 56, 1–28.

Ringrose-Voase, A.J., Paydar, Z., Huth, N.I., Banks, R.G., Cresswell, H.P., Keating, B.A., Young, R.R., Bernardi, A.L., Holland, J.F., Daniels, I., 1999. Modelling deep drainage of different land use systems. 2. Catchment wide application. In: Oxley, L., Scrimgeour, F. (Eds.), Proceedings of the International Congress on Modelling and Simulation, Vol. 1. University of Waikato, Hamilton, New Zealand, pp. 43–48.

Rodrigo, A., Recous, S., Neel, C., Mary, B., 1997. Modelling temperature and moisture effects on C–N transformations in soils: comparison of nine models. Ecol. Model. 102, 325–339.

Silburn, D.M., Connolly, R.D., 1995. Distributed parameter hydrology model (ANSWERS) applied to a range of catchment scales using rainfall simulator data. I: infiltration modelling and parameter measurement. J. Hydrol. 172, 87–104.

Smith, K.A., 1980. A model of the extent of anaerobic zones in aggregated soils, and its potential application to estimates of denitrification. J. Soil Sci. 31, 263–277.

Smith, P., Smith, J.U., Powlson, D.S., McGill, W.B., Arah, J.R.M., Chertov, O.G., Coleman, K., Franko, U., Frolking, S., Jenkinson, D.S., Jensen, L.S., Kelly, R.H., Klein-Gunnewiek, H., Komarov, A.S., Li, C., Molina, J.A.E., Mueller, T., Parton, W.J., Thornley, J.H.M., Whitmore, A.P., 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81, 153–225.

Snow, V.O., Bond, W.J., Myers, B.J., Theiveyanathan, S., Smith, C.J., Benyon, R.G., 1999. Modelling the water balance of effluent-irrigated trees. Agric. Water Mgmt. 39, 47–67.

Thornley, J.H.M., 1997. Grassland Dynamics: An Ecosystem Simulation Model. CAB International, Wallingford.

Verburg, K. (Ed.), 1996. Methodology in soil water and solute balance modelling: an evaluation of the APSIM-SoilWat and SWIMv2 models. Divisional Report No. 131. CSIRO Division of Soils, Canberra, Australia.

Verburg, K., Ross, P.J., Bristow, K.L., 1996. SWIM v2.1 User Manual. Divisional Report No. 130. CSIRO Division of Soils, Canberra, Australia.

Verburg, K., Hochman, Z., Probert, M.E., Keating, B.A., 1998. Soil acidification prediction and quantification using APSIM–SWIM. In: Michalk, D.L., Pratley, J.E. (Eds.), Agronomy — Growing a Greener Future. Proceedings of the Ninth Australian Agronomy Conference, Wagga Wagga, pp. 789–790.