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Simulation of legume–cereal systems using APSIM

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Abstract. A major issue for the sustainability of cropping systems is the maintenance of soil fertility and especially the supply of nitrogen to cereal crops. Choice of appropriate management strategies, including the role of legumes, is problematic, especially where climatic variation is large. Simulation models provide the means of extrapolation from the site- and season-specific bounds of experimental data to permit scenario analyses that can explore alternative management options.

This paper is a status report on the capabilities of the APSIM modelling framework to simulate legume–cereal systems. APSIM deals with water and nitrogen constraints to crop growth and is well suited to the task of modelling whole systems involving crop rotations. The components that are not yet fully developed are modules for growing the legume crops and coupling these with the module describing the dynamics of soil organic matter to obtain sensible predictions of nitrogen supply to subsequent crops. Evidence is provided that those parts of the system that can be represented by current APSIM modules are predicted satisfactorily. The closest approach to a whole system that has been simulated to date is grass or legume (*Stylosanthes hamata* cv. Verano) leys followed by crops of maize or sorghum grown in experiments at Katherine, NT. Predictions of the yields of the leys and the cereal crops, especially the benefit from the legume leys to a second crop, were sufficiently close to measured yields to suggest that there are good prospects for developing useful models of other systems involving legumes and cereals. A simulation scenario exploring a chickpea–wheat system demonstrates how models can be used to analyse both productivity and sustainability aspects of the system.

Additional keywords: farming systems, modelling, nitrogen, water.

Introduction

Legumes, when effectively nodulated with rhizobia, fix nitrogen from the atmosphere. Whereas non-leguminous plants depend on obtaining their nitrogen requirements from the soil, legumes are able to satisfy at least some of their nitrogen needs from a source that is not available to other plants. This fixed N is an input to the plant–soil system. When plant components are added to the soil (upon senescence, after crops are harvested, or after being grazed), any fixed N becomes part of the soil nitrogen cycle and may subsequently be used by other plants.

Important agricultural legumes can be divided into 3 groups: crops that are grown for their commodities (for example grain legumes), forage legumes that may be grazed or harvested for animal feed, and trees or shrubs in agroforestry systems. The contribution they make to the overall N balance of the farming system depends on 2 factors: how much nitrogen they fix and the proportion of this nitrogen that is returned to the soil. Crops where much of the nitrogen in the plant is removed in the harvested produce do not have as great a contribution as green manuring, where all of the crop is incorporated into the soil.

Continuous cereal systems, with no replacement of the nutrients being exported in the harvested crop, must ultimately deplete the soil of nutrients. Nitrogen is often the first nutrient to become limiting and

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when this occurs, crop yields and grain quality decline; protein content of cereal grain may decrease before yields are reduced. Inputs of nitrogen become essential and the only known sources are either imports as fertiliser and manures or symbiotically fixed N. How nitrogen is to be supplied to the cereal crops becomes a matter of economics. For the fertiliser option, the economics are relatively simple (especially if residual effects of the fertiliser are ignored) and the increased returns from the crop must pay for the fertiliser. The legume option is more complex, and must resolve the economics of the total enterprise. The legume phase of the system has value in its own right (as a saleable commodity or as animal feed) and also as a source of nitrogen for other crops, but at a cost in that it uses water and occupies land that otherwise could have been used to grow other cereal crops.

Coupled with the variability of climate, the interactions within legume–cereal systems are difficult to handle experimentally. Results will always be specific to site and season and effects may change from year to year depending on the distribution of rainfall; some aspects of system performance change relatively slowly in response to management; and there will be repercussions of management and crop sequences in following crops. Interpretation of experimental data is always likely to raise questions in relation to how the system would have responded to other treatments or management practices.

It is this complexity, in terms of both the management options and the economics, that makes a simulation capability an attractive tool for evaluating alternative strategies and providing the probabilistic information needed to assess risk (e.g. Keating *et al*. 1991). Models need to represent our understanding of the behaviour of the system, thereby providing a means for extrapolation beyond the experimental data base to other seasons and sites, and exploration of other scenarios and longer term issues. As well as being a component of the researcher's skills that are needed to understand and analyse system behaviour, we are finding that models have an important place in the dialogue between farmers, their advisers, and scientists that results in more informed decision making and changed management practices (Foale and Carberry 1996).

Modelling the legume–cereal system

There are certain features that a model must capture to be useful for analysing the management strategies that might be employed to improve the performance of a legume–cereal system. Those that focus on water and nitrogen as limiting factors affecting system performance include the ability to simulate:

(1) the growth and yield of all the crops and pastures that comprise the system, including situations where a legume is undersown with a cereal crop;
(2) the water balance for the system, estimating water use by crops and predicting the water available to following crops;
(3) the response of the crops and pastures to the soil nitrogen supply and inputs as fertiliser;
(4) the effect of crop residues on soil fertility through their impact on the dynamics of soil organic matter;
(5) (where applicable) the effects of grazing animals on the growth of pastures and redistribution of nitrogen via excreta.

Legumes also have a role in farming systems as break crops for control of diseases, pests, and weeds. However, limitations due to disease and pests, and also deficiencies of other nutrients, are outside the bounds of the models being discussed and the scope of this paper.

Crop modellers have generally concentrated on building models to simulate the growth and development of individual crops. Thus, most crop models have their own built-in routines that simulate the dynamics of soil water and nitrogen. This has been a major obstacle where the desire is to model systems where different crops are grown in succession or as mixtures. In addressing this issue, one approach has been to simplify the scale at which the system is simulated by using generic crop growth routines that trade-off some accuracy for an increased systems capability. The EPIC (Erosion Productivity Impact Calculator) model is a widely used systems model that has tended to follow this approach (Steiner *et al*. 1987). Another solution has been to take existing crop models and link them via user-environments such as the DSSAT (Decision Support System for Agrotechnology Transfer) software (Uehara 1989). More recent efforts have been targeted at specifically designing and developing modelling frameworks to deal with cropping systems, including the simulation of crops grown in rotation or as mixtures. The Agricultural Production Systems Simulator (APSIM) is such a modelling framework for simulation of farming systems that has been developed in Australia (McCown *et al*. 1996).

The Agricultural Production System Simulator

The APSIM modelling framework provides a suite of modules that can be configured to specify diverse farming systems. Modules are essentially 1-dimensional and are typically driven by daily climatic data (maximum and minimum temperature, radiation, and rainfall). Systems simulation is achieved by having the same modules that describe the status of soil water and soil organic matter interfaced with all of the various crop modules. As crops come and go, they encounter the system in some state, grow, thereby affecting the status of soil water and nitrogen, and leave the system in an altered state for a following crop. An intercropping situation is dealt with by having 2 or more crops 'growing' concurrently; the only additional requirement beyond what is needed to simulate sole crops is some rules to specify how the crops share, or compete for, the different resources of light, water, and nitrogen. The intercropping capability provides a means of dealing with competition between an undersown legume and cereal crops, between weeds and crops, or in mixed pastures.

Another feature of APSIM is its capability to 'farm' according to a set of rules. Where the desire is to simulate actual situations (for example the treatments from an experiment or the performance of the crops grown by a farmer) these rules specify the particular management of the system, and would include details of sowing dates for the various crops, plant densities, fertiliser inputs, tillage operations, etc. In other situations, however, it might be desired to simulate a hypothetical system where the management, including choice of crop, is responsive to the prevailing conditions such as rainfall, and the amount of water or mineral-N in the soil. APSIM, through its MANAGER module, provides the flexibility to do this.

The suite of crop and resource modules available in APSIM is not static. New modules are being developed by users to meet their requirements for particular purposes, whilst improvements are being made to existing modules. Table 1 lists the present status of modules that are of interest in the context of legume–cereal systems.

Table 1. APSIM modules of relevance to legume–cereal cropping systems

APSWIM is SWIMv2 by arrangement with CSIRO Land and Water and the cotton module is OZCOT by arrangement with CSIRO Plant Industry

Available	Under development	Planned
	Resource modules	
SoilN	APSWIM	
SoilWat		
Residue		
Erosion		
	Crop–pasture modules	
Sorghum	Cowpea	Annual medic
Maize	Soybean	Faba bean
Wheat	Lucerne	Lupin
Barley	Pearl millet	Lentil
Sunflower	Pigeonpea	
Peanut	Generic grass	
Cotton	Generic tree	
Chickpea		
Mungbean		
Stylosanthes		

The resource modules

The SOILWAT, SOILN, and RESIDUE modules are described by Probert *et al.* (1998), who show that these modules are capable of adequately simulating the changes in soil water and mineral-N during fallows (thereby avoiding complications that could arise if a crop module was not correctly predicting water use and nitrogen uptake) on both vertisols and alfisols. Furthermore, when used with various crop modules (for example wheat, maize, sorghum, sugarcane), crop growth and uptake of nitrogen by the crops are usually predicted satisfactorily thereby providing additional evidence that the dynamics of water and mineral N in soil are being well simulated.

SOILN simulates the dynamics of soil organic matter, not just nitrogen. The organic matter content of soil is controlled largely by the inputs of carbon to the system. In order to predict long-term changes in the nitrogen supply from the soil via mineralisation, it is necessary to have a description of both carbon and nitrogen. Under many continuous cropping systems, there is a decrease in soil organic matter content with a corresponding decrease in the soil's capacity to mineralise N (Dalal and Mayer 1986, 1987), which may occur even where fertiliser N is applied (Dalal 1992).

When cereals are grown in rotation with leys, especially leguminous leys, the benefit in terms of improved nitrogen supply arises from 2 sources. Firstly there is a contribution from any crop residues remaining from the previous crop. This source will be relatively short-lived, being restricted to the time during which the residues decompose, and the amount of nitrogen mineralised is determined by the C : N ratio of the residues. Net mineralisation occurs when there is more nitrogen in the residues than is needed to meet the demands of the microbes that are responsible for the decomposition, and this occurs when the C : N ratio of the residues is less than about 25.

The second source arises where there has been an increase in the soil organic matter content of the soil under the ley. When cropped, the soil organic matter content will decrease towards the steady state concentration that is commensurate with the cropping system and some of the nitrogen that had been incorporated into the soil organic matter during the ley phase is mineralised. The nitrogen supply to a sequence of cereal crops declines through time. For the initial crops following the ley, the additional mineralisation is out of proportion to the increase in the total content of soil organic matter that occurred during the ley. This indicates that there is a quality aspect of the soil organic matter; it does not behave as a uniform pool. In the APSIM SOILN module, as in many other models, this behaviour is accommodated by having 2 soil organic matter pools. The pool that turns over more rapidly is identified with the soil microbial biomass, though it is not yet clear exactly how the various soil organic matter pools should be defined or how we can measure soil properties that permit the conceptual pools in the models to be initialised and predicted behaviour validated. It is noteworthy that Parton *et al.* (1992) consider the active pool of soil organic matter in the CENTURY model to be 2–3 times larger than the live microbial biomass that is conventionally measured.

SOILWAT is a cascading water balance module that specifies the water characteristics of the soil in terms of the lower limit, drained upper limit, and saturated water contents in each layer. An alternative water balance module (APSWIM) is based on the simultaneous solution of Richards' equation for water flow and the convective-dispersion equation for solute transport (Ross 1990; Verburg *et al.* 1996). However, APSWIM is not yet available for use with all crop modules. Only modules for sugarcane and wheat currently have the necessary interfaces to use APSWIM.

The EROSION module deals with soil loss through erosion and has been based on the routines used by Littleboy *et al.* (1992). When erosion occurs, this module removes soil organic matter and mineral N from the top of the soil profile and reduces the thickness of the uppermost soil layer. Thus it provides means for erosion to influence both the nitrogen supply and the water storage capacity of the soil. To date, there has been little effort to apply this capability to the simulation of the effects of erosion on the long-term sustainability of Australian farming systems, but it has been applied to an erosion-prone system in the Philippines (Nelson *et al.* 1996).

The crop modules

The crop modules listed in Table 1 vary considerably in the extent to which they have been validated under different environments. The distinction between the 2 groups, 'available' and 'under development', reflects this to some degree. The 'under development' group is an indication that for these modules the key information needed to build the modules (for example the relationships for leaf area development, biomass accumulation, dry matter partitioning, phenological development, transpiration, and nitrogen uptake, etc.) is incomplete and/or few data sets are available to test them under a wide range of conditions.

Validation of all aspects of the model for some of the crop modules shown in Table 1 as 'available' may also be less than one would wish for. The performance of crop models typically focuses on how well they predict the various components of crop growth and development for individual crops. Claims that a model is performing satisfactorily are likely to be based on close agreement between observed and predicted phenology, leaf area, total above-ground biomass, grain yields, and nitrogen uptake. It is much less likely that testing of model performance will have included aspects such as the amount of soil water remaining in the soil at harvest or root biomass and its nitrogen content. Yet these are crucial aspects where the desire is to simulate a sequence of crops including effects on soil organic matter.

The goodness of performance for 3 crops modules that differ markedly in their degree of validation is illustrated below.

Wheat

Much effort, over several years, has been directed towards modelling cereal crops (maize, sorghum, and wheat) under the range of climatic conditions encountered in northern Australia. The APSIM modules for these crops generally perform well in terms of predicting phenology, leaf area, total above-ground biomass, grain yield, and nitrogen uptake; the modules for these crops have also been shown to perform satisfactorily in terms of the soil water balance. Fig. 1 shows an example of the predictive ability of the wheat module

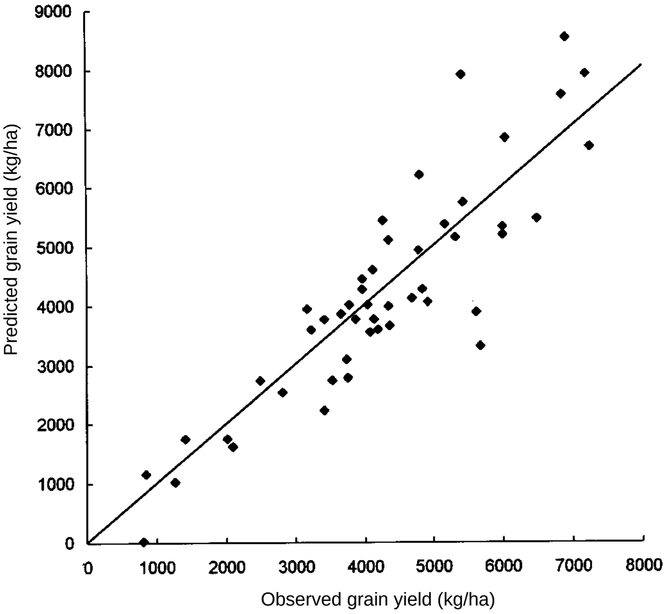

Fig. 1. Comparison of observed and predicted grain yields of wheat grown at Gatton, Qld (1992–95), for various nitrogen treatments, water regimes and planting dates. Line of best fit: Predicted yield = $1\cdot03\times$observed yield − 207 ($R^2 = 0\cdot78$) (Data source: unpublished data of B. A. Keating and M. E. Probert.)

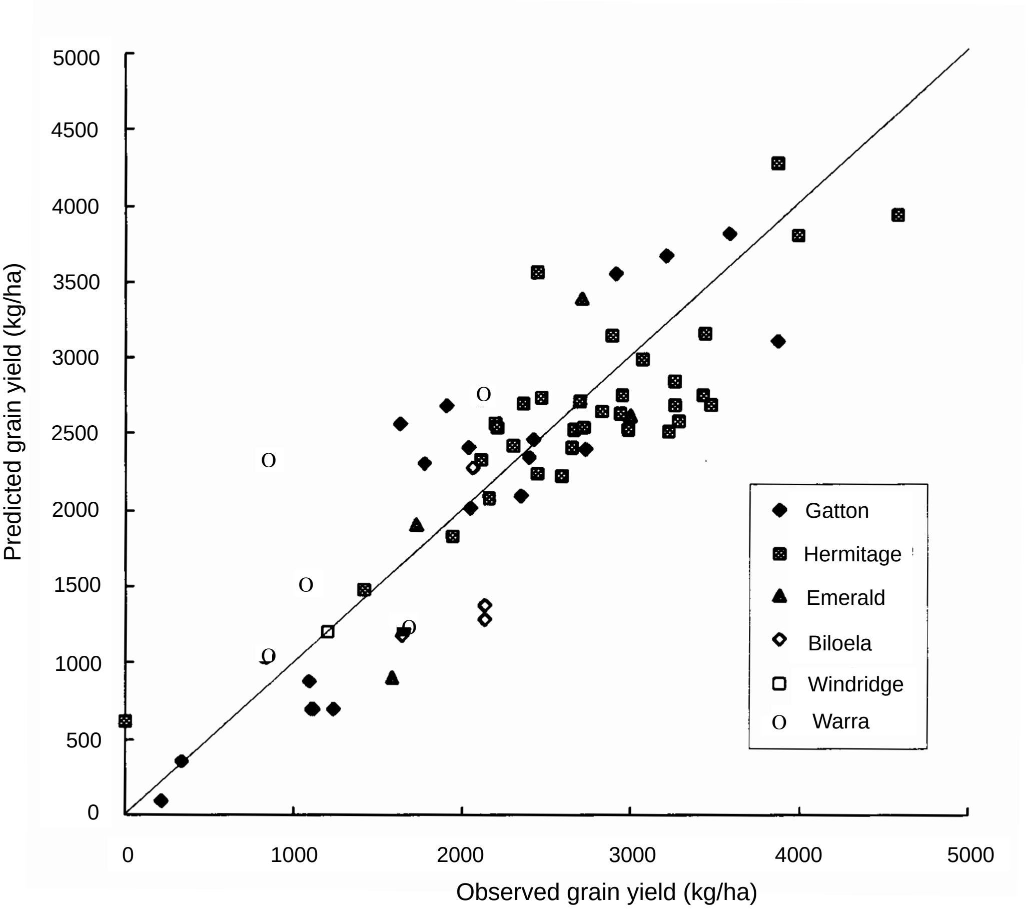

Fig. 2. Comparison of observed and predicted grain yields of chickpea at several sites. Line of best fit:

$$\text{Predicted yield} = 0\cdot 82\times\text{observed yield}+381\ (R^2 = 0\cdot 74)$$

(Data sources: unpublished data of P. S. Carberry, R. Brimsmead, R. C. Dalal, and H. Marcellos.)

for a number of wheat crops grown at Gatton, Qld, during 1992–95 with a range of nitrogen inputs and under different moisture regimes. In each case the model has been initialised with values for soil organic carbon, mineral N, and soil water prior to planting, but otherwise this constitutes a validation of the model.

A more demanding test of the wheat module has been presented by Probert *et al.* (1995) when they endeavoured to simulate, as a continuous run, the sequence of yields observed in a long-term experiment. They showed that such simulations can be very sensitive to carry-over errors in the water balance from one crop to the next. They encountered instances where the observed N response by the crop was incorrectly predicted because of errors in simulation of water use by the preceding crop. Such difficulties will be no less important when we come to simulating rotations of crops.

Chickpea

The chickpea module has been subjected to considerably less testing than the cereal modules. Experimental data are available from several sites, some of which experienced water stress during crop growth, and agreement between observed and predicted yields is shown in Fig. 2. However, to date there has been little progress in testing whether the model accurately predicts water remaining in the soil at the end of the crop or how the growth of a chickpea crop, through its above-ground residues and roots, influences the nitrogen status of the soil.

Lucerne

This is an example of a crop module that is still under development. The experimental database for developing the module comes from 1 site under non-

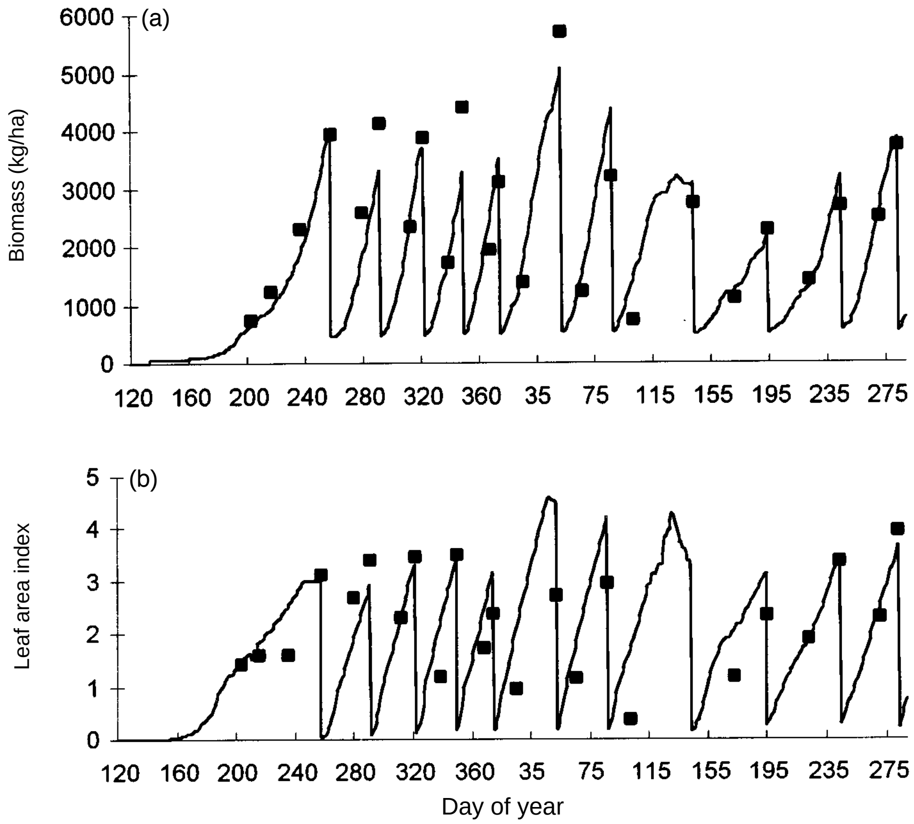

Fig. 3. Comparison of observed and predicted (*a*) above-ground biomass (kg/ha) and (*b*) leaf area index of lucerne grown at Gatton, Qld. Observed data shown as symbols, predictions as lines. The crop was cut using a forage harvester each time it flowered. (Data source: unpublished data of M. E. Probert and R. L. McCown.)

water-stressed condition. Data for light interception, radiation use efficiency, partitioning of dry matter into leaf and stem, and nitrogen concentrations in these components have enabled the generic APSIM crop template to be specified for lucerne. Fig. 3 shows the predicted dry matter yields and leaf area index through a series of harvests over a period of approximately 18 months. This module has not yet been tested across a range of environments, and especially under conditions of water stress, nor in regard to how the growth of lucerne affects soil organic matter.

Simulation of legume–crop rotations

It is obvious from the above that all of the ‘building blocks’ needed to simulate legume–crop rotations are not yet in place. However, in progressing towards this objective, we are able to test the performance of parts of the model under restricted conditions, thereby assessing whether the concepts embodied in the models are capable of capturing certain aspects of the system behaviour.

Systems involving added residues

Probert and Keating (1996) reported an experiment where 3 different residue treatments (none, lucerne hay, and barley straw) were incorporated into soil in factorial combination with 4 rates of applied nitrogen fertiliser and a wheat crop grown. Measurements were made through the growth of the crop to determine biomass and N uptake, and also soil microbial biomass and mineral-N. Simulation of this experiment shows generally good agreement between observed and predicted yields of biomass and grain, and nitrogen uptake by the crop. Fig. 4 illustrates the comparison between observed and predicted grain yields.

The treatment that was simulated least well was where barley straw had been added without fertiliser. The pattern of response in the soil microbial biomass indicated a tendency for the model to predict too rapid decomposition of the barley straw, thereby immobilising too much nitrogen (Probert and Keating 1996). In essence the model predicts that under circumstances where residues with high C : N ratio are present, the soil microbes win out over the plant for the small

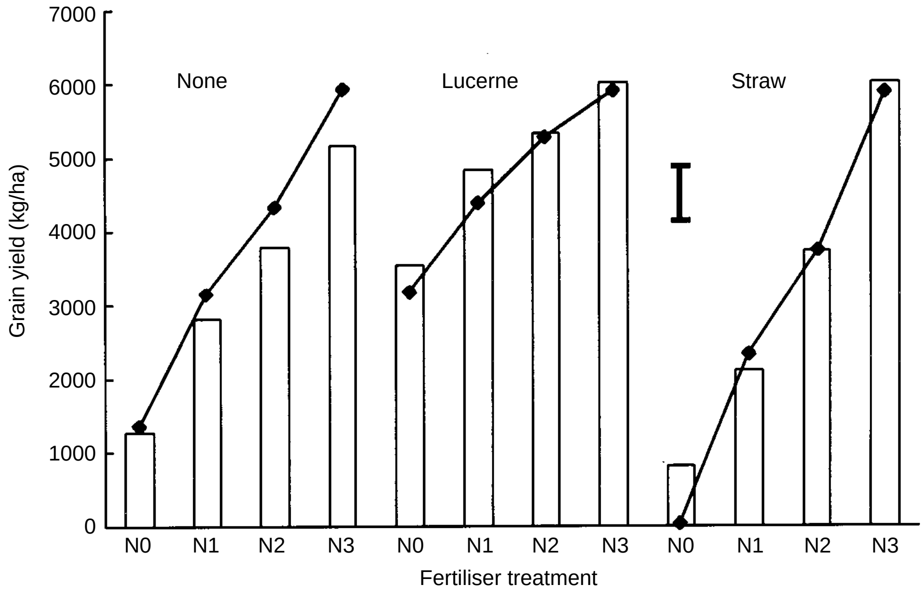

Fig. 4. Comparison of observed (bars) and predicted (symbols and lines) grain yields of wheat at Gatton, Qld. The experiment comprised 3 residue treatments (none, or 4 t/ha of either lucerne hay or barley straw that was rotovated into the soil 26 days prior to sowing) in factorial combination with 4 rates of application of fertiliser N (N0–N3, 0, 40, 80, 200 kg/ha). Error bar denotes the least significant difference ($P = 0{\cdot}05$) between treatment means based on the error derived from an analysis of variance of the observed data. (Data source: unpublished data of B. A. Keating and M. E. Probert.)

amount of mineral N available in the soil. In reality the plant was able to obtain enough N to make some growth. Any short-coming in how the decomposition of residues is modelled in the SOILN module, and especially the effect of their C : N ratio, arises in the first few weeks after incorporation. Over a longer time span, such as normally occurs during the fallow between harvest of one wheat crop and planting of the next, simulation of the accumulation of nitrate has been shown to be satisfactory (Probert *et al.* 1998).

Effects of preceding legume leys

Turpin *et al.* (1996) used APSIM to simulate crop yields for the experiments conducted by Holford (1980, 1989), who examined the effects of lucerne leys on subsequent production of wheat and sorghum on a black earth compared with a continuous cereal system. In performing these simulations, it was necessary to make assumptions as to how the legume ley had altered the partitioning of the soil organic matter into its more and less labile components. The model was then used to predict the growth of the following crops. The simulations for the sorghum phase agreed closely with the experimental results in that the relative yield, defined as the quotient of the yield following the ley and the yield for the continuous cereals without nitrogen fertiliser, was increased to approximately 2 in the first 2 seasons after the ley had been ploughed out and then declined over the next 2 seasons. For the wheat phase, the agreement between the model and the observed data was not good. The model produced expected behaviour (as indeed it must because it is based on conventional wisdom), but the experimental results indicated surprisingly large residual effects from the ley, persisting for up to 8 years after the ley had been removed. Experimental data for mineral N in soil for these experiments are rather sparse, but such data as do exist show good conformity with predictions for the mineral N in the 0–15 cm layer during the wheat phase (Turpin *et al.* 1996).

This study demonstrates that APSIM is capable of representing the supply of nitrogen to cereal crops following a legume ley. However, it raises questions about the assumptions concerning how the lucerne phase had changed the soil organic matter status of the soil, and whether such effects can be simulated when using a model to 'grow' the lucerne ley.

Grass and stylo ley–cereal systems in the Northern Territory

To date, the only 'whole' systems involving rotations of legumes and cereals where observed data can be compared with simulations using APSIM relate to farming systems in the Northern Territory. Carberry *et al*. (1996) described the performance of APSIM modules for maize, sorghum, and stylo (*Stylosanthes hamata* cv. Verano) against experimental data sets from Katherine, NT, including situations where maize was grown with an understorey of the legume and stylo–sorghum rotations. APSIM was able to reproduce the measured yields as sole crops, as intercrops, or in rotations.

The experiments reported by Jones *et al*. (1996) encompassed a wider range of ley management. They compared the growth and responsiveness to nitrogen fertiliser of 2 maize crops following grass and stylo leys that were of 1 and 3 years duration. The model was initialised prior to establishment of the leys and the simulation carried out as a continuous run over both the leys and the following crops, so that the soil properties were simulated in response to the growth of the leys under the imposed management practices. For the stylo leys, there were 3 treatments: rotovated at the end of each growing season (green manure), a hay treatment where the above-ground material was removed, and a standing treatment where the material was allowed to stand from one season to the next.

Performance of the model, judged by yields and nitrogen uptakes of the leys and the maize crops, was generally good, with the model capturing the greater benefit of the legume on nitrogen uptake by maize where it had been incorporated or left standing compared with where it had been removed as hay. The effects of the leys were still evident in the second maize crop, and this also was captured by the model. For those experiments there was no direct means of verifying the predictions of changes in the soil organic matter and especially the more labile biomass pool, but the inference can be drawn that they must have been responding in sensible ways in order to predict the nitrogen supply to following maize crops.

A chickpea–wheat rotation

We conclude this section on the simulation of legume–crop rotations by presenting the output for a hypothetical chickpea–wheat rotation as an example of how models permit analysis of different scenarios. For this example, we have not attempted to simulate any particular experiment, mainly because experiments containing adequate data for modelling have only recently become available.

The soil specified was a clay soil that is typical of those found on the Darling Downs, Qld. It has an available soil water capacity of 260 mm to a depth of 1·8 m and organic carbon content of the surface 0–10 cm of 0·8% with a soil C : N ratio of 14·5. The weather data were for Brookstead. Six cropping systems were modelled over 25 years commencing in 1971. These were 4 continuous wheat systems with varying nitrogen fertiliser inputs (0, 40, 80, and 120 kg/ha applied at sowing) and both phases of a chickpea–wheat rotation without applied fertiliser. Crops were planted in response to a rainfall event of 25 mm over 5 days in a 90-day window commencing on 1 May.

Some output from these simulations is shown in Fig. 5. In terms of average annual wheat yields, the site was responsive to fertiliser N. The average chickpea grain yield was 2810 kg/ha. The benefit of the chickpea crops to the following wheat crop was equivalent to approximately 40 kg of N applied as fertiliser. The effect of growing the legume was also evident in the soil nitrate at the time of planting the next crop. Averaged over all years, 42 kg/ha of nitrate-N was present in the profile prior to planting in the unfertilised continuous wheat treatment compared with 118 kg/ha following chickpea. Although the average yield of chickpea and the increase in nitrate-N seem rather high, this pattern of response is similar to what has been found experimentally for chickpea–wheat rotations (e.g. Felton *et al*. 1998; Marcellos *et al*. 1998).

The year-to-year variation in rainfall masks any discernible trend in unfertilised wheat yields through time (data not shown). In contrast, there were clear trends in the simulated soil data. Continuous wheat cropping for 25 years without any input of fertiliser resulted in declining soil organic matter and nitrogen. The losses were greatest in the near surface layers, amounting to more than 40% of the total nitrogen initially present in the 0–30 cm soil layer (Fig. 5*b*). The inclusion of the legume in a rotation with wheat considerably reduced the degradation of soil fertility, as did inputs of nitrogen fertiliser.

This example demonstrates how a model (that has been adequately validated to ensure that its output is believable) will be useful for addressing aspects of cropping system performance in terms of both productivity and sustainability issues.

Discussion

To simulate legume–cereal rotations sufficiently well that the models can be used confidently to analyse the behaviour of dryland cropping systems in northern Australia is a demanding challenge. In this paper, we have described progress in developing APSIM for this purpose. It has been shown that APSIM modules are capable of capturing many of the features of these systems, notably the response of cereal crops to inputs of crop residues and fertiliser N (Fig. 4) and, with some assumptions about how a legume ley modified soil organic carbon, the nitrogen supply to subsequent crops (Turpin *et al*. 1996). Our experience in sim-

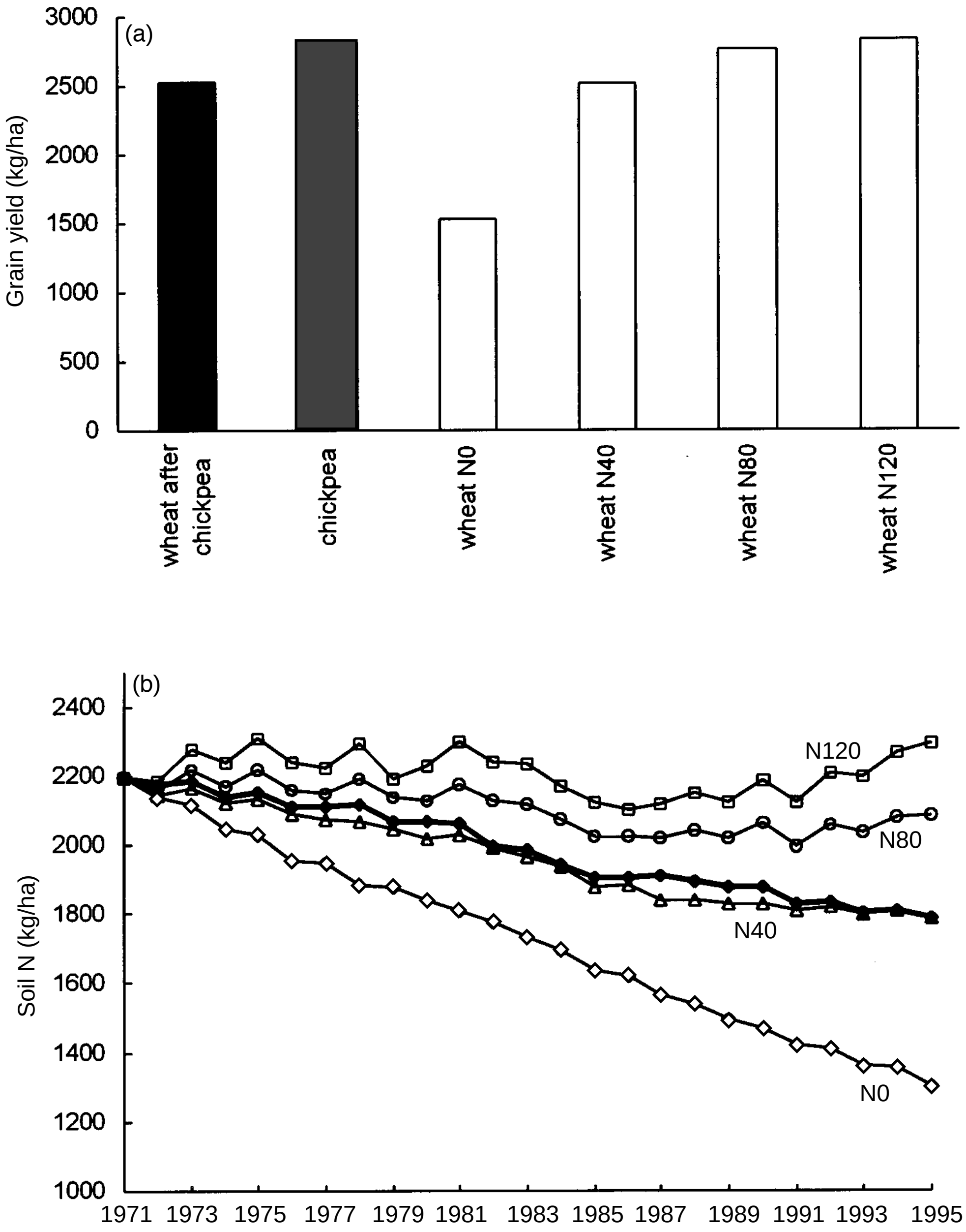

Fig. 5. Simulation of different cropping systems over 25 years on a clay soil at Brookstead, Qld. (*a*) Average grain yields for continuous wheat (annual input of 0, 40, 80, 120 kg/ha of fertiliser N) compared with yields of wheat and chickpea grown in rotation without fertiliser N. (*b*) Changes predicted to occur in total soil N in the 0–30 cm layer; solid diamonds and bold line refer to the average of the 2 phases of the chickpea–wheat rotations, open symbols to the various rates of N application (kg/ha) for continuous wheat as indicated.

ulating the experiments at Katherine, where maize and sorghum crops followed grass and legume leys of different duration and with different management practices, is encouraging. Although the task is not yet complete, we suggest that development of a simulation capacity for a range of legume–cereal systems is now achievable.

The key to success will be the progressive development of the building blocks that ultimately make up a model of a whole system. The modules for the cereal crops and those describing the dynamics of water, soil organic matter, and surface residues have been tested under a range of conditions and generally perform adequately. The dynamics of the decomposition of incorporated residues (especially during the first few weeks) have been identified as an aspect of the SOILN module that needs improvement. Modules for the legumes of interest are at a less advanced stage of development.

The creation of modules that adequately simulate the growth of individual crops, where the model can be initialised to specify soil water and mineral nitrogen prior to sowing, is a necessary and important part of the process. But the challenge of being able to use the same modules to simulate a sequence of crops, where the soil conditions are carried forward from crop to crop, should not be underestimated. The efforts of Probert *et al.* (1995) highlighted that even in the case of continuous wheat crops there could be problems with carryover effects from crop to crop. In their case, the problem was largely associated with predicting soil water remaining in the soil at harvest. When it comes to crop rotations involving legumes, the issue of soil water will be no less important. In addition, there will be the issue of simulating how the nitrogen supply of the soil responds to the growing of the different crops.

It remains to be shown that the conceptual soil organic matter pools, as represented in the model, are responding sensibly to residues, including roots, from previous crops (especially after legume crops). Ideally this would be achieved by direct measurement of the various pools. However, there are some methodological problems. For example, it is not known with certainty what the more active soil organic matter pool consists of, how large it is, or how it can be determined. Few experiments that examine effects of rotations on supply of nitrogen to subsequent crops have investigated the changes that are occurring to the organic matter components of the soil. The alternative is to show that the model can accurately predict the nitrogen supply to a sequence of crops and infer from this that the conceptual pools in the model are responding sensibly. Poor understanding of the amounts of carbon and nitrogen in roots and the timescale over which root material ceases to be part of the crop and enters the soil system (for example the sloughing of roots and the response of root systems to above-ground defoliation) causes uncertainty in the fluxes of carbon and nitrogen into and out of the various pools of the model.

In this paper, we have ignored the effects of grazing animals. However, for many systems where legumes are grown in rotation with cereals, the grazing animal is an important component that has an influence on the distribution and dynamics of carbon and nitrogen. There is therefore a requirement for models that do include the effects of grazing. The pasture and animal models of CSIRO's GRAZPLAN project (Freer *et al.* 1997; Moore *et al.* 1997) have this capability. Linking of the GRAZPLAN models and APSIM modules into a common software framework is now under way.

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