Europ. J. Agronomy 18 (2003) 267–288

European Journal of Agronomy

www.elsevier.com/locate/eja

An overview of APSIM, a model designed for farming systems simulation

B.A. Keating[a,*], P.S. Carberry[a], G.L. Hammer[b], M.E. Probert[a], M.J. Robertson[a], D. Holzworth[a], N.I. Huth[a], J.N.G. Hargreaves[a], H. Meinke[b], Z. Hochman[a], G. McLean[b], K. Verburg[c], V. Snow[c], J.P. Dimes[a,d,e], M. Silburn[e], E. Wang[b], S. Brown[a], K.L. Bristow[c], S. Asseng[f], S. Chapman[b,f], R.L. McCown[a], D.M. Freebairn[e], C.J. Smith[c]

[a] *CSIRO Sustainable Ecosystems/APSRU, 120 Meiers Road, Indooroopilly, Qld 4068, Australia*
[b] *Department of Primary Industries/APSRU, Toowoomba, Qld, Australia*
[c] *CSIRO Land and Water/APSRU, Canberra, Australia*
[d] *ICRISAT, Bulawayo, Zimbabwe*
[e] *Department of Natural Resources and Mines/APSRU, Toowoomba, Australia*
[f] *CSIRO Plant Industry, Perth, Australia*

Abstract

The Agricultural Production Systems Simulator (APSIM) is a modular modelling framework that has been developed by the Agricultural Production Systems Research Unit in Australia. APSIM was developed to simulate biophysical process in farming systems, in particular where there is interest in the economic and ecological outcomes of management practice in the face of climatic risk. The paper outlines APSIM's structure and provides details of the concepts behind the different plant, soil and management modules. These modules include a diverse range of crops, pastures and trees, soil processes including water balance, N and P transformations, soil pH, erosion and a full range of management controls. Reports of APSIM testing in a diverse range of systems and environments are summarised. An example of model performance in a long-term cropping systems trial is provided. APSIM has been used in a broad range of applications, including support for on-farm decision making, farming systems design for production or resource management objectives, assessment of the value of seasonal climate forecasting, analysis of supply chain issues in agribusiness activities, development of waste management guidelines, risk assessment for government policy making and as a guide to research and education activity. An extensive citation list for these model testing and application studies is provided.

Keywords: Farming systems modelling; APSIM; Simulation model

1. Introduction

Agricultural Production Systems Simulator (APSIM) is a modelling framework that allows

---

* Corresponding author. Tel.: +61-7-32142373; fax: +61-7-32142308

E-mail address: brian.keating@csiro.au (B.A. Keating).

PII: S1161-0301(02)00108-9

individual modules of key components of the farming system (defined by model developer and selected by model user) to be 'plugged in' (McCown et al., 1996). APSIM has been developed by the Agricultural Production Systems Research Unit (APSRU), a collaborative group made up from CSIRO and Queensland State Government agencies. Development started with the formation of APSRU in 1991 and the effort has grown from an initial team of 2 programmers and 6 scientists (actively engaged in model design and elaboration) to the current team of 6 programmers and software engineers and 12 scientists.

The initial stimulus to develop APSIM came from a perceived need for modelling tools that provided accurate predictions of crop production in relation to climate, genotype, soil and management factors, whilst addressing long-term resource management issues in farming systems. In 1991, we were influenced by the strength of models like CERES and GRO distributed by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project (Uehara and Tsuji, 1991) and subsequently linked together in the DSSAT shell (Jones et al., 1998). We were also influenced by the phenomenological approaches to crop modelling pioneered by Sinclair (1986). We also recognised at this time that these stand-alone crop models did not address important 'systems' aspects of cropping. These aspects included dealing with rotations, fallows, residues, crop establishment, crop death, dynamic management decisions that were responsive to weather or soil conditions, longer term soil processes such as loss or organic matter, soil erosion, structural degradation, soil acidification and so on. We were also familiar with simulators such as NTRM (Shaffer et al., 1983), CENTURY (Parton et al., 1987), EPIC (Williams, 1983) and PERFECT (Littleboy et al., 1989) and recognised the strengths of these models in dealing with the fate of the soil resources in the long term, but recognised their limited ability to address crop management issues where accurate simulation of crop yields in response to weather, genotype and management practices was required (Steiner et al., 1987). APSIM was designed at the outset as a farming systems simulator that sought to combine accurate yield estimation in response to management with prediction of the long-term consequences of farming practice on the soil resource (e.g. soil organic matter dynamics, erosion, acidification etc.).

2. Overview of the APSIM system and its components

The APSIM modelling framework is made up of;

a) a set of biophysical modules that simulate biological and physical processes in farming systems,
b) a set of management modules that allow the user to specify the intended management rules that characterise the scenario being simulated and that control the conduct of the simulation
c) various modules to facilitate data input and output to and from the simulation,
d) a simulation engine that drives the simulation process and controls all messages passing between the independent modules.

These elements of the APSIM framework have been illustrated by the 'spider diagram' (Fig. 1), which more correctly represents a 'hub and spokes' metaphor. Framework in this context refers to a set of structures that support the higher order goal of farming systems simulation.

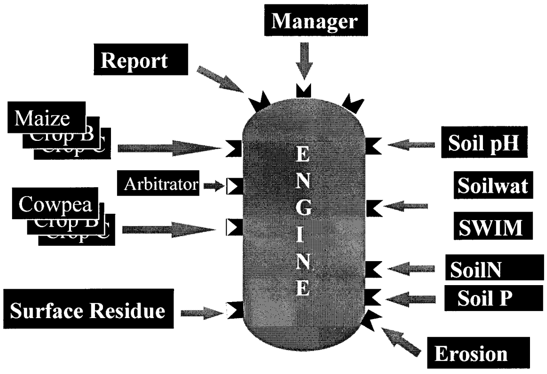

Fig. 1. Diagrammatic representation of the APSIM simulation framework with individual crop and soil modules, module interfaces and the simulation engine.

In addition to the science and infrastructure elements of the APSIM simulator, the framework also includes:

a) various user interfaces for model construction, testing and application (e.g. APSFRONT, APSIM-Explorer, APSWIZ),
b) various interfaces and associated database tools for visualisation and further analysis of simulation output (e.g. APSGRAPH, APSIM-Outlook),
c) various model development, testing and documentation tools (e.g. APSEUDO, APSTOOL) and
d) a web-based user and developer support facility that provides documentation, distribution and defect/change request tracking capability (e.g. www.apsim-help.tag.csiro.au).

While APSIM includes a generic simulation framework, it can only be applied in situations where the appropriate biophysical modules are available. In this respect, APSIM's capability is most developed for cropping systems, with crop modules available for the majority of the grain and fibre crops grown in temperate and tropical areas. APSIM's strongly modular design (Jones et al., 2001) has made it possible to easily build links to component models developed by other groups. An example of this has been the inclusion of the plant aspects of the OZCOT model (Hearn, 1994) from CSIRO Plant Industry in the APSIM framework. One important crop missing from APSIM's current capability is rice, and a rice module is currently under development in collaboration with the International Consortium for Agricultural Systems Applications (ICASA) group.

Only limited capability currently exists within APSIM modules to address pastures and there is currently no well developed capability to address animal production systems issues involving meat, dairy or wool production. Collaboration with the group in CSIRO Plant Industry responsible for the GRASSGRO/GRASFEED models (Donnelly et al., 1994) seeks to enable more seamless linkages between APSIM and these other modelling frameworks (Wright et al., 1997). The inclusion of a generic forest module for APSIM (Huth et al., 2001) has recently expanded the range of farming systems that can be addressed. This capability is being applied to both production forestry systems as well as natural vegetation systems. One of the most active areas of biophysical module development for APSIM has been with respect to soil processes. Modules exist for soil water, solute movement, soil nitrogen (including organic matter dynamics), soil phosphorus, soil pH, and erosion. In addition, APSIM includes a modules on soil surface residue dynamics, with linkages to water and nutrient processes.

APSIM version 1 (last release was ver 1.61 in 30th May 2000) was restricted to a single point simulation, something that is generally considered to represent a paddock with uniform soil and management. With the release of APSIM version 2 on 24th February, 2001, a multi-point capability has been included in the simulation infrastructure. This means that multiple instances of any APSIM module can be created at the outset or during a simulation. The elaboration of APSIM science modules to make use of this new software capability is the subject of current research. The issues receiving attention include; agroforestry systems, in which multi-point simulations of tree–crop interface zones are being explored (Huth et al., 2001), crop–animal interactions, in which a multi-paddock representation of a farming system is needed to address animal management issues, on-farm water capture and storage, in which a farm dam module is developed, filled from farm runoff or irrigation supplies and used to supply water to multiple paddocks growing crops at the same time. While these multi-point capabilities are not well developed or widely applied as yet, they are expected to have a large impact on the utility of APSIM over the next 5 year period in its development.

3. Details of APSIM components

3.1. Crops, pastures and forest

APSIM contains an array of modules for simulating growth, development and yield of crops, pastures and forests and their interactions with the soil. Currently crop modules are available for barley, canola, chickpea, cotton, cowpea, hemp, fababean, lupin, maize, millet, mucuna, mungbean, navybean, peanut, pigeonpea, sorghum, soybean, sunflower, wheat and sugarcane. In addition there are general modules for forest, pasture and weed as well as specific implementations for the pasture species lucerne and stylo. Citation details for these modules are provided where available in Table 1. The scientific bases of simulation approaches employed for all functional components are included in module documentation on the APSIM web site (www.apsim-help.tag.csiro.au). In the majority of cases these science documents include information on module performance against observed data.

The plant modules simulate key underpinning physiological processes and operate on a daily time step in response to input daily weather data, soil characteristics and crop management actions. The crop modules have evolved from early versions for focus crops such as maize (Carberry and Abrecht, 1991), peanut (Hammer et al., 1995), sorghum (Hammer and Muchow, 1991) and sunflower (Chapman et al., 1993). The initial crop modules of APSIM utilised concepts from existing models available at the time (e.g. Jones and Kiniry, 1986; Sinclair, 1986) and added concept enhancements from local research to improve existing models as required.

Currently in APSIM, all plant species use the same physiological principles to capture resources and use these resources to grow. The main differences are the thresholds and shapes of their response functions. Descriptions of these processes are covered by Wang et al. (2003). Many of these processes have been coded into sub-routines in a process library, held in a stand-alone module, which individual crops can call. The routines in the library are structured in separate blocks corresponding to the crop model components of phenology, biomass, canopy, root system, senescence pools, water, nitrogen and phosphorus. The sub-modules contain the science and understanding needed to simulate major functional components of crop growth and development. Crop ontogeny is simulated via relationships defining observed responses to temperature and photoperiod (e.g. Hammer et al., 1982; Birch et al., 1998). Leaf area production and senescence is simulated

Table 1
Current crop modules in APSIM and relevant references

APSIM module	Original model	References	APSIM module	Original model	References
Barley			Navybean		
Canola		Robertson et al. (1999)	Pasture		
Chickpea		Robertson et al. (2001c)	Peanut	QNUT	Robertson et al. 2001a
Cotton	OZCOT	Hearn and Da Rosa (1985)	Pigeonpea		Robertson et al. 2001a
Cowpea	APSIM-cowpea	Adiku et al. (1993)	Sorghum	QSORG AUSIM-Sorghum	Hammer and Muchow (1991, 1994), Carberry and Abrecht (1991)
Hemp		Lisson et al. (2000a)	Soybean		Robertson and Carberry (1998)
Fababean			Sunflower	QSUN	Chapman et al. (1993)
Forest		Huth et al. (2001)			
Lupin					
Maize	AUSIM-maize	Carberry and Abrecht (1991)	Wheat	Nwheat and I_Wheat	Keating et al. (2001), Meinke et al. (1998)
Lucerne		Robertson et al. (2001b), Probert et al. (1998a)	Stylo		
Millet		van Oosterom et al. (2001)	Sugarcane		Keating et al. (1999a)
Mucuna					
Mungbean		Robertson et al. (2001d)	Weed		

via relationships of leaf initiation rate, leaf appearance rate and plant leaf area with temperature (e.g. Keating and Wafula, 1991; Hammer et al., 1993; Carberry et al., 1993a,b). Potential crop water uptake is simulated via relationships with root exploration and extraction potential, which depends on soil and crop factors (e.g. Meinke et al., 1993; Robertson et al., 1993). All coefficients for general crop responses and crop/cultivar specific coefficients are stored external to the code to allow ease of use and transition across crops/cultivars. The process library includes a number of options for modelling specific functions and processes, which have been drawn from a range of existing APSIM crop models. The ability to switch between optional processes within sub-modules or between optional entire sub-modules facilitates logical comparative analysis of modelling approaches. The process library has substantially reduced the amount of code needed for simulating multiple crops, resulting in greater transparency, more robust code with lower maintenance costs.

Externalised constants and parameters from the code are stored in crop parameter files. Each file is considered as crop species-specific. It consists of two major parts: crop-specific constants and cultivar-specific parameters. Within some individual crop species the category of a ‘crop class’ has been developed. The crop class represents a category of crop below that of the species and is distinctly different enough to justify a separate parameter section. An example of the use of the crop class concept would be the identification of plant and ratoon crops of sugarcane as distinct crop classes. The separation of code and parameters makes it easy to re-parameterise an existing module for a new crop with few source code changes and significantly accelerates testing and validation procedures. An instance of many of the crop modules can be created and the parameter values from the crop parameter file of a similar crop can be evaluated if simulation of a new crop becomes necessary. This facilitates a quick means by which a module developer can ‘derive’ the first version of the model for the new crop. This is particularly helpful when expensive experimental data are not available.

Plant module development in APSIM continues to evolve towards the concept of a generic template as described by Wang et al. (2003). Such a template, often referred to as a ‘crop template’ but potentially applicable beyond just crops, provides a means to capture unifying principles, testing new insights, and comparing approaches to component modelling, while maintaining a focus on predictive capability. The crop template is based on the concepts described by Hammer (1998) and Wang et al. (2003). All crops are simulated with the same code, with each species being a specific instance and parameterised through its own crop parameter file. The ability to simulate processes using different simulation approaches is met using switches that are specified in the crop parameter file. All crops use the same interface with other modules in APSIM, and there is there is a common set of variable names. A group consisting of scientists responsible for crop model development and software engineers and programmers responsible for APSIM code development and maintenance oversees the evolution of the crop template. Currently versions exist for cereals (Wang et al., 2003), legumes (Robertson et al., 2001c), sugar cane (Keating et al., 1999b) and forest (Huth et al., 2001) and the extent to which a single generic template can be achieved across this range of vegetation types is the subject of on-going research.

3.2. Soil water balance and solute movement

In APSIM there are modules for the two major modelling approaches that are commonly used for the soil water balance, namely cascading layer and Richard’s equation methods.

SOILWAT (Probert et al., 1998c) is a cascading layer model that owes much to its precursors in CERES (Ritchie, 1972; Jones and Kiniry, 1986) and PERFECT (Littleboy et al., 1989, 1992). It operates on a daily time step. The water characteristics of the soil are specified in terms of the lower limit (LL15), drained upper limit (DUL) and saturated (SAT) volumetric water contents of a sequence of soil layers. The thickness of each layer is specified by the user; typically layer thickness of 100 or 150 mm is used for the uppermost layer and

300–500 mm at the base of the profile; the whole profile might be represented by up to 10 or more layers. As with all layered models, the empirical soil parameters are influenced by the number and thickness of specified layers.

Processes represented in SOILWAT, adapted from a long history of ‘cascading bucket’ style water balances such as WATBAL (Keig and McAlpine, 1969) and CERES (Ritchie, 1972; Jones and Kiniry, 1986) include:

- runoff which is calculated using a modified USDA curve number approach, that include effects of soil water content, soil cover both from crop and crop residue, and roughness due to tillage.
- evaporation which is based on potential evaporation (Priestly–Taylor or Penman–Monteith) and modified according to the cover provided by surface residues or growing plant
- saturated flow which occurs when any layer ‘fills’ above DUL; a specified proportion (swcon) of the water in excess of DUL drains to the next layer
- unsaturated flow at water contents below DUL where gradients in soil water content occur between layers (e.g. in response to rainfall events or evaporation)
- movement of solutes associated with saturated and unsaturated flow of water are calculated using a ‘mixing’ algorithm whereby existing and incoming solutes and water are fully mixed to determine the concentration of solute in the water leaving any layer.

Processes adapted from PERFECT includes (i) the effects of surface residues and crop cover on modifying runoff and reducing potential soil evaporation and (ii) specification of the second stage evaporation coefficient (*cona*) as an input parameter, providing more flexibility for describing differences in long-term soil drying due to soil texture and environmental effects. The module is interfaced with the RESIDUE and crop modules so that simulation of the soil water balance responds to change in the status of surface residues and crop cover (via tillage, decomposition and crop growth). Enhancements beyond CERES and PERFECT include (i) specification of swcon for each layer, being the proportion of soil water above DUL that drains in 1 day, (ii) isolation from the code of the coefficients determining diffusivity as a function of soil water (used in calculating unsaturated flow) and (iii) inclusion of code to simulate perched water tables (Asseng et al., 1997).

APSWIM is based on a numerical solution of Richards’ equation combined with the convection-dispersion equation to model solute movement. The implementation in the APSIM model is based on the ‘stand alone’ SWIMv2.1 (Soil Water Infiltration and Movement; Verburg et al. (1996a)). SWIM has it’s own internal time step which is governed by the magnitude of water fluxes in the soil, i.e., larger fluxes lead to smaller time steps). Parameterisation of the soil water properties for APSWIM requires specification of the moisture characteristic and hydraulic conductivity relationships in each soil layer. Runoff is dealt with by considering surface roughness. This capability to detain surface water can change through time, e.g. increasing as a result of cultivation, or decreasing due to the impact of raindrops. Infiltration into soils that seal or crust are dealt with through the conductance of an infinitely thin surface membrane. As for surface roughness, seal conductance can also be specified to vary in response to rainfall or tillage.

Both modules (e.g. SOILWAT and SWIMv2) are one-dimensional and do not consider lateral flow or horizontal heterogeneity. Some soil water issues can be represented better by the more mechanistic approach in APSWIM involving the simultaneous solution of the flux equations describing the sources and sinks and the re-distribution of water in the whole profile. Examples are the ability to specify alternative boundary conditions at the base of the profile, to handle effects of surface sealing, and to represent soils with an abrupt change in soil texture (duplex soils). Connolly et al. (2001) used APSWIM to explore soil–crop interactions associated with crop-pasture rotations. The ability to explicitly represent changes in soil hydraulic properties using SWIM added value to this analysis. However for many applications, 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).

3.3. Soil organic matter and nitrogen

The evolution of APSIM was foremost as a modelling framework for simulation of cropping systems in response to climate and management. 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., 1998c) can be traced back via CERES models (e.g. Jones and Kiniry, 1986) to PAPRAN (Seligman and van Keulen, 1981).

A distinction from CERES (as developed in CERES-Maize, Jones and Kiniry, 1986) is that crop residues that are on the soil surface are handled by the RESIDUE module. This has been done so that surface residues can have an impact on the soil water balance through runoff and evaporation.

The greatest change that has been made from CERES is that the soil organic matter in APSIM is treated as a three pool system, instead of the two pools used in CERES. 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). However decomposition of FOM results in formation of soil organic matter comprising the BIOM and HUM pools. The BIOM pool is notionally the more labile organic matter associated with soil microbial biomass; whilst it makes up a relatively small part of the total soil organic matter, it 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 enable better representation of situations where ‘soil fertility’ improves following a legume ley. A single soil organic matter pool can not deal realistically with such situations. Another weakness that had been identified with CERES was that treating all the soil organic matter as being equally susceptible to mineralisation results in unrealistic rates of mineralisation in the sub-surface soil layers. This, together with the lack of a full carbon balance, made use of CERES for long-term simulations of soil organic matter content inappropriate. In SOILN, a portion of the stable organic matter pool is considered to be inert and thus not susceptible to decomposition; this provides a means of preventing decomposition of soil organic matter in the deeper soil layers.

The release of nitrogen from the decomposing organic matter pools is determined by the mineralisation and immobilization processes that are occurring. The carbon that is decomposed is either evolved as CO_2 or is synthesized into soil organic matter. APSIM assumes that the pathway for synthesis of stable soil organic matter is predominantly through initial formation of soil microbial biomass (BIOM), though some carbon is 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 formation of BIOM and HUM thus creates an immobilization 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 during the decomposition process in excess of the immobilization demand results in an increase in the ammonium-N.

The rates of decomposition of the various soil organic matter pools are dependent on soil temperature and soil water content of the layers where decomposition is occurring. In those circumstances where there is inadequate mineral N to meet an immobilization demand the decomposition process is halted. Other processes dealt with in SOILN are nitrification, denitrification and urea hydrolysis.

3.4. Residues

The surface residue module (RESIDUE) has been described by Probert et al. (1998c). Crop residues are added to 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, new weighted (mass) average values are calculated to describe the total amount of residues present.

The amount of residue may decrease due to:

(1) Removal of residue (e.g. by burning or baling); such action does not alter the C:N ratio of the residues.

(2) Incorporation of residues in the soil. A tillage event transfers a proportion of the surface residues into the soil FOM pools to a nominated depth.

(3) Decomposition in situ. The decomposition routine is similar to that used for the soil organic matter pools in the SOILN module. Any immobilization demand is met from the surface soil layer, whilst the soil organic matter formed and ammonium-N mineralised is added in to the surface soil layer. The temperature dependency is related to mean ambient temperature. Because the soil water balance does not include the litter layer, the moisture dependency is assumed to be unconstrained immediately after rainfall, 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. (2000, 2001) have investigated the importance of the contact factor for sugarcane systems that involve large amounts of surface residues (up to 20 t/ha).

Much of the tillage incorporation and cover relationships are retained from PERFECT (Littleboy et al., 1989, 1992, 1996), but a more mechanistic basis for the decomposition of surface residue decomposition was required to maintain the carbon and nitrogen balances.

3.5. Phosphorus

Unlike the management of N, there has been little need for detailed crop models to evaluate alternative strategies for management of P (Probert and Keating, 2000). Particularly in high input agricultural systems there are few prospects for improving management of P beyond recommendations for amount and method of application of fertiliser. Empirical relationships between yield and soil P tests have been adequate to gain insights into crop responsiveness to alternative fertiliser P sources and their residual effects. However this is not the case for low input systems. Many soils on which subsistence crops are grown are deficient in both N and P and the inputs used (manures, composts) are potentially sources of both N and P. Integrated nutrient management, involving the combined use of organic and inorganic sources of nutrients, is promoted as the sustainable means of managing soil fertility in the tropics.

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 have also required modification; P uptake needs to be simulated and P stress in the plant calculated so that crop growth is constrained under P limiting conditions. Challenges in incorporating P constraints into crop growth models include scale issues. Understanding of P uptake focuses largely at the dimension of the root radius, but most crop modelling assumes soil systems are uniform within soil layers (e.g. for water and nitrogen). The SOILP and MANURE models have been developed in collaboration with researchers at the International Crops Research Institute for the semi-arid tropics (ICRISAT) and tropical soil biology and fertility (TSBF)/International Center for tropical agriculture in India and Africa and are currently being evaluated under a range of field conditions.

3.6. SOILpH

The APSIM SOILpH module 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) (Verburg et al., 2001b).

SOILpH is based on the proton balance of Helyar and Porter (1989). These authors showed how the balance of hydrogen ions in the soil–plant system can be calculated and related to changes in soil pH. All the fluxes of protons, especially those associated with nitrogen transformations on a soil layer basis, can be predicted in soil–plant models. Accordingly SOILpH uses the simulation of N and 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).

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 currently 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. Soil processes such as mineralisation, nitrification and urea hydrolysis are pH dependent. Whilst the SOILN module does include routines to represent the effects of pH on the dynamics of soil C and N, its ability to capture the consequences of soil acidification on N mineralisation or C balance has not been studied.

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.

3.7. EROSION

Soil erosion by water from a hillslope or paddock scale is calculated using runoff volume from SOILWAT, cover from RESIDUE and crop modules, and sediment concentration calculated using either of two options:

(1) The model of Rose (1985), which calculates daily average sediment concentration as a function of cover and user defined parameters: land slope, soil parameter 'efficiency of entrainment'. The bed and suspended load components of soil loss can be calculated separately, e.g. where suspended load is required as an index of off-site impacts (M. Silburn, unpublished).

(2) An equation from PERFECT (Littleboy et al., 1992), based on Freebairn and Wockner (1986), which calculates daily average sediment concentration from a cover-concentration function, modified using the USLE slope-length, erodibility and practice factors to provide generality. Thus USLE soil erodibility values can be used as a starting point for estimating soil loss, but the model is not constrained to calculating annual average soil loss and is linked to runoff rather than rainfall erosivity. The cover-concentration function was derived from measured data (Freebairn and Wockner, 1986) and is more suitable for Vertisols than the USLE cover factor. The model also performed well on Alfisols (Littleboy et al., 1996).

These daily models accounts for variation in soil loss with cover and runoff volume, the main factors that can be managed, but will not predict the variation in erosion due to within day variation in rainfall intensity and runoff rates. They are intended to get long-term soil loss reasonably correct and to correctly predict the relative differences between management systems, rather than to accurately predict individual soil loss events.

Effects of erosion on productivity are modelled, based on routines from PERFECT, by reducing the soil water, N, P and organic matter stores as erosion progresses. The EROSION module and erosion-productivity simulation were evaluated by Nelson et al. (1998a,b).

3.8. MANAGER

The early recognition that all the possible management configurations required of the simulator could not be explicitly identified and addressed a priori, led to the development of the MANAGER module in APSIM. This module enables users to apply simple concepts of states, events, actions and conditional logic to build complex management systems whose scope goes well beyond anything envisaged by the early developers. The MANAGER must be present in all APSIM configurations and it provides control over individual components and the overall simulation. This module 'manages' by issuing messages to other modules in the system, many of which are conditional upon states or events within the modules during simulation. It also allows the user to create their own variables and define these as a function of other variables within APSIM. The MANAGER script files are prepared by users defining the intended simulation and are compiled at runtime.

The APSIM MANAGER module can be used to invoke any action available by any module. Possible actions include:

- Resetting individual module values.
- Reinitialising all data in modules to a given state.
- Sowing, harvesting or killing crops.
- Applications of fertiliser, irrigation or tillage to soil.
- Calculation of additional variables to track system state.
- Reporting of system state in response to events and/or conditional logic.

A full range of mathematical operators and functions can be used in APSIM MANAGER files.

3.9. Intercropping/weeds/mixed species systems

In APSIM, crop modules communicate at daily intervals with resource-supply modules only via the APSIM engine. The effect of one crop on another is therefore simulated by its influence on the level of resource stocks/fluxes supplied by the radiation, water and nitrogen modules. The absence of any direct communication among crop modules in APSIM is the key versatility in modelling inter-species competition. APSIM allows for any number of the biological modules to compete on a daily basis via allocation rules specified wholly within an 'Arbitrator' module that is linked to the APSIM engine along with the competing crop modules. This approach can be used successfully to simulate allocation of light, water, and nitrogen to competing APSIM modules. Carberry et al. (1996a) have described the scientific basis to simulating competition in APSIM.

Evaluation of APSIM's capability to simulate competition in intercrops or crop-weed mixtures has taken place in: (i) maize and cowpea intercropped under a range of soil water and fertility conditions, and with the cowpea planted at different times relative to the maize planting time (Carberry et al., 1996a) (ii) growth and yield of maize and an undersown *Stylosanthes hamata* pasture (Carberry et al., 1996a) and (iii) yield of canola and an associated weed (*Raphanus raphanistrum* L) with the weed sown at a range of densities and times relative to the time of sowing of the canola (Robertson et al., 2001c). Application of the competition capability in APSIM has been as diverse as exploring weed management in cropping systems (Keating et al., 1999a; Robertson et al., 2001c), productivity tradeoffs between components in low-input intercropping (Carberry et al., 1996a), and comparing alternative novel farming systems that integrate perennial and annual species to manipulate seasonal water use (Keating et al., 2001). Simulating multi-species mixtures will find increasing application as APSIM is applied to more complex issues in farming systems.

3.10. Multi-point simulations

Recent developments on the inter-module communications protocol have led application of APSIM to issues which contain a spatial component. The modules within APSIM are essentially point-based models which represent behaviour of the system at some single point in space. The new software design allows the point-based models to be instantiated multiple times within a single simulation, with communication of data between each discrete point in space. For example, a simulation of a farming enterprise may contain individual simulations of each management unit or paddock. The management of each unit can be based on the state of other units, thus allowing the simulation of a broader range of farm management issues.

Huth et al. (2001) illustrate the use of this functionality to simulate discrete points within the zone of influence of a windbreak. In this case, the simulated state of the trees within the windbreak is used to alter the below-ground competition and microclimatic effects of the windbreak at various distances from the trees. The resource use by the trees from the soil in paddock feeds back into the calculations for tree productivity. Investigations are commencing into the use of this capability for the simulation of the hydrology of hillslopes which water is routed between discrete portions of a catchment. There is no technical constraint to the number of discrete simulation points, though more complex configurations will place greater demands on computer processing power.

4. Data requirements

An APSIM simulation is configured by specifying the modules to be used in the simulation and the data sets required by those modules. APSIM modules typically require initialisation data and temporal data as the simulation proceeds. Initialisation data is usually categorised into generic data (which defines the module for all simulations) and simulation specific parameter data such as site, cultivar and management characteristics.

Typical site parameters are soil characteristics for soil modules, climate measurements for meteorological modules, soil surface characteristics and surface residue definition. Management is specified using a simple language to define a set of rules, calculations and messages to modules that are used during the simulation.

Data is currently stored in keyword free format grouped into sections stored in text files. Keyword format is in the form *keyword* = *value* (*units*)! *description*, sections are defined by a section header of the form (*data_name.module_name.parameter_type*). The order of keywords and location of sections is defined by the user. Temporal data such as climate and observed measurements are stored in free format columns headed with parameter names and units. The order of columns is arbitrary. A configuration file specifies the modules to be used in the simulation and a control file specifies each simulation with associated data files and section names for each module locate its data. Further details on the data input requirements for individual APSIM modules can be found at www.apsim-help.tag.csiro.au.

5. Software implementation

5.1. APSIM software

APSIM modules implement a specific simulation process and communicate with other modules via a central simulation engine. Modules are completely self-contained ‘black boxes’, responsible for their own reading of parameters and internal configuration and can be written in any programming language. The user has the capability of plugging different combinations of modules together to configure APSIM for different simulations. The simulation engine is a simple message passing system whose sole function is to pass messages from a given source module to its destination. Direct module-to-module communication is not allowed, providing a loose intermodule coupling or independence. This design allows developers to test and compare different approaches for a given process in a controlled way and allows new simulation capability to be added quickly without requiring wholesale system modifications. Users have the ability to precisely configure a given simulation, allowing them to select the level of detail that is appropriate.

To help with the selection and parameterisation of the modules, two user interfaces are provided targeting different segments of the user population. APSIM Explorer is aimed at module developers and those users wanting access to the full APSIM capability. It is modelled on the traditional integrated development environment that comes with most compilers. It provides links to editors, compilers, debuggers and the other tools these types of users require. It provides full access to all APSIM parameters via simple text files.

APSFront, shields the user from these complexities allowing them to focus on the problem domain. The user selects pre-built weather, soil, crop and management functions. These functions have various options that provide a finer level of configuration. Libraries of these functions have been built up over time and cover different areas of simulation capability.

Both simulation configuration interfaces also provide links to two different simulation output visualisation packages. APSVIS provides raw simulation output graphics in several different formats e.g., scatter plots, probability plots, frequency plots and depth plots. APSIM Outlook provides a richer set of analysis tools allowing the user to perform gross margin analyse on simulation outputs. These analyses can then be filtered and charted in several different formats and related to other data sources, such as the phases of the Southern Oscillation Index.

Key processes used in APSIM software engineering include:

- All software is stored in an automatically backed-up version control system. This allows developers to compare different versions of source or document files. It also allows the SEG to recreate any previous version of APSIM.
- All software is automatically extracted from the version control system each night and then built from scratch. This build is then run over a set of regression tests. The outputs of these tests are then checked each morning for errors. This helps remove unexpected simulation output changes—*the ripple effect*.
- All defects and changes are managed through a central database system. This system allows assigning and tracking of all user specified defects and change requests.
- All software engineering tasks are tracked, with times spent on each task recorded. This improves our estimation of how long future tasks will take.

A web-based defect/change management system and the procedures database supports this software engineering effort. The APSIM help desk also provides the APSIM user community with the latest release of APSIM, full APSIM documentation, a method for submitting defect reports or change requests and a entry point for all APSIM related queries and questions.

6. Model testing

The comparison of APSIM simulations with observed data has been conducted by many model users under a wide range of conditions. A recent inventory of papers and reports that contain some detail of APSIM predictions against observed data identified 55 items. This list has been loaded onto the APSIM help web site (www.apsim-help.tag.csiro.au) and is not repeated here for reasons of space.

Some of the key reports that include model test results are listed in Table 2. The key citations for individual modules (Table 1) also generally contain testing results.

Some studies focused on the performance of individual crop modules (e.g. Asseng et al., 1998b; Keating et al., 1999b, 2001). Other reports focused on performance of particular soil modules in the absence of a growing crop (e.g. Probert et al., 1998c). Because APSIM was intended to be a model that could be applied to complex farming systems issues, the reports that compare model predictions with farming system performance over long-term crop/forage rotations are particularly important (e.g. Probert et al., 1995; Jones et al. 1996; Probert et al., 1998b; Paydar et al., 1999; Probert and McCown, 2000). The most useful model evaluation reports are those that have examined predicted and observed values of a range of plant and soil state variables over an extended period. Studies that include a range of treatments are also of great value. An example of an excellent

Table 2
A subset of the reports on APSIM testing

Study	Major focus	Key references
Test data sets for SOILWAT and SOILN modules	Soil water balance and soil nitrogen balance in the absence of crops	Probert et al. (1998c)
Hermitage long-term trial, southern Qld	Tillage and residue retention effects on continuous what systems with differing levels on N fertiliser inputs	Probert et al. (1995), Turpin et al. (1996)
Warra long-term trial, southern Qld	Crop growth, yield, N uptake, soil water and soil nitrogen balance for continuous wheat, wheat/grain legume and wheat/lucerne rotations on a run-down heavy clay soil	Probert and McCown (2000)
Test data sets for the NWheat module	Wheat growth, yield, N uptake and protein in relation to soil water and soil N supply, as influence by fertiliser inputs and residue inputs	Keating et al. (2001)
Runoff plot studies in southern Qld	Agronomic/runoff studies at 4 sites (Fairlands, Billa Billa, Goodger and Greenmount) in southern Queensland were used to test APSIM-SWIM's prediction of runoff, soil water, and crop growth in a cropping system context at the large plot or contour bay scale	Connolly et al. (2001)
Cropping systems at Katherine, NT	Crop and soil dimensions of legume-cereal systems on a red-earth soil in a semi-arid tropical environment	Probert et al. (1998b), Jones et al. (1996)
Liverpool Plains, NSW	Water balance and crop/forage production in different rotations on a heavy black cracking clay	Paydar et al. (1999)
Lucerne modelling in Qld, WA and NZ	Lucerne dry matter, N content and water balance in different environments	Probert et al. (1998a), Moot et al. (2001), Dolling et al. (2001)
Wheat systems in WA	Wheat growth and yield and soil water and nitrogen balance for sands and duplex soils in the WA wheat belt	Asseng et al. (1995, 1997, 1998a,b, 2000, 2001)
Effluent irrigation trials in southern Australia	Water and nitrogen balance in forest systems in southern Australia irrigated with effluent	Snow and Dillon (1998), Snow et al. (1998, 1999a,b)
Sugarcane systems	Sugarcane growth and yield and water and N balance at various locations within the sugar industry	Keating et al. (1997, 1999a), Inman-Bamber and Muchow (2001)
International studies: Africa	Maize and grain legumes in low input farming systems in Zimbabwe	Robertson et al. (2000a), Shamudzarira and Robertson (2000), Shamudzarira et al. (2000)
International studies: Netherlands	High input wheat systems in Netherlands	Asseng et al. (2000)

data set for testing the robustness of APSIM's systems modelling capability is that collected by Dalal et al. (1995). This data set consists of wheat based farming system on the Darling downs of south-east Queensland, Australia. The modelling of this long-term trial has been reported by Probert and McCown (2000). Examples of some of the comparisons between simulated and observed data are shown in Fig. 2a and b. In these studies, the model was initialised at the start of the experiment and allowed to simulate the system state continuously without resetting over the 10 year period of the observed data. The good agreement between predictions and observations for soil water, soil nitrogen, crop biomass and crop yield demonstrates the model's validity and robustness in these circumstances. Model performance was good at both low and high nutrient input for both continuous wheat/fallow systems (Fig. 2a) and wheat/lucerne rotations (Fig. 2b).

7. Model application

A recent search for reports of APSIM applications identified 107 items published over the 1996–2001 period. This list of citations and where possible, the associated reports have been loaded onto the APSIM web site (www.apsim-help.tag.csiro.au). These applications can be classified into

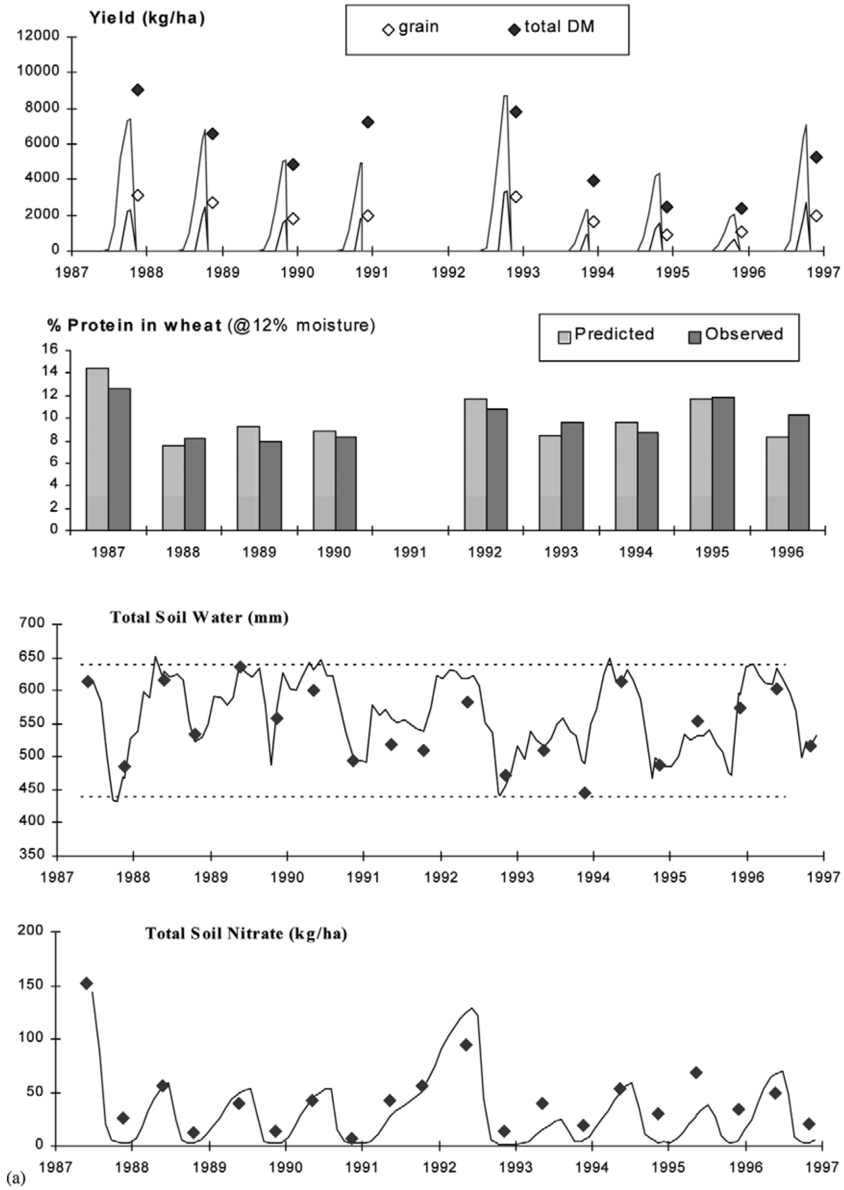

Fig. 2. (a) Simulation of yields and protein content of wheat, and soil water and nitrate-N for a continuous wheat treatment at Warra, with conventional tillage and without fertiliser N. The symbols represent the measured data. For the yield data, the date of harvest for the measured data has been offset by 27 days so that the symbols do not obscure the predicted data. Soil water and nitrate refer to the totals in the 0–1.5 m profile. The dashed lines on the soil water figure show the assumed DUL and LL for wheat. (Measured data from R. Dalal and modelling after Probert and McCown, 2000). (b) Simulation of wheat and lucerne yields, protein content of wheat, and soil water and nitrate-N for the lucerne-wheat rotation treatment at Warra, southern Qld, Australia. Other details as for Fig. 2a.

eight categories, namely crop management, water balance, climate impacts, cropping systems, species interactions, land use studies, soil impacts (erosion, acidity and nitrate leaching) and crop adaptation/breeding (Table 3). These applications are so diverse it is impossible to provide a concise summary. Suffice it to say the applications extend from highly practical use in on-farm decision

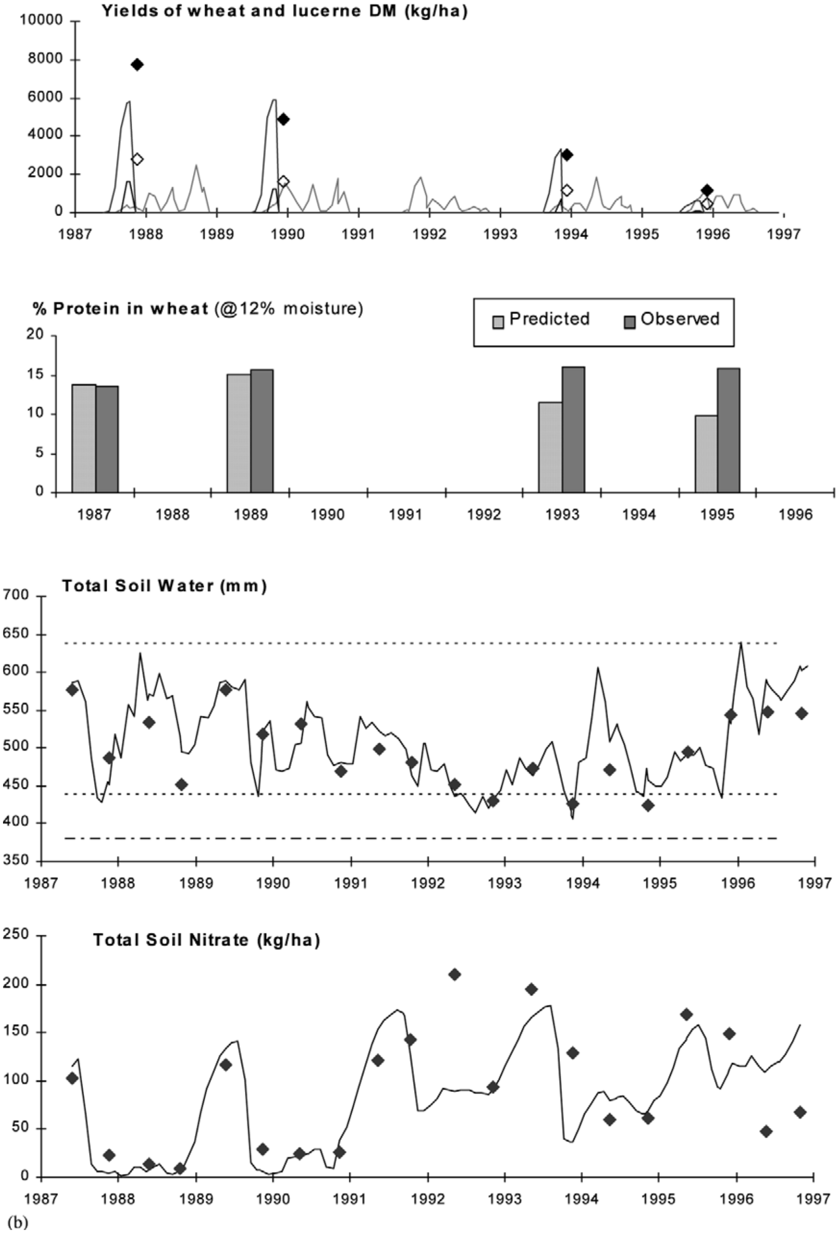

Fig. 2 (*Continued*)

making through to more research focused applications in which current and alternative farming system designs have been explored. Both production and resource management issues have featured prominently in model application.

8. Closing the loop between development and application

Testing simulation models in realm of science has typically involved an assessment of how well they simulate measured experimental data and how plausibly they represent system behaviour in normative scenario applications targeted at exploring what land managers should do to improve system performance—the preceding sections provide numerous references to the scientific testing of APSIM. The question remains, however, as to how well simulation models perform in relation to real-world agriculture and whether they have been able to gain credibility within industry. Such questions have been the focus of the FARMSCAPE program of research activities (McCown et al., 1998) which tested and applied APSIM in everyday farming practice (Hochman et al., 2000) and in agribusiness practice (Brennan et al., 2001).

The FARMSCAPE program recognised early on that, if we wanted to explore ways in which farmers could better manage their farms, then these farmers needed not just to be consulted on the design of what should be done, but they also needed to participate in the implementation of the research and the interpretation of its outcomes. In other words, instead of using scientific models to build derivative tools which we scientists believed could help farm managers—for instance computerised Decision Support System, which historically have been poorly adopted by farmers (McCown, 2001)—we took APSIM out onto farms and asked farmer and agribusiness collaborators to design and test applications for their own situations (Hochman et al., 2000). What emerged has been confirmation of the benefits of farmers gaining better knowledge of their soil resources and the discovery of a role for APSIM in assisting the management of cropping systems (Coutts et al., 1998). FARMSCAPE has helped demonstrate that the key to farm managers valuing simulation is the positioning of these simulations in the context of their own farming situation. A simulator enables information to be specified to an individual paddock, its results can be tested against one's own crop performance and a simulator such as APSIM can be used to explore a range of issues (Carberry and Bange, 1998). APSIM's credibility and applicability has been tested and endorsed in Australian farming systems as evidenced by demand for its access and commercial delivery (Carberry, 2001; Hochman et al., 2001).

9. Distribution policy

APSIM distribution is managed via a licence system that protects the integrity of the product, meets the legal liability requirements of our

Table 3
Summary of reports of APSIM application over the 1996–2001 period

Category	Number of reports	Examples
Crop management	22	Inman-Bamber and Muchow (2001), Keating et al. (1997), Muchow and Keating (1997), Robertson et al. (2000b, 2001d)
Water balance	12	Asseng et al. (2001), Dunin et al. (1999), Ringrose-Voase et al. (1999), Snow et al. (1999a), Verburg et al. (2001a)
Climate risk and impacts	22	Carberry et al. (in press), Cheeroo-Nayamuth et al. (2000), Hammer et al. (1996a), Keating and Meinke (1997), Meinke and Hammer (1995a), Reyenga et al. (1999)
Cropping systems	14	Carberry et al. (1996b), Lisson et al. (2000b), Probert et al. (1998b)
Intercropping and species interactions	4	Carberry et al. (1996a), Carberry et al. in press, Keating et al. (1999b)
Land use studies	6	Meinke and Hammer (1995b), Rosenthal et al. (1998)
Soil impacts (erosion, acidity, organic matter, leaching)	20	Connolly et al. (1999), Nelson et al. (1998b), Snow et al. (1999b), Thorburn et al. 2000; Verburg et al. (1996b, 2001b)
Crop adaptation/breeding	7	Hammer et al. (1996b), Robertson et al. (1997)

institutions and enables an orderly development pathway. Many large modelling efforts in the agricultural research community have been devalued by uncontrolled model evolution that has led to multiple versions of unknown pedigree. We have tried to address this problem by implementing a strict version control and distribution system, the principles of which apply both internally and externally to the core development group. Users can form partnerships with developers to develop new routines and modules, but this happens in a managed way with proper version control and system testing. The training and support requirements for successful application in a complex R&D program can be substantial. For this reason, licences are issued only once it is clear that these training and support requirements can be met. A demonstration version can be directly downloaded from the APSIM help web site, and can be used to assess model capability without the need to establish a licence. The fully flexible version requires a user specific key for installation and a licence that specifies the intended application and support arrangements. Collaborative arrangements for joint module development are often established. Source code of all science modules is available in html format on the APSIM help web site. This html formatted material provides a clear exposition of the science in the APSIM modules. The original source code is available in situations where an agreed program of joint development is taking place.

Acknowledgements

We are grateful to the many colleagues who have shared their data for model development/testing and their approaches to modelling plant and soil processes. While we have tried to recognise the efforts of the development team in the authorship of this paper, there are many others not recognised who have made significant contributions to the utility of the current product. We acknowledge in particular the effort of Drs Val Veraart and Sid Wright, who taught us the value of software engineering. We also acknowledge the inputs of collaborating institutions, in particular CSIRO Plant Industry, CRC for Sustainable Sugar Production, ICRISAT, CIMMYT, TSBF and Australian agribusiness and farmers. While APSIM has been developed with core resources from CSIRO and the Queensland State Government, funding for its application has been critical to its development and in particular we acknowledge support from Grains R&D Corp., Rural Industries R&D Corp., Sugar R&D Corp., Land and Water Australia and Australian Center for International Agricultural Research.

References

Adiku, S.K., Carberry, P.S., Rose, C.W., McCown, R.L., Braddock, R., 1993. Assessing the performance of maize (*Zea mays*—cowpea (*Vigna unguiculata*)) intercrop under variable soil and climate conditions in the tropics. Proceedings of the Seventh Australian Society of Agronomy Conference, September, Adelaide, South Australia, p. 382.

Asseng, S., Keating, B.A., Fillery, I.R.P., 1995. Wheat crop simulation in a Mediterranean environment on duplex soil. In: Binning, P., Bridgman, H., Williams, B. (Eds.), Proceedings of MODSIM 95, International Congress on Modelling and Simulation. The University of Newcastle, vol. 455, NSW, Australia, pp. 62–67.

Asseng, S., Keating, B.A., Huth, N.I., Eastham, J., 1997. Simulation of perched water tables in a duplex soil. In: Proceedings of the International Conference on Modelling and Simulation, 8–10 December 1997, Hobart, Tasmania, Australia: Modelling and Simulation Society of Australia, vol. 2, pp. 538–543.

Asseng, S., Fillery, I.R.P., Anderson, G.C., Dolling, P.J., Dunin, F.X., Keating, B.A., 1998a. Use of the APSIM wheat model to predict yield, drainage, and NO-3 leaching for a deep sand. Aust. J. Agric. Res. 49, 363–378.

Asseng, S., Keating, B.A., Fillery, I.R.P., Gregory, P.J., Bowden, J.W., Turner, N.C., Palta, J.A., Abrecht, D.G., 1998b. Performance of the APSIM-wheat model in Western Australia. Field Crops Res. 57 (2), 163–179.

Asseng, S., van Keulen, H., Stol, W., 2000. Performance and application of the APSIM Nwheat model in the Netherlands. Eur. J. Agronomy 12, 37–54.

Asseng, S., Fillery, I.R.P., Dunin, F.X., Keating, B.A., Meinke, H., 2001. Potential deep drainage under wheat crops in a Mediterranean climate. 1. Temporal and spatial variability. Aust. J. Agric. Res. 52, 45–56.

Birch, C.J., Hammer, G.L., Rickert, K.G., 1998. Temperature and photoperiod sensitivity of development in five cultivars of maize (*Zea mays* L.) from emergence to tassel initiation. Field Crops Res. 55, 93–107.

Brennan, L.E., Carberry, P.S., Hochman, Z., 2001. Participative Res. on use of enhanced climate variability information within agribusiness? AARES 45th Conference, January 22–25, Adelaide.

Carberry, P.S., 2001. Are science rigour and industry relevance both achievable in participatory action Res.? Proceedings of the Tenth Australian Agronomy Conference, Aust. Society of Agronomy: Hobart, Tas, www.regional.org.au/au/asa/2001/.

Carberry, P.S., Abrecht, D.G., 1991. Tailoring crop models to the semi-arid tropics. 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, UK, pp. 157–182.

Carberry, P.S., Bange, M.P. 1998. Using systems models in farm management. In Proceedings Ninth Australian Cotton Conference, August 10–14, Gold Coast Australia. The Aust. Cotton Growers Res. Organisation, pp. 153–160.

Carberry, P.S., Hammer, G.L., Muchow, R.C., 1993a. Modelling genotypic and environmental control of leaf area dynamics in grain sorghum. III. Senescence and prediction of green leaf area. Field Crops Res. 33, 329–351.

Carberry, P.S., Muchow, R.C., Hammer, G.L., 1993b. Modelling genotypic and environmental control of leaf area dynamics in grain sorghum. II. Individual leaf level. Field Crops Res. 33, 311–328.

Carberry, P.S., Adiku, S.G.K., McCown, R.L., Keating, B.A., 1996a. Application of the APSIM cropping systems model to intercropping systems. In: Ito, C., Johansen, C., Adu-Gyamfi, K., Katayama, K., Kumar-Rao, J.V.D.K., Rego, T.J. (Eds.), Dynamics of roots and nitrogen in cropping systems of the semi-arid tropics. Japan Int. Res. Centre Agric. Sci., pp. 637–648.

Carberry, P.S., McCown, R.L., Muchow, R.C., Dimes, J.P., Probert, M.E., Poulton, P.L., Dalgliesh, N.P., 1996b. Simulation of a legume ley farming system in northern Australia using the Agric. production systems simulator. Aust. J. Exp. Agric. 36, 1037–1048.

Carberry, P.S., Hammer, G.L., Meinke, H., Bange, M., The potential value of seasonal climate forecasting in managing cropping sytems. In: Hammer, G.L., Nicholls, N., Mitchell, C. (Eds.), Applications of seasonal climate forecasting in Agriculture and natural ecosystems—the Australian experience, Kluwer Academic, The Netherlands, in press.

Chapman, S.C., Hammer, G.L., Meinke, H., 1993. A sunflower simulation model: I. Model development. Agronomy J. 85, 725–735.

Cheeroo-Nayamuth, F.C., Robertson, M.J., Wegener, M.K., Nayamuth, A.R.H., 2000. Using a simulation model to assess potential and attainable sugar cane yield in Mauritius. Field Crops Res. 66, 225–243.

Connolly, R.D., Carroll, C., Francis, J., Silburn, D.M., Simpson, B., Freebairn, D.M., 1999. A simulation study of erosion in the Emerald irrigation area. Aust. J. Soil Res. 37, 479–494.

Connolly, R.D., Bell, M., Huth, N.I., Freebairn, D.M., Thomas, G., 2001. Simulating infiltration and the water-balance in cropping systems with APSIM-SWIM. Aust. J. Soil Res. 38, 221–242.

Coutts, J.A., Hochman, Z., Foale, M.A., McCown, R.L., Carberry, P.S., 1998. Evaluation of participative approaches to RD&E: a case study of FARMSCAPE. Proceedings of the ninth Aust. Society of Agronomy Conference. Aust. Society of Agronomy, Wagga Wagga, NSW, pp. 681–682.

Dalal, R.C., Strong, W.M., Weston, E.J., Cooper, J.E., Lehane, K.J., King, A.J., Chicken, C.J., 1995. Sustaining productivity of a Vertisol at Warra, Queensland, with fertilisers, no-tillage, or legumes. 1. Organic matter status. Aust. J. Exp. Agric. 35, 903–913.

Dolling, P., Latta, R., Lyons, A., Asseng, S., Robertson, M.J., Cocks, P., Ewing, M., 2001. Adapting APSIM Lucerne to the Western Aust. environment. 2001 Australian Agronomy Conference, Hobart, Tasmania, www.regional.org.au/au/asa/2001/.

Donnelly, J.R., Freer, M., Moore, A.D., 1994. Evaluating pasture breeding objectives using computer models. N. Z. J. Agric. Res. 37, 269–275.

Dunin, F.X., Williams, J., Verburg, K., Keating, B.A., 1999. Can Agric. management emulate natural ecosystems in recharge control in south eastern Australia? Agroforestry Syst. 45, 343–364.

Freebairn, D.M., Wockner, G.H., 1986. A study of soil erosion on Vertisols of the eastern Darling Downs, Queensland. II The effect of soil, rainfall and flow conditions on suspended sediment losses. Aust. J. Soil Res. 24, 159–172.

Hammer, G.L., 1998. Crop modelling: current status and opportunities to advance. Acta Horticulturae 456, 27–36.

Hammer, G.L., Muchow, R.C., 1994. Assessing climatic risk to sorghum production in water-limited subtropical environments I. Development and testing of a simulation model. Field Crops Res. 36, 221–234.

Hammer, G.L., Goyne, P.J., Woodruff, D.R., 1982. Phenology of sunflower cultivars. III. Models for prediction in field environments. Aust. J. Agric. Res. 33, 263–274.

Hammer, G.L., Muchow, R.C., 1991. Quantifying climatic risk to sorghum in Australia's semiarid tropics and subtropics: model development and simulation. 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, UK, pp. 205–232.

Hammer, G.L., Sinclair, T.R., Boote, K.J., Wright, G.C., Meinke, H., Bell, M.J., 1995. A peanut simulation model: 1. Model development and testing. Agronomy J. 87, 1085–1093.

Hammer, G.L., Carberry, P.S., Muchow, R.C., 1993. Modelling genotypic and environmental control of leaf area dynamics in grain sorghum. I. Whole plant level. Field Crops Res. 33, 293–310.

Hammer, G.L., Holzworth, D.P., Stone, R.C., 1996a. The value of skill in seasonal climate forecasting to wheat crop management in a region with high climatic variability. Aust. J. Agric. Res. 47, 717–737.

Hammer, G.L., Butler, D., Muchow, R.C., Meinke, H., 1996b. Integrating physiological understanding and plant breeding via crop modelling and optimisation. In: Cooper, M., Hammer, G.L. (Eds.), Plant Adaptation and Crop Improvement, CAB International, ICRISAT&IRRI pp. 419–441.

Hearn, A.B., 1994. OZCOT: a simulation model for cotton crop management. Agric. Syst. 44, 257–299.

Hearn, A.B., Da Rosa, D.A., 1985. A simple model for crop management applications for cotton. Field Crops Res. 12, 46–69.

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, Australia, 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 Ninth Australian Agronomy Conference, Wagga Wagga, pp. 709–712.

Hochman, Z., Coutts, J., Carberry, P.S., McCown, R.L., 2000. The FARMSCAPE experience. Simulations aid participative learning in Risky Farming Systems in Australia. In: Cerf, M., Gibbon, D., Hubert, B., Ison, R., Jiggins, J., Paine, M., Proost, J., Röling, N. (Eds.), Cow Up a Tree: Knowing and Learning for Change in Agriculture. Case Studies from Industrialised Countries. Coll. Science Update, INRA Editions, Paris, pp. 175–188.

Hochman, Z., Carberry, P.S., McCown, R.L., Dalgliesh, N.P., Foale, M.A., Brennan, 2001. APSIM in the Marketplace: a Tale of Kitchen Tables, Boardrooms and Courtrooms. In: Proceedings of the 2nd International Symposium on Application of Modelling as an Innovative Technology in the Agri-food Chain, Palmerston North, New Zealand, 9–13 December 2001.

Huth, N.I., Snow, V.O., Keating, B.A., 2001. Integrating a forest modelling capability into an Agric. production systems modelling environment-current applications and future possibilities. Proceedings of the International Congress on Modelling and Simulation, Aust. National University, December, pp. 1895–1900.

Inman-Bamber, G., Muchow, R.C., 2001. Modelling water stress response in sugarcane: Validation and application of the APSIM-Sugarcane model. 2001 Australian Agronomy Conference, Hobart, Tasmania, www.regional.org.au/au/asa/2001/.

Jones, J.W., Keating, B.A., Porter, C., 2001. Approaches for modular model development. Agric. Syst. 70, 421–444.

Jones, C.A., Kiniry, J.R. (Eds.), CERES-Maize: a simulation model of maize growth and development. Texas A&M University Press, College Station 1986, p. 194.

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. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agric. Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 157–177.

Jones, R.K., Probert, M.E., Dalgliesh, N.P., McCown, R.L., 1996. Nitrogen inputs from a pasture legume in rotations with cereals in the semi-arid tropics of northern Australia: experimentation and modelling on a clay loam soil. Aust. J. Exp. Agric. 36, 985–994.

Keating, B.A., Meinke, H., 1997. Assesssing exceptional drought with a cropping systems simulator: a case study for grain production in north-east Australia. Agric. Syst. 57, 315–332.

Keating, B.A., Wafula, B.M., 1991. Modelling the fully expanded area of maize leaves. Field Crops Res. 29, 163–176.

Keating, B.A., Verburg, K., Huth, N.I., Robertson, M.J., 1997. Nitrogen management in intensive agriculture: sugarcane in Australia. In: Keating, B.A., Wilson, J.R. (Eds.), Intensive Sugarcane Production: Meeting the Challenges Beyond 2000. CAB International, Wallingford, UK, pp. 221–242.

Keating, B.A., Carberry, P.S., Robertson, M.J., 1999a. Simulating N fertiliser response in low-input farming systems 2. Effects of weed competition. In: Donatelli, M., Stockle, C., Villalobus, F., Villar Mir, J.M. (Eds.), Proceedings of the International Symposium: 'Modeling Cropping Systems', Lleida, Spain, June 21–23, 1999.

Keating, B.A., Robertson, M.J., Muchow, R.C., Huth, N.I., 1999b. Modelling sugarcane production systems. I. Description and validation of the sugarcane module. Field Crops Res. 61, 253–271.

Keating, B.A., Meinke, H., Probert, M.E., Huth, N.I., Hills, I.G., 2001. Nwheat: documentation and performance of a wheat module for APSIM. Tropical Agronomy Memorandum, CSIRO Division of Tropical Agriculture, 306 Carmody Rd, St. Lucia, Qld 4067, Australia.

Keig, G., McAlpine, J.R., 1969. WATBAL: a computer system for the estimation and analysis of soil moisture regimes from simple climatic data. Tech. Memo. 69/9 CSIRO Division of Land Use Research, Canberra.

Lisson, S.N., Mendham, N.J., Carberry, P.S., 2000a. The development of a hemp (*Cannabis sativa* L.) simulation model: IV Model description and validation. Aust. J. Exp. Agric. 40, 423–425.

Lisson, S.N., Robertson, M.J., Keating, B.A., Muchow, R.C., 2000b. Modelling sugarcane production systems II: analysis of system performance and methodology issues. Field Crops Res. 68, 31–48.

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.

Littleboy, M., Silburn, D.M., Freebairn, D.M., Woodruff, D.R., Hammer, G.L., Leslie, J.K., 1992. Impact of soil erosion on production in cropping systems. I. Development and validation of a simulation model. Aust. J. Soil Res. 30, 757–774.

Littleboy, M., Cogle, A.L., Smith, G.D., Yule, D.F., Rao, K.P.C., 1996. Soil management and production of Alfisols in the semi-arid tropics. I Modelling the effects of soil management on runoff and erosion. Aust. J. Soil Res. 34, 91–102.

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 Res. and intervention from design to dialogue. Aust. J. Agric. Res. 52, 549–571.

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.

McCown, R.L., Carberry, P.S., Foale, M.A., Hochman, Z., Coutts, J.A., Dalgliesh, N.P., 1998. The FARMSCAPE approach to farming systems Res. Proceedings of the ninth Aust. Society of Agronomy Conference, Aust. Society of Agronomy, Wagga Wagga, NSW, pp. 633–636.

Meinke, H., Hammer, G.L., 1995a. Climatic risk to peanut production: a simulation study for Northern Australia. Aust. J. Exp. Agric. 35, 777–780.

Meinke, H., Hammer, G.L., 1995b. A peanut simulation model. II. Assessing regional production potential. Agronomy J. 87, 1093–1099.

Meinke, H., Hammer, G.L., Want, P., 1993. Potential soil water extraction by sunflower on a range of soils. Field Crops Res. 32, 59–81.

Meinke, H., Hammer, G.L., van Keulen, H., Rabbinge, R., 1998. Improving wheat simulation capabilities in Australia from a cropping systems perspective. III. The integrated wheat model (I_WHEAT). Eur. J. Agronomy 8, 101–116.

Moot, D., Robertson, M.J., Pollock, K., 2001. Validation of the APSIM-Lucerne model for phenological development in a cool-temperate climate. 2001 Aust. Agronomy Conference, Hobart, Tasmania, www.regional.org.au/au/asa/2001/.

Muchow, R.C., Keating, B.A., 1997. Assessing irrigation requirements in the Ord Sugar Industry using a simulation modelling approach. Aust. J. Exp. Agric. 38, 345–354.

Nelson, R.A., Dimes, J.P., Paningbatan, E.P., Silburn, D.M., 1998a. Erosion/productivity modelling of maize farming in the Philippine uplands. Part I: parameterising the Agric. Production Systems Simulator. Agric. Syst. 58 (1), 129–146.

Nelson, R.A., Dimes, J.P., Silburn, D.M., Paningbatan, E.P., Cramb, R.A., 1998b. Erosion/productivity modelling of maize farming in the Philippine uplands. Part 2: Simulation of alternative farming methods. Agric. Syst. 58, 147–163.

Parton, W.J., Schimel, D.S., Cole, C.V., Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in great plains grasslands. Soil Sci. Soc. Am.J. 51, 1173–1179.

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. Proceedings of the International Congress on Modelling and Simulation. In: Oxley, L., Scrimgeour, F. (Eds.), University of Waikato, 1, Hamilton, New Zealand, pp. 37–42.

Probert, M.E., Keating, B.A., 2000. What soil constraints should be included in crop and forest models? Agric., Ecosyst. Environ. 82, 273–281.

Probert, M.E. and McCown, R.L., 2000. Evaluation of legume-based strategies for profitable and sustainable grain-grazing systems using simulation modelling. Final report for GRDC. CSIRO Sutainable Ecosystems.

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.

Probert, M.E., Robertson, M.J., Poulton, P.L., Carberry, P.S., Weston, E.J., Lehane, K.J., 1998a. Modelling lucerne growth using APSIM. Proceedings of the Ninth Australian Agronomy Conference, Wagga Wagga, pp. 247–250.

Probert, M.E., Carberry, P.S., McCown, R.L., Turpin, J.E., 1998b. Simulation of legume-cereal systems using APSIM. Aust. J. Agric. Res. 49, 317–328.

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

Reyenga, P.J., Howden, S.M., Meinke, H., McKeon, G.M., 1999. Modelling global change impacts on wheat cropping in south-east Queensland, Australia. Environ. Modelling Software Environ. Data News 14, 297–306.

Ritchie, J.T., 1972. A model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8, 1204–1213.

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., I. Daniels, I., 1999. Modelling deep drainage of different land use systems. 2. Catchment wide application. Proceedings of MODSIM'99, vol. 1, Hamilton, New Zealand, December 6–9, pp. 43–48.

Robertson, M.J., Fukai, S., Ludlow, M.M., Hammer, G.L., 1993. Water extraction by grain sorghum in a sub-humid environment. I. Analysis of the water extraction pattern. Field Crops Res. 33, 81–97.

Robertson, M.J., Carberry, P.S., Wright, G.C., Singh, D.P., 1997. Assessing the value of putative traits for food legumes using models from a cropping systems perspective. International Food Legumes Conference, Adelaide.

Robertson, M.J. and Carberry, P.S 1998. Simulating growth and development of soybean in APSIM. Proceedings Tenth Australian Soybean Conference, Brisbane, 15–17 September, 130–136.

Robertson, M.J., Holland, J.F., Kirkegaard, J.A., Smith, C.J., 1999. Simulating growth and development of canola in Australia. Proceedings tenth International Rapeseed Congress. (CD-Rom Proceedings).

Robertson, M.J., Benson, T., Shamudzarira, Z. 2000a. 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.

Robertson, M.J., Carberry, P.S., Lucy, M., 2000b. Evaluation of a new cropping option using a participatory approach with on-farm monitoring and simulation: a case study of spring-sown mungbeans. Aust. J. Agric. Res. 51 (1), 1–12 (00049409).

Robertson, M.J., Carberry, P.S., Chauhan, Y.S., Ranganathan, R., O'Leary, G.J., 2001a. Predicting growth and development of pigeonpea: A simulation model. Field Crops Res. 71, 195–210.

Robertson, M.J., Whish, J., Smith, F.P., 2001b. Simulating competition between canola and wild radish. Proceedings of the twelveth Aust. Res. Assembly on Brassicas, October, Geelong, Australia.

Robertson, M.J., Carberry, P.S., Huth, N.I., Turpin, J.E., Probert, M.E., Poulton, P.L., Bell, M., Wright, G.C., Yeates, S.J., Brinsmead, R.B., 2001c. Simulation of growth and development of diverse legume species in APSIM. Aust. J. Agric. Res. 53, 429–446.

Robertson, M.J., Holland, J.F., Cawley, S., Bambach, R., Cocks, B., Watkinson, A.R., 2001d. Phenology of canola cultivars in the northern region and implications for frost risk. 2001 Aust. Agronomy Conference, Hobart Tasmania, www.regional.org.au/au/asa/2001/.

Rose, C.W., 1985. Developments in soil erosion and deposition models. Adv. Soil Sci. 2, 1–63.

Rosenthal, W.D., Hammer, G.L., Butler, D., 1998. Predicting regional grain sorghum production in Australia using spatial data and crop simulation modelling. Agric. Forest Meteorol. 91, 263–274.

Seligman, N.G., 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 Behavior of Soil-Plant Systems. PUDOC, Wageningen, The Netherlands, pp. 192–221.

Shaffer, M.J., Gupta, S.C., Linden, D.R., Molina, J.A.E., Clapp, L.E., Larson, W.E., 1983. Simulation of nitrogen, tillage, and residue management effects on soil fertility. In: Lauenroth, W.K., Skogerboe, G.V., Flug, M. (Eds.), Analysis of Ecological Systems: State-of-the-Art in Ecological Modelling. Elsevier, New York.

Shamudzarira, Z., 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., 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.

Sinclair, T.R., 1986. Water and nitrogen limitations in soybean grain production. I. Model development. Field Crops Res. 15, 125–141.

Snow, V., Dillon, P., 1998. Aust. design method for sustainable land treatment of rural industry and sewage effluent. Final report on project CWW17, Centre for Groundwater Studies CGS Report No. 82.

Snow, V.O., Bond, W.J., Myers, B.J., Smith, C.J., Polglase, P.J., Theiveyanathan, S., Falkiner, R.A., Benyon, R.G., Verburg, K., Dillon, P.J., 1998. APSIM-WASTE: Prediction of the fate of water, salt, and nitrogen following irrigation with effluent. In: Mulvey, P., (Ed.), 'National Soils Conference, Environmental Benefits of Soil Management, Brisbane, 27–29 April 1998'. Aust. Soil Science Society, Clayton, Vic. pp. 145–153.

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

Snow, V.O., Smith, C.J., Polglase, P.J., Probert, M.E., 1999b. Nitrogen dynamics in a eucalypt plantation irrigated with sewage effluent or bore water. Aust. J. Soil Res. 37, 527–544.

Steiner, J.L., Williams, J.R., Jones, O.R., 1987. Evaluation of the EPIC simulation model using dryland wheat-sorghum-fallow crop rotation. Agronomy J. 79, 732–738.

Thorburn, P.J., Keating, B.A., Robertson, F.A., Wood, A.W., 2000. Changes in soil carbon and nitrogen under trash blanketing. Proceedings of the Australian Society of Sugarcane Technologists. Conference, pp. 217–224.

Thorburn, P.J., Probert, M.E., Robertson, F.A., 2001. Modelling decomposition of sugarcane surface residues with APSIM-Residue. Field Crops Res. 70, 223–232.

Turpin, J.E., Probert, M.E., Holford, I.C.R., Poulton, P.L., 1996. Simulation of cereal-legume rotations using APSIM. Proceedings—Eighth Australian Agronomy Conference Toowoomba, Australia, pp. 562–565.

Uehara, G., Tsuji, G.Y., 1991. Progress in crop modelling in the IBSNAT Project. In: Muchow, R.C., Bellamy, J.A. (Eds.), Climatic Risk in Crop Production: models and Management in the Semi-Arid Tropics and Subtropics. CAB International, Wallingford, pp. 143–156.

van Oosterom, E.J., Carberry, P.S., Hargreaves, J.N.G., O'Leary, G.J., 2001. Simulating growth, development, and yield of tillering pearl millet. 2. Simulation of canopy development. Field Crops Res. 72, 67–91.

Verburg, K., (Ed.), 1996. Methodolody 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., Keating, B.A., Bristow, K.L., Huth, N.I., Ross, P.J., 1996a. Modelling nitrate leaching under sugarcane using APSIM-SWIM. Proceedings—Eighth Australian Agronomy Conference Toowoomba, p. 724.

Verburg, K., Ross, P.J., Bristow, K.L., 1996b. 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 Ninth Australian Agronomy Conference, Wagga Wagga, pp. 789–790.

Verburg, K., Bond, W.J., Keating, B.A., Smith, C.J., Robertson, M.J., Hutchinson, P., 2001a. Simulation of tactical use of phase farming to reduce deep drainage. Aust. Agronomy Conference, Hobart, www.regional.org.au/au/asa/2001/.

Verburg, K., Braschkat, J., Hochman, Z., Moore, A.D., Helyar, K.R., Probert, M.E., Hargreaves, J.N.G., Simpson, R.J., 2001b. Modelling acidification processes in Agric. systems. In: Rengel, Z. (Ed.), Handbook of soil acidity. Marcel Dekker, New York.

Wang, E., Robertson, M.R., Hammer, G.L., Carberry, P., Holzworth, D., Hargreaves, J., Huth, N., Chapman, S., Meinke, H., McLean, G., 2003. Design and implementation of a generic crop module template in the cropping system model APSIM. Eur J Agronomy, 18, 121–140.

Williams, J.R. 1983. EPIC, The Erosion-Productivity Impact Calculator, Volume 1. Model Documentation, Agric. Res. Service, United States Department of Agriculture.

Wright, S.L., Veraart, V.E., Moore, A., Keating, B.A., 1997. A Software Protocol for Connecting Different Crop, Soil and Pasture Simulation Models. American Society Agronomy Abstracts, Anaheim, California, p. 21.