Integrating a Forest Modelling Capability into an Agricultural Production Systems Modelling Environment - Current Applications and Future Possibilities

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Abstract: The sustainability of Australia's agricultural and natural systems is under threat from several processes, in particular dryland salinity. Adverse impacts on the environment from current agricultural practice are well documented and several changes in land management have been roposed to increase sustainability. Evaluation of these land management systems requires examination of the trade-off between better outcomes for the environment against changed long-term productivity. In addressing these issues scientists often call upon simulation tools to integrate the complex processes and interactions to aid the analysis. Difficulties can arise when analysis of the system requires study across scientific disciplines or requires a range of existing modelling approaches to be brought together. In addressing this issue, modern software principles can be used to facilitate the integration of scientific models. The Agricultural Production Systems Simulator (APSIM) utilises a component-based design to facilitate the integration of models via a common communication protocol. The growing interest in novel agricultural systems involving on-farm forestry has led to the development of a forest modelling capability within the APSIM framework. The APSIM Forest model can thus be used in conjunction with existing soil water, carbon and nitrogen, surface residue, crop growth, and farm management modules. In this paper, the background to this new capability and a range of existing applications and future possibilities is described.

Keywords: APSIM; Simulation; Modelling; Agricultural systems; Forestry

1. INTRODUCTION

For many years simulation has been seen as an important tool for evaluating options for natural resource management. The ability to test the likely outcomes resulting from changes in land management is an invaluable tool for extending and adding value to traditional experimental analysis. As a result, a range of models for either agricultural or forestry systems has been developed to address the questions relevant to particular land uses. However, until recently, there has been only limited interdisciplinary exchange between researchers involved in agricultural and forestry land uses resulting in few models capable of simulating the interaction between trees and crops grown in an agro-forestry system. This paper describes current and future work utilising a new tree growth model within the APSIM modelling framework.

2. THE STATE OF PLAY IN CROP AND FOREST SIMULATION IN AUSTRALIA

2. 1 APSIM – a modern integrated crop simulation framework

The Agricultural Production Systems Simulator (APSIM) [McCown et al., 1996] has been specifically designed to facilitate cross-disciplinary simulation-based research. A component-based design allows individual models to communicate via a common communications engine. At present, over twenty individual crop and pasture models are available within APSIM for use in simulating diverse farming systems. These crop modules communicate with existing modules for simulating soil processes such as carbon, nitrogen and phosphorous cycling, surface residue dynamics, water and solute fluxes, soil temperature, and soil acidity.

2.2 Models of Forest Productivity

A wide range of forest modelling tools is currently being used nationally and internationally. Each individual model has particular strengths resulting from being designed to investigate a particular aspect of forest productivity or ecosystem function. Some of the models relevant to this discussion are listed in Table 1.

Whilst these models are proving useful for current analyses, their ability to address a wider range of agro-forestry issues is sometimes limited. Depending on the nature of the model's heritage, various system processes seen as less important to the developers are dealt with via fairly simple means. One common simplification is that in many of the models, soil fertility is described using a simple modifier on potential tree growth rate. As the interests of the model users change, simplifications become constraints to model application. Attempts to overcome this limitation have led to the integration of existing soil water and nitrogen models with these forest productivity models. For example, the GDAY model of Comins and McMurtrie [1993] and King's Eucalyptus productivity model have utilised existing soil fertility models to calculate responses in forest growth to site fertility or nutrient management. Whilst this has opened up a wider range of possibilities for model application, model evolution such as this invariably leads to maintenance and ongoing development problems unless a well-designed framework suited to model integration is employed [Jones et al., 2001]. APSIM provides such a framework.

2.3 A Forest Production Model for APSIM

The APSIM FOREST module is based on the lessons learned from the above-mentioned crop and forest productivity models. A range of APSIM modules provide daily data for meteorological conditions and uptake of water and nitrogen and so that time step is used for all growth calculations. Growth is calculated as,

$$\Delta G = R_{int}\ LUE\ \min(F_t, F_n, F_{vpd})\ F_w \qquad (1)$$

Where ΔG is daily growth, R_{int} is daily intercepted solar radiation (MJ/m^2), LUE is the light use efficiency (g/MJ) and F_t, F_n, F_{vpd} and F_w are growth modifiers for temperature, nitrogen, vapour pressure deficit and soil water supply respectively. R_{int} is calculated using crown cover, leaf area, and an assumption of exponential light extinction. Tree water demand is calculated using the Micromet module which is developed from the work of Snow et al. [1999] and Kelliher et al. [1995], while tree water uptake is calculated using one of the two soil water modules available in APSIM.

Table 1. Some of the existing forest growth models investigated during development of the APSIM FOREST modelling capability.

Model	Reference
PPPG	Landsberg and Waring [1997]
PROMOD	Battaglia and Sands [1998]
BIOMASS	McMurtrie et al. [1990]
GDAY	Comins and McMurtrie [1993]
E. seiberi	King [1996]

Daily growth is partitioned to leaf, stem, bark, branch, taproot, and roots using specified partitioning rules which vary with tree size and water or nitrogen stress. Leaf area growth is calculated from daily leaf biomass growth and an age-dependant specific leaf area. Similarly, root length calculations utilise a specific root length, with root length partitioned spatially according to supplies and demands for both water and nitrogen. All biomass pools can undergo senescence and detachment. Simple first-order decay rates can be specified and these are modified according to daily growth potential to capture annual variation in litter fall rates. Nitrogen taken up from the soil mineral pools is partitioned to individual plant parts according to sink strengths calculated from nitrogen deficits in each plant part. Nitrogen in the biomass detaching from the living plant is returned to the soil or surface fresh organic matter pools depending on the source of the material.

The various model components are similar to many of those employed in existing forest productivity models. However, the uniqueness of APSIM is the ability to combine these components with existing state-of-the-art biophysical models to investigate wider system issues.

3. CURRENT APPLICATIONS USING THE APSIM FOREST MODEL

The following section presents examples of application of the Forest model in the APSIM modelling framework. The examples have been chosen to demonstrate the capability of the model to address a diverse range of issues relevant to both natural and managed systems.

3.1 Forest Productivity in Response to Management

Cromer et al. [1993] describe experimental results giving the response of *Eucalyptus grandis* to combinations of irrigation and nitrogen fertiliser at the Toolara State Forest near Gympie, Queensland.

After three years the irrigation treatment showed no increase in growth compared to the control. In contrast the fertiliser treatment had significantly increased growth but there was no additional response when irrigation was supplied as well as fertiliser. Later measurements indicated a severe decrease in growth rate for fertiliser + irrigation treatment, probably due to the effects of sub-soil acidification (P. Ryan, pers. comm.).

APSIM has been used to investigate the water and nitrogen balance of this experiment. Daily climate information was obtained for the Toolara State Forest Research Station. The water and nitrogen-carbon balances were simulated using APSIM's Soilwat2 and SoilN2 modules [Probert et al., 1998]. Soil properties were derived from information in a soil survey of the site [Ross and Thompson, 1991]. Information on the timing and amounts of fertiliser application, and daily volumes of irrigation, were used to specify each of the four treatments [Cromer et al., 1993].

The model was able to describe three of the four treatments (Figure 1). Nutrient availability was a major limitation to growth, such that a response to irrigation in the absence of fertiliser was negligible. The model predicted a response to irrigation under fertilised conditions and the simulated stem volume at age 10 closely followed other published data [Birk and Turner, 1992] for irrigated and fertilised *E. grandis* in a similar environment. This response was not seen in the measurements. The model predicted that 650 kg NO_3-N /ha was leached and it is likely that the soil acidification resulting from that leaching significantly reduced tree growth, a process that is not included in the tree growth model.

In order to evaluate possible management options to reduce the risk of soil acidification induced by nitrate leaching whilst maintaining growth, a range of fertiliser application rates were simulated (Figure 2). This simple analysis suggests that the trees can only utilise 400 kg N /ha within the first three years. Any fertiliser application beyond that amount is likely to significantly enhance leaching and acidify the soil profile.

3.2 Exploring Eucalypt Plantations for "On-farm" Salt Management

Reafforestation of agricultural areas with shallow water tables has been investigated as a means of managing adverse effects of changes in land management on the soil water and salt balance. Previous experimental and simulation studies at Kyabram in Victoria have shown that while trees can lower water tables, this water use results in a localised build up of salt and the eventual reduction in tree growth [Heuperman, 1999].

APSIM is being utilised to investigate the rate of salt build-up and tree growth for a range of environmental and management scenarios. For example, the long term experimental data from Kyabram has evaluated various forestry options on a site with a moderately saline water table initially at a depth of two meters. These data have been used in developing a capability for simulating these shallow groundwater systems.

The complex water and salt balance of this system was simulated using the APSIM-SWIM water and solute model. APSIM-SWIM [Verburg et al., 1996] calculates water and solute fluxes using a numerical solution to the Richards' and convection-dispersion equations. A range of flexible boundary conditions allow the user to describe the range of water table conditions relevant to this type of forestry system. Although APSIM is a point-based model, here it was been

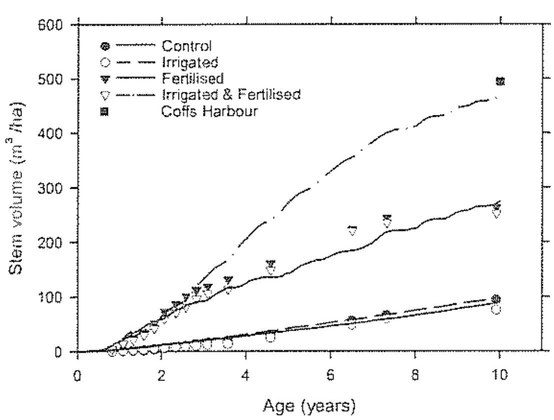

Figure 1. Stem volume data (symbols) and simulation results (lines) for *E. grandis* data Toolara State Forest. Stem volume from Birk and Turner [1992] at Coffs Harbour is also shown.

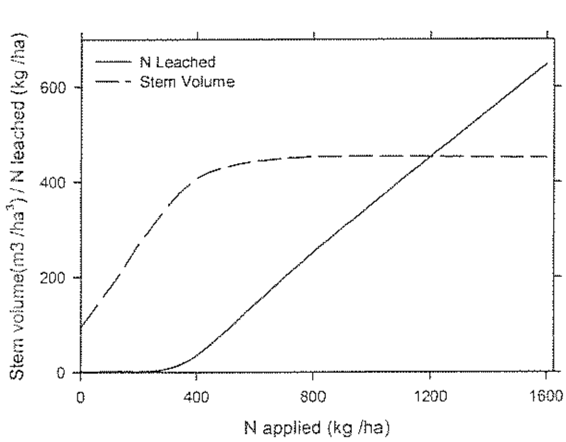

Figure 2. Simulation results showing stem volume and accumulated nitrogen leaching at 10 years for several nitrogen application rates.

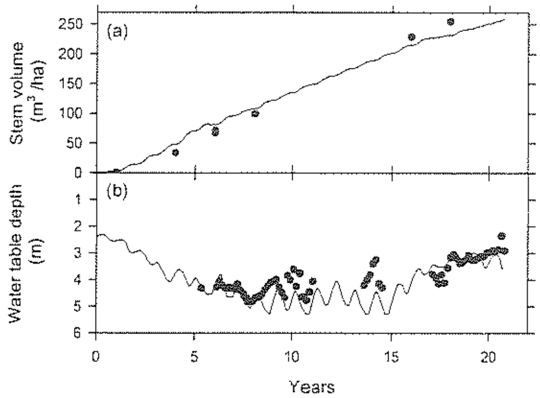

Figure 3. Stem volume (a) and water table depth (b) data for *E. grandis* grown over a shallow groundwater table at Kyabram. Observed data shown as symbols and simulations results as lines.

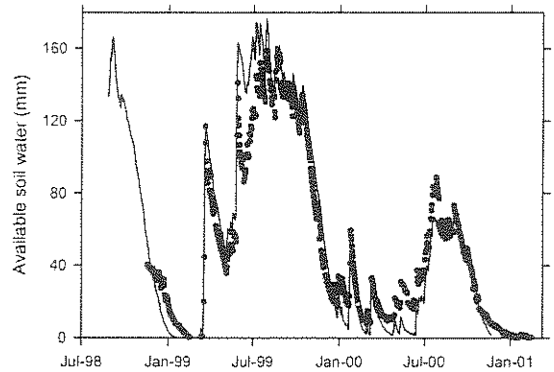

Figure 4. Data (symbols) and simulation results (lines) of plant-available soil water storage to a depth of 4.5 m at Moora under *Banksia* woodland.

configured to simulate lateral and vertical flow of water into the plantation caused by differences between water table depths inside and outside of the plantation. The flow of water into the plantation root zone results in an accumulation of salt that reduces tree water uptake and growth. Eventually the rate of tree water use falls below the rate of inflow of water to the plantation and this results in the water under the plantation rising back toward the original level (Figure 3).

Use of the model to extrapolate to other conditions is illustrated in Table 2. Here, the experimental conditions were revisited, but with a range of ground water salinity levels. The effect of salinity on the time required to accumulate enough salt to severely limit tree growth is shown. The model indicates that even moderately saline ground water would have led to build up of salt with a significant effect on tree growth.

Table 2. Effect of ground water salinity on water table rise and stem volume for the Kyabram experimental conditions.

Ground water salinity (dS /m)	Time to water table rise (years)	Stem volume at 20 years (m^3 /ha)
0.5	> 20	300
2	15	265
5	10	210
10	8	190

3.3 Exploring the Hydrological Character of Native Woodlands

Pate and Bell [1999] describe the water and nutrient cycling behaviour of *Banksia* woodlands in an attempt to identify the key characteristics required for ecosystem mimicry by novel agricultural systems. Extensive investigation of the water balance of this natural system has been undertaken. It is hoped that these results can be extrapolated both in time and space by coupling this experimental work with further simulation analysis. Current effort is centred on the *Banksia prionotes* woodland near Moora in Western Australia. This system consists functionally of a dominant *Banksia* over-storey and a winter-active woody under-storey growing on a deep sand profile. The root system of the over-storey is deep enough to gain access to a fresh water table whereas the root system of the under-storey is quite shallow (about 0.6 m) [Pate and Bell, 1999].

APSIM was configured to contain two instances of the forest model to represent the functional components of the woodland. Whilst each component was constrained to the observed climax state, each was parameterised to describe its seasonal growth behaviour. Simulations were compared to daily measurements of evapo-transpiration (not shown) and soil moisture storage (Figure 4).

The ability of the model to describe both the soil water storage and the combined soil and plant evaporative losses gives confidence in the other water balance components calculated by the model. Preliminary results clearly indicate the importance of simulation for extrapolation of results. Long-term simulations of the site demonstrate the episodic nature of the drainage of water into the water table. For example, the model demonstrates that the bulk of the recharge occurs in a small subset of years, a condition that cannot feasibly be determined experimentally. Comparison of annual drainage rates for the last forty years indicate that drainage during the winter of 1999 was certainly above average. As a result, any water balance estimate based purely on the field measurement period would certainly be not representative of the longer term.

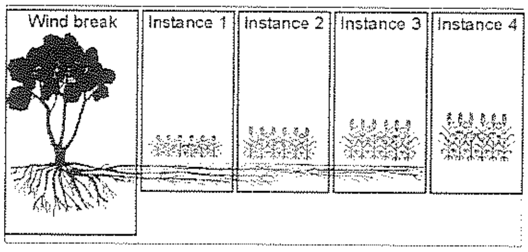

Figure 5. Graphical representation of an agro-forestry simulation configuration in APSIM with special emphasis on competition for soil moisture.

4. WHERE TO FROM HERE?

Whilst the above examples show the benefit gained by utilising the existing modelling capabilities for various soil processes and management options, further opportunities exist for simulation analyses consisting of tree and crop models operating together. APSIM is currently being developed to allow for the investigation of spatial variation in crop production next to tree belts and wind breaks.

Figure 5 shows the approach taken in the simulation of the tree-crop competition zone. Each simulation consists of several instances of a crop-soil system executing simultaneously. The figure shows three instances within the competition zone and one outside the influence of the trees. There are no interactions between each instance except that they contain a part of a common tree root system. The demand for water and nutrients by the trees is distributed dynamically according to rooting and resource supply.

This configuration provides a framework for quantifying the trade-offs between tree and crop productivity on farms. Figure 6 shows sample yield transects away from a tree break simulated using ten spatial increments and forty individual growing seasons. The effect of the trees on storage of soil moisture over the fallow period and final yield shows a significant seasonal variation. Three seasons have been highlighted for further comment.

Table 3. Simulated open paddock yield and in-season rainfall for three seasons at Dalby.

Season	Yield (kg/ha)	Rainfall (mm) May-Sep	Oct
1980	3533	98	119
1983	6702	371	121
1998	5424	375	27

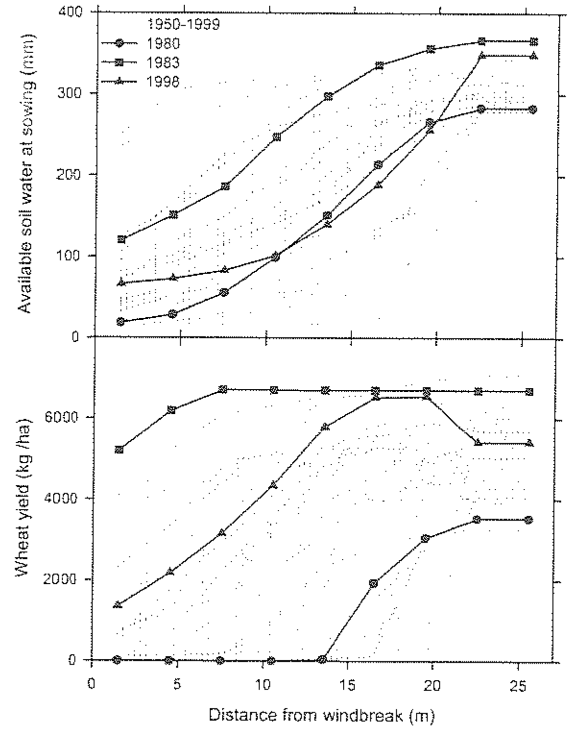

Figure 6. Simulated available soil water and yield for wheat grown at various distances from a hypothetical windbreak between 1950 and 1999 at Dalby, Queensland.

The effect of trees on crop growth can be broken into two main components: tree-crop competition and reductions in fallow water storage. These are clearly evident in the simulation results shown in Figure 6. Low cropping-season rainfall (see table 3) during 1980 resulted in soil moisture at sowing having a large effect on subsequent crop yield. In contrast, the higher rainfall in 1983 largely masked the effect of competition by the trees and available moisture at sowing on subsequent crop yield. Although early season rainfall in 1998 and 1983 was similar, yield depression next to the trees was greater in 1998 due to reduced soil moisture at sowing. At the extremity of the competition zone, tree water use has actually led to yields higher than those for the open paddock in 1998. The reason for this is apparent when rainfall distribution during the season is taken into account. Early reductions in crop growth due to competition have led to more conservative water use thus avoiding reductions in harvest index due to the dry finish to the 1998 season.

The ability of the model to quantify the effects of such complex tree-crop interactions will be used in the future to investigate diverse agro-forestry options for a range of environments.

5. CONCLUSIONS

Simulation models are regularly used for investigating management issues for forestry or agricultural systems. The combination of models from these two fields within a common framework now allows the user to make use of experience gained from a wider range of disciplines. In addition, the use of modern software design principles in the development of tools such as APSIM allows us to ask new types of questions of our existing tree, crop and soil models. Problems involving complex systems with multiple vegetative components are coming within the grasp of modern modelling software.

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