Application of the APSIM Cropping Systems Model to Intercropping Systems

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Abstract

The APSIM (Agricultural Production System sIMulator) model represents a versatile software system for simulating the production and environmental consequences of agricultural production systems. It is not a model of a particular cropping system, but rather a collection of modules, each describing a specific process, that can be combined in meaningful ways to represent systems of interest. Given current access to modules, APSIM has the ability to simulate a range of crop and soil processes, in response to management options that include crop sequences and species mixtures.

In this paper, APSIM has been specified for two mixed-crop systems: a maize-cowpea intercrop system and a crop-undersown pasture system. In the former case, APSIM was able to simulate the growth, development, and yield of both maize and cowpea grown under a range of soil water and fertility conditions. Measured data were collated from experiments and from the literature where crops were arranged as sole crops, intercrops and where the relative time of sowing of each crop also changed. In the latter case, a mixture of pasture legume (Stylosanthes hamata) under a maize crop was simulated; growth of the mixture was predicted under conditions where the maize and pasture competed for light, water, and nitrogen during the cropping season. Predicted grain yield of maize and biomass yield of the pasture legume were similar to observed yields for both intercrop and sole crop and pasture treatments.

A simple example is given that demonstrates how the capability of APSIM to simulate competition between crops in mixtures can be used in exploring the consequences of intercropping systems.

Introduction

The debate on the value of intercropping as a management practice has been ongoing for some time. The fact that many farmers in the tropics continue to practice intercropping as a management option suggests some advantage over sole cropping for some conditions.

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While the basis for this advantage has been attributed, at least in part, to an improved biological efficiency of resource use by intercrops (Willey 1979a,b; Ofori and Stern 1987), efforts to generalize the added value of intercropping across seasons or regions have often proved difficult (e.g. Russell and Caldwell 1989). Consequently, the value of intercropping is continually being tested in new research initiatives (Fukai 1993b) without a resolution to the debate appearing imminent.

In a recent compilation of reviews on intercropping (Fukai 1993a), the complexity of such farming systems was often highlighted as a major reason for the difficulty in attributing cause and effect to experimental results. Many reviewers suggested that simulation modeling could ideally contribute to the quantitative evaluation of the processes involved. However, the consensus at the time was that the existing simulation models were not yet capable of modeling complex intercropping systems.

Modeling intercropping systems, in fact, has received relatively little effort, especially when considered against the efforts in modeling crop-weed associations. Kropff and van Laar (1993) recently summarized the status of modeling the effects of weed competition on crops resulting from the efforts of the many Dutch researchers working in this area. Interestingly, even in this area of extensive research effort, modeling crop-weed interactions has been principally restricted to competition for light. Competition for nitrogen has not as yet been simulated nor has competition for water between species been dealt with comprehensively (Kropff and van Laar 1993). In the low-input systems where intercropping is principally practiced, any modeling effort would require, at a minimum, the ability to simulate competition for light, water, and nitrogen between component crops of the intercropping system of interest.

Caldwell and Hansen (1993) describe the most prominent effort to date on modeling intercropping systems in their development of the CropSys simulation model. CropSys version 2.0 is a model specifically developed to deal with multiple cropping systems where competition for light, water, and nitrogen are simulated. To achieve this objective, a number of existing crop models were modified and linked to enable simulation of inter-species competition. Caldwell and Hansen (1993) provided no estimates on how successful this approach was at simulating measured data, although the current status of CropSys is updated by Caldwell et al. (1996).

The aim of this paper is to describe the application of the APSIM (Agricultural Production Systems sIMulator) systems model to the simulation of multi-species systems. The APSIM model has been described generally by McCown et al. (1996) and specifically for use in a maize-cowpea intercropping system by Adiku et al. (1995). In this paper, we will briefly review the structure and capabilities of the APSIM model, and describe how inter-species competition is modeled. The ability of APSIM to simulate inter-species competition is then tested against experimental data for two mixed crop systems: a maize-cowpea intercrop system and a crop-understorey pasture system. Finally, an example is given on the use of APSIM to explore production strategies of maize and cowpea as either sole crops or as an intercrop system.

APSIM - Agricultural production systems simulator

General description

The APSIM model was developed primarily to simulate the agricultural production systems of interest in northern Australia (McCown et al. 1996). To this end, APSIM has the ability to simulate the response of a range of crops to climate, to a wide spectrum of soil water and nitrogen environments, to alternative management options, and to changes in cropping sequence. Crop options currently include wheat, barley, sorghum, maize, sunflower, sugarcane, cotton, and cowpea with peanut, soybean, chickpea, mungbean, and several grass and legume pastures soon to be added to the APSIM library of biological modules. Importantly, simulations with APSIM are accomplished in a way by which the soil accrues the effects of the agricultural practices of cropping, fallowing, residue management, and tillage in order to enable the simulation of long-term trends in soil productivity due to fertility depletion or soil erosion. While APSIM was not designed specifically to deal with intercropping systems, past research interests in low-input agriculture in the semi-arid tropics of Kenya (Probert 1992) and northern Australia (McCown et al. 1985) led to the initial design specifications of APSIM incorporating the facility to simulate competition for resources by species grown in mixtures.

The APSIM model is a flexible software environment for simulating systems rather than a model of a particular cropping system. In achieving this end, an object-oriented design approach was adopted. Within APSIM there is a library of modules, each describing specific processes, that can be combined in meaningful ways to represent agricultural systems. Modules can be either biological (e.g. crop, pasture, or surface residue), environmental (e.g., water balance, N-balance, or soil erosion), managerial (e.g., tillage, irrigation, fertilization) or economic (e.g., event log), and they communicate with each other via the APSIM "engine". The engine passes information between modules according to a standard protocol that allows modules to be plugged in or pulled out of the engine depending on the specifications for the simulation task. In this way, the simulation capacity of APSIM is limited only by the availability of modules to simulate aspects of the system of interest.

The APSIM model is a point-scale model that can predict the production consequences of the management of individual, homogeneous fields over time. It has adopted many of the existing models that simulate crop, pasture, and soil processes in Australia and elsewhere (McCown et al. 1996). Existing crop modules can be attached simply by decoupling their own soil processes and adding the APSIM interface. However, in most cases, this "patching" into APSIM of original model code is only a preliminary step. To ensure rigor in software development and maintenance, the code for each module needs to be redesigned and re-engineered to achieve APSIM programming standards. To facilitate this process, a generic crop template has been developed that can easily be programmed to reflect the workings of existing models. In common with its precursor models, FORTRAN remains the standard programming language in module development.

A major investment in APSIM has been the development of software that is easy to use and efficient to maintain under continual change. Configuring the system of interest is made easy by APSIM's modular plug in/pull out interface with the APSIM engine. Rigorous software standards have been used to ensure program reliability and maintainability, including subroutine design protocols, readability of code, program testing, and version control. A modeling environment was created via a user-interface shell (written in the C++ language) to facilitate the use of APSIM for both program development and maintenance and for operational research purposes. The APSIM shell uses a Microsoft Windows™ operating environment, although it can be simply run under DOS or other operating systems.

Simulating inter-species competition with APSIM

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 modeling inter-species competition. The APSIM model 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 into the APSIM engine along with the competing crop modules. This approach can be used to successfully simulate allocation of light, water, and nitrogen to competing APSIM modules.

The APSIM model, being a point-scale model, is currently specified only for additive intercropping systems - i.e., where one crop component is planted as if a sole crop and the other components are added to the system. Downward attenuation of light within canopies of additive intercrops can be adequately described using the same approach used for sole crops (Keating and Carberry 1993). Using Beer's Law, the fractional light interception (f_j) within canopy layer j can be described by

$$f_j = (1 - e^{-(k_{j1} L_{j1} + k_{j2} L_{j2})}) \quad (1)$$

where k_{j1}, k_{j2} and L_{j1}, L_{j2} are the extinction coefficients and leaf area indices contained within layer j for the two mixed canopies. The fraction of light intercepted by species 1 within layer j (f_{j1}) can be estimated using

$$f_{j1} = f_j \frac{k_{j1} L_{j1}}{k_{j1} L_{j1} + k_{j2} L_{j2}} \quad (2)$$

and similarly for species 2. Fractional daily light interception for the whole intercrop canopy and for each species is determined by summing over all layers the values of f_j and f_{j1}, f_{j2} respectively. In APSIM, the amount of light intercepted by different crops grown in a mixture is determined each day by the arbitrator using information passed, via the engine, from each crop module on their leaf area index, extinction coefficient, and height. Within the arbitrator, the number of competing crops determines the number of canopy layers -

i.e., two crops results in two layers, one where the two canopies are mixed, the second containing only the canopy of the taller species. At present, each crop's leaf area is distributed between canopy layers using the assumption that leaf area index increases exponentially with crop height. Using equations 1 and 2, the arbitrator passes back, via the engine, a daily value for fractional light interception to each crop module.

Allocation of water and nitrogen (N) resources can similarly be calculated in the arbitrator given the passing of appropriate demand and supply variables and the specification of allocation rules. However, as a simple alternative to determining these allocation rules, APSIM also allows prediction of below-ground competition for resources by simulating water and N-extraction of each crop in turn, with the order of extraction alternated between crops each day. Therefore, each day, crop A has first use of resources, to be followed by crop B. Next day, crop B accesses soil resources first before crop A. It is argued that this daily rotation in the order of calls to different crop modules adequately represents allocation of resources to competing crops because the daily time-step of APSIM is small relative to the length of the total growing season. This results in the daily removal of resources being small relative to their total pool size. A similar approach to modeling competition between two species has been successfully used by Carberry et al. (1992, 1993a), although the alternative of always allowing one species first priority has also been employed in simulating species competition (Kiniry et al. 1992).

In order to test the applicability of the rotating call system of resource allocation, a version of APSIM was specified containing two identical maize crop modules (MZ-1 and MZ-2). This version of APSIM was run for a 30-year period of climatic data with both maize crops planted on the same day at the same plant population each year, but with the order of water and N-extraction alternated between crops each day (rotating call system). This simulation was repeated four times: with N-fertilizer and irrigation applied to create optimal growth conditions every year, with N-fertilizer but no irrigation, with irrigation but no N-fertilizer, and, finally, with neither N-fertilizer nor irrigation applied. Simulations were then duplicated with MZ-1 always receiving first allocation of resources every day (set call system).

Figure 1 shows the cumulative probability of *differences* in grain yield of the two competing maize crops for both the rotating call and the set call systems over the 120 seasons that were simulated. Perfect resource allocation would have resulted in identical yields for the two maize crops in all seasons. Rotating the order of water and nitrogen extraction resulted in a less than 5% difference in maize yields in 90% of seasons (the difference was less than 1% in 54% of seasons). Letting one module always receive first allocation resulted in a less than 5% difference in 38% of seasons (less than 1% in only 4% of seasons). Clearly, when one crop is allowed priority access to resources at the expense of another, a competitive advantage will often accrue. Rotating the order in which these crops access resources did not significantly bias resource allocation in the majority of simulated crops. Interestingly, the significant bias resulting from the rotation system in a few seasons (Fig. 1), in each case, resulted from water stress coinciding with the few days when grain numbers are determined in the maize model.

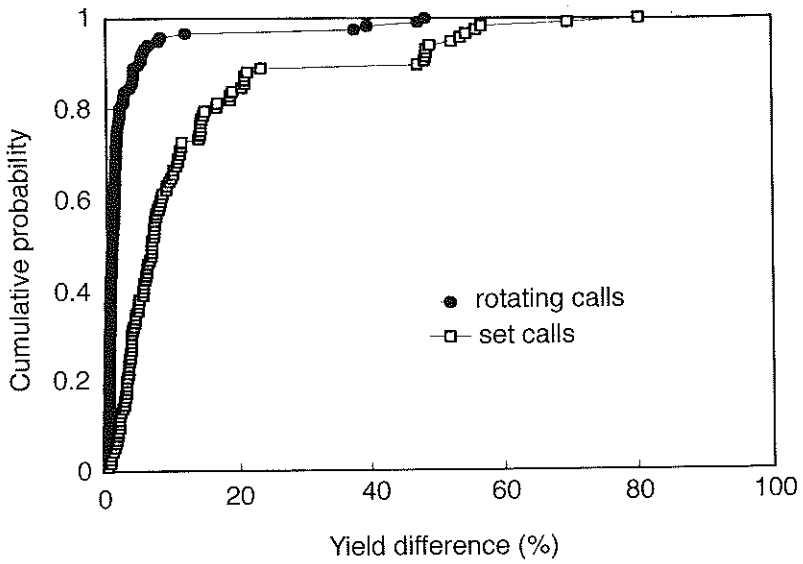

Fig. 1. Cumulative probabilities for the difference in grain yield of the two competing maize crops for both the rotating call and set call systems that allocate water and nitrogen resources between crops. [Rotating call system is where order of resource extraction alternated between crops each day. Set call system is where one crop always receives first allocation of resources each day.]

Modeling multiple cropping systems with APSIM

While McCown et al. (1996) provided a general description of APSIM, details on individual modules and validation of simulation results are yet to be published. Moreover, the application of APSIM to multiple cropping systems is only a recent development. Nevertheless, the specification of APSIM for two distinct cropping systems is described and limited testing of APSIM predictions against observed experimental data is presented in the following sections.

A maize-cowpea intercropping system

The APSIM model is currently being used to simulate intercropping systems as part of a project aimed at assessing the performance of maize-cowpea intercrops grown under variable water and nitrogen environments. Much of this work has been reported previously by Adiku et al. (1995). For the purpose of this project, APSIM was configured with (1) a maize module, developed by re-engineering the maize model described by Carberry and Abrecht (1991); (2) a cowpea module, developed using the APSIM crop template (Adiku et al. 1995), but similar in design to the soybean model of Sinclair (1986); (3) a soil water balance module, a derivative of the CERES (Jones and Kiniry 1986) and PERFECT (Littleboy et al. 1992) water balances; (4) a soil nitrogen balance module, also derived from CERES (Jones and Kiniry 1986); (5) the arbitrator module, configured to simulate competition for light (equations 1 and 2); and (6) APSIM utility modules that permit

implementation of management options (sowing, harvest, irrigation, fertilization, etc.) and the reporting of simulation output. The rotating call system of resource allocation was employed to simulate competition for water and nitrogen between the maize and cowpea modules.

To test APSIM performance, data on maize and cowpea, grown both as sole crops and intercrops, were collated from a number of experimental sources (Ofori 1986; Carberry and Abrecht 1991; Carberry et al. 1993a; Muchow et al. 1993; Adiku et al. 1995). Experiments included a range of locations, seasons, sowing times, cultivars, plant densities, water regimes, and N-fertilizer rates. A comparison of predicted grain yields against observed grain yields in Figure 2 illustrates the current overall ability of APSIM to simulate maize and cowpea yields under a wide range of sole crop and intercrop growing conditions. Most pleasing is the ability of APSIM to realistically respond to the alternative management strategies possible with intercropping systems. Using the data of Ofori (1986) as an example, the simulated response of APSIM closely followed the measured grain and total dry matter yields for an intercrop experiment where cowpea was planted at different times relative to the maize planting time (Fig. 3).

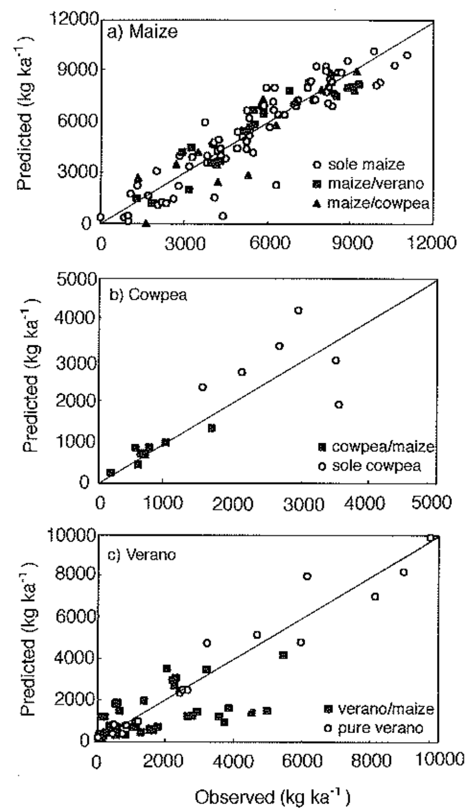

Fig. 2. Comparison of predicted versus observed values of (a) grain yield for sole and intercropped maize [n = 111, R^2 = 0.85, Y = 0.98 (± 0.04) X - 5.5 (± 240)]; (b) grain yield for sole and intercropped cowpea [n = 15, R^2 = 0.91, Y = 0.93 (± 0.08) X - 31.6 (± 34.6)]; and (c) biomass for sole and intercropped verano pasture [n = 63, R^2 = 0.78, Y = 0.84 (± 0.06) X - 131.7 (± 171)].

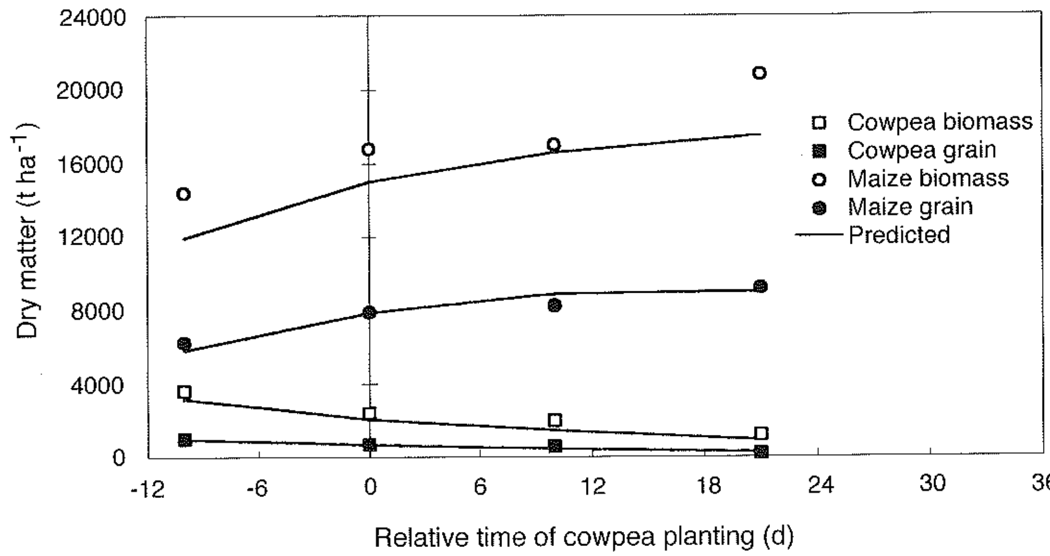

Fig. 3. Predicted and observed grain yields and total dry weights for maize and cowpea grown as intercrops where the timing of cowpea planting was in relation to maize planting time (Ofori 1986).

A crop-pasture mixture

McCown et al. (1985) proposed an innovative cropping system for the semi-arid tropics of northern Australia where rainfed crop production was closely integrated with ley pastures and livestock grazing. A component of this system involved planting a crop of maize or sorghum and allowing a legume pasture to establish as an understorey during the cropping season. This crop-pasture mixture provided high quality feed for cattle during the following dry season as well as permitting seed production of the legume for re-establishment of the ley pasture in the following wet season. A simulation model of this crop-pasture mixture was developed by Carberry et al. (1992, 1993a) to assess the production advantages of this cropping system against the potential loss in crop yield through competition for water and nitrogen by the legume understorey. Recently, this system was modeled within the APSIM simulation environment.

In simulating the maize-pasture mixture, APSIM was configured the same as for the maize-cowpea intercrop presented above. The exception was the substitution of a module describing the growth of a *Stylosanthes hamata* (cultivar Verano) sward for the cowpea module. The verano module was developed by inserting the relationships of Carberry et al. (1992, 1993a) into the APSIM crop template. Again, competition for water and nitrogen was simulated using the rotating call system of resource allocation. The ability of APSIM to predict the production of maize and verano grown alone or as a mixture is presented in Figure 2. This predictive ability was close to that demonstrated by the original maize-verano model (Carberry et al. 1993a).

An example APSIM application

The capability to simulate competition between crops in mixtures opens up possibilities of exploring many of the consequences of intercropping systems. However, there is not the opportunity within this paper to undertake this task, except for one small application as an example of these possibilities.

The APSIM model, configured as previously outlined for a maize-cowpea intercrop, was used to predict yields of sole crops and intercrops for each of 30 years of example climate data. The simulation runs compared two systems of management: (1) a "low input" system where maize is planted at a low plant population with no N-fertilizer, and (2) a "high input" system with double the maize and N applied as fertilizer. The intercrop in both systems consisted of cowpea planted 14 days after the planting date of maize.

Of interest in this particular analysis is the trade-off between the loss of maize yield in the intercrop relative to the sole crop (due to competition) against the gain in cowpea yield in the two intercropping systems (Fig. 4a). Judgment on whether such trade-offs are positive or negative clearly necessitates an economic perspective as the result will depend on the relative value of each crop. To further investigate this trade-off, the value of cowpea grain needed to offset the loss in maize grain was calculated for each year of simulation. This nominal price for cowpea grain is expressed in maize equivalent units (1 MEU is the value of 1 t ha^{-1} maize). Cumulative probabilities of this required cowpea value (Fig. 4b)

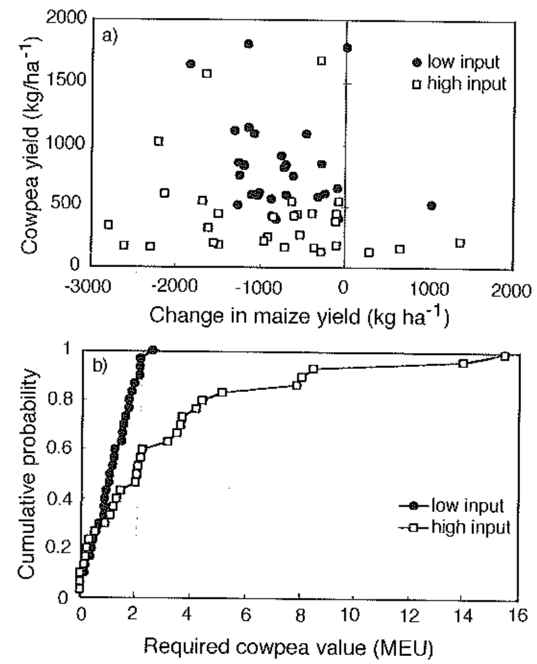

Fig. 4. (a) Grain yield of intercropped cowpea plotted against the change in grain yield of intercropped maize relative to that for sole maize for the two input systems;
(b) Cumulative probabilities of the required value for cowpea grain (MEU: maize equivalent units) needed to offset the corresponding maize yield loss resulting from intercropping under the two input systems.

suggest that, for this scenario, intercropping is more often a viable option under low rather than high input conditions. For example, if cowpea grain was worth double the value of maize (2 MEU), then intercropping was economically attractive in 29 of the 30 seasons under the low input system; but this was the case in only 50% seasons when input conditions were high. While this analysis is by no means comprehensive, it does illustrate to a degree why intercropping systems are predominantly practiced under low input systems around the world.

Conclusion

The APSIM cropping systems model is a relatively new product that is still rapidly developing. Its application to multiple cropping systems is one of the many new developments currently underway. A distinguishing feature of APSIM is that no one particular process has been the focus in its development. Rather, APSIM was developed to provide a flexible software system for simulating any component of agricultural production systems using the best available routines for that process. In this regard, APSIM differs significantly from many other modeling efforts, including the CropSys model (Caldwell and Hansen 1993), which was developed specifically to simulate multiple cropping systems.

The two examples of using APSIM to predict yields of crops grown in mixtures gave promising results, considering the limited investment that has been possible to date in this area of APSIM development. Opportunities for improvement are already identifiable, e.g., by providing in the arbitrator the capability to use canopy profiles if predicted by crop modules (Carberry et al. 1993b). Of considerable promise is the system of rotating the order of resource allocation between crops to simulate competition for soil water and nitrogen. Such a system is clearly superior to a set order of allocation (see Kiniry et al. 1992) and appears to result in little bias in simulation results (Fig. 1). Further work will continue on comparing this approach with alternatives that deal more explicitly with allocating resources between crops. The issue of spatially heterogeneous cropping systems, such as replacement intercrops, also needs to be considered.

The importance of this ability to simulate competition between species in the agricultural systems of northern Australia is mainly in simulating the effect of weeds and undersown pasture on crop performance. However, of particular interest elsewhere in the tropics is in the analysis of intercropping systems in relation to sole cropping. We hope to be able to collaborate in this application of APSIM in future research activities. The APSIM model represents a convenient and cost-effective means by which these objectives can be achieved.

Acknowledgments

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