Agricultural Systems Models Require High Modularity, Flexibility and Sound Component Science

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Abstract: The number of possible crops in rotations, the number of rotations possible at any location and the multitude of management options for each crop result in a problem of 'multi-dimensionality' that makes it impractical to use experimental approaches to assess decision options in agricultural production systems. Simulation analysis however can reduce this problem to something that is at least computable. In this paper we demonstrate how scientific rigour combined with sound software engineering has made the Agricultural Production Systems SIMulator (APSIM) a flexible simulation environment that allows crops, soils and management options to be freely configured to address issues at a range of scales and complexities. A crop module template that captures the common physiological principles across crops provides a generic modular structure for simulations of multiple crops and objective comparisons of model approaches at the component level. Management practices like crop choice, timing and sequencing of crops can be specified for short- and long-term simulations. Model applications range from genetic trait evaluation, cultivar and crop choice, to the design of the most suitable cropping systems in highly variable rainfall environments.

Keywords: Generic crop modelling; Modularity; Component simulation; APSIM

1 INTRODUCTION

Simulation modelling has become an important quantitative tool to evaluate options and to assist decision making in modern agriculture. Numerous simulation models for plant growth and soil processes have been developed for different purposes during the last decades. Originally, crop models were able to simulate a single crop and several soil processes such as soil water or nitrogen [van Keulen and Seligman, 1987; Chapman et al., 1993]. Later developments resulted in the separation of plant and soil processes and integration of multiple crop models into a cropping systems model [Tsuji et al., 1994; van Evert and Campbell, 1994]. The multitude of potential crops in cropping systems and the code repetition in the adapted crop models inspired the development of generic code for crop modelling [Tsuji et al., 1994; Reynolds and Acock, 1997; Wang and Engel, 2000; McCown et al., 1996; Wang et al., 2001b]. The complexity of cropping systems under a changing climate and evolving management system requires a highly flexible structure of cropping system models that can be configured to address issues at a range of scales and facilitates the rapid advance of component science.

The Agricultural Production systems SIMulator (APSIM) is a cropping system modelling environment that simulates the dynamics of soil-plant-management systems under variable climate [McCown et al., 1996]. APSIM combines scientific rigour and software engineering principles that aim to make the system highly flexible and provide sound component science. In this paper we demonstrate how these combined efforts contribute to the APSIM development by addressing both science and engineering with a focus on the model's predictive ability.

2 APSIM STRUCTURE AND MODULES

APSIM consists of a central interface Engine connected to a series of plug-in/pull-out modules simulating soil processes, numerous crops, trees or pastures and various management options (Figure 1). In the design of APSIM, a process-oriented approach has been followed and essential processes of each system component are clearly identified. For example, soil modules are responsible for simulating water, nutrient/chemical dynamics and other soil processes. A crop module is designed to contain only crop physiological processes. Other modules include those for management interventions and economical evaluation of system performance.

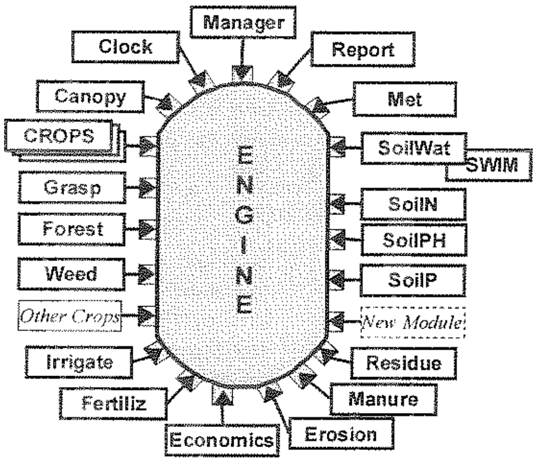

Figure 1. The modular structure of APSIM, illustrating the options of having alternative representations of certain processes (eg SoilWat or APSWIM for the water balance) and multiple crops.

Several key features of APSIM distinguish it from most other cropping system models. In APSIM, the soil, not the crops, provides the central focus. Changes in the status of the soil state variables are simulated continuously in response to weather and management. Crops come and go, finding the soil in a particular state and leaving it in an altered state [McCown et al., 1996]. Another key feature in the software design is the action/event driven modular structure together with the "plug-in-pull-out" approach. Modules in APSIM perform tasks in response to actions from within and outside the module. This action-based system allows modules to be loosely coupled, providing the key advantages of increased flexibility, maintenance and reuse. This arrangement offers great flexibility for comparing alternative representations of different parts of the system without modification of the rest of the model.

APSIM has pioneered flexible specification of management regimes in farming systems modelling. The Manager module is controlled by a script language, which enables a diverse range of management operations to be specified in ways that can be conditional on the state of the simulated system (weather, soil, crops). The timing and nature of operations such as sowing, tillage, residue management, fertilisation, irrigation, crop management, harvesting etc are all specified by users using this script language.

Another significant feature that combines the efforts of both the crop scientists and software engineers in APSRU is the use of a generic crop template (GCROP) to simulate multiple crops. GCROP has been developed to capture the general physiological principles that are applicable for all crops and to provide a generic framework for crop modelling with high science transparency and code efficiency [Wang et al., 2001]. It comprises a Standard Crop Interface (SCI) to the APSIM Engine, a Generic crop Model Structure (GMS), a Crop Process Library (CPL), and well-structured Crop Parameter Files (CPF). GMS allows the crop components to be loosely coupled and process-based sub-modules to be largely order-independent. CPL contains the major science underpinning the crop models and incorporates generic routines based on common physiological principles. CPF contains all the externalised model parameters. SCI generalises the model inputs and outputs, and supplies a standard interface to communicate with other APSIM modules. GMS and SCI form a standard crop template module (CTM) that can be instantiated multiple times to simulate different crops. All the instantiated modules share the same code but each of them, via a crop specific CPF, simulates a given crop. GCROP has become an important scientific tool for hypothesis testing of physiological processes. It makes APSIM an increasingly useful tool for research into genetics and "functional genomics" by connecting the disciplines of genetic engineering, plant breeding and crop physiology.

3 GENERIC COMPONENT MODELLING – A NEW WAY TO ENHANCE UNDERSTANDING

The continuous development of the generic crop template GCROP in APSIM creates new challenges both to science and engineering. Generic algorithms can only be developed based on sound understanding of the physiological processes. Hence, we are forced to seek the true mechanisms that govern the physiology across species. By gathering and integrating such knowledge across species, we try to generate generalised responses that capture the true nature of underlying processes and to gain understanding at a lower process level. A component that cannot be quantitatively generalised reveals either significant uniqueness of a given species or an area requiring further research. GCROP captures all the individual components/processes into the context of whole crop production responding to any given environment. We are able to use this to examine and assess the relative importance of modifications to each component/process and any needed research investment. We believe this approach can significantly contribute to rapid multidisciplinary scientific advance as well as set the directions for future research.

The implementation of such a generic approach can only be done based on our current level of understanding. It is essential that this engineering be based on well-structured science. It is equally important that it takes the full advantage of software techniques to facilitate the advance of science. For a system component where the processes are well understood, the highly modular component- or process-oriented design can well serve as the integration of knowledge and significantly promote the application of science. In this case, we try to use generalised ***relationships*** in the program code to capture the mechanisms and to modify externalised ***parameters*** to generate a diversity of response for various crops. Examples are canopy light interception and temperature-driven total plant leaf area modelling. For processes that are not well understood, engineering should allow easy testing and comparison of new theories. In order to create generic code, we use externalised ***relationships*** to facilitate future modifications once new understanding has been gained. It is important to remember that the final goal is to understand the processes and to derive generalised ***relationships*** from available data. Although a process sub-module is most generic if all the ***relationships*** are externalised, such a sub-module itself contains little science and may be less helpful for enhancing our understanding to derive the true response. In reality, there needs to be a balance between externalising process relationships and understanding the science.

The predictive ability of the model must remain a major focus. Hence, the level of complexity, understanding and data availability must be well balanced, with this balance being dependent on the modelling purpose. A framework that allows complex and detailed issues to be addressed does not imply that a model needs to be complex and detailed. Increases in complexity also increase parameter uncertainty and may result in loss of predictive ability [Spitters, 1990]. Simplified summary relationships can maintain comprehensiveness through their connection to the underlying theory [Hammer, 1998], which can ensure both scientific accuracy and model predictive ability.

4 ADDRESSING ISSUES AT A RANGE OF SCALES

Agricultural systems models with sound component science and solid software engineering, such as APSIM, have vast opportunities for application. The following examples demonstrate several features of APSIM to enable different users to address issues and problems across a range of different scales and complexity.

4.1 Alternative Approaches for Process Simulation, eg, Grain Growth

The process-oriented modular design of the crop template, together with the interchangeable process sub-modules allows essential processes such as grain yield/quality formation to be studied separately, and modelling approaches for the same process to be easily interchanged and tested. For example, the harvest index (HI) approach was used in many APSIM crop models, where a maximum harvest index, which can be reduced by stress, is assumed for a given crop genotype. A daily increase in harvest index is then used to simulate grain growth [Hammer and Muchow, 1994; Meinke et al., 1997]. Grain nitrogen is often simulated in a similar way by either using a constant maximum grain N concentration [Meinke et al., 1997] or a grain N concentration that could be changed by temperature and water/N stress [Hammer et al., unpublished]. This approach was considered to be simple and robust because of the linear increase in harvest index found in many situations [Chapman et al., 1993]. It had been used successfully to address issues at farm scale, eg, production risk analysis and evaluation of management options [Meinke et al., 1993; Meinke et al., 1997]. However, a detailed study with sorghum revealed that variations in final HI associated with maturity were not clearly related to any one aspect of HI increase (slope or timing), and that certain environments experienced during grain filling affect HI slope [Broard and Hammer, 2001]. Further, with this HI approach, mechanisms at the yield component level cannot be explored. Utilising the modular design, an alternative grain number/size (GNS) approach was plugged into GCROP without changing any other components of the model. This GNS approach represents more insights on the dynamics of yield formation. For example, yield variation in wheat is mainly due to variation in grain number rather than grain size (Figure 2a,b). This emphasises the importance of understanding how grain number is determined under various conditions and reflecting this relationship in simulation models. Using this approach, APSIM-Wheat [Wang et al., in preparation] now captures this relationship (Figure

2c), thereby increasing the confidence to use it to examine related quality issues. The differences in grain filling rates for carbohydrates and nitrogen and their different cardinal temperatures used in this approach provide insights to understanding grain quality formation. The model can generate different yield/quality levels under various environments and explain the yield or quality differences providing a sound basis for adjustment of management decisions and further improvement of yield [eg. Asseng et al., 2001].

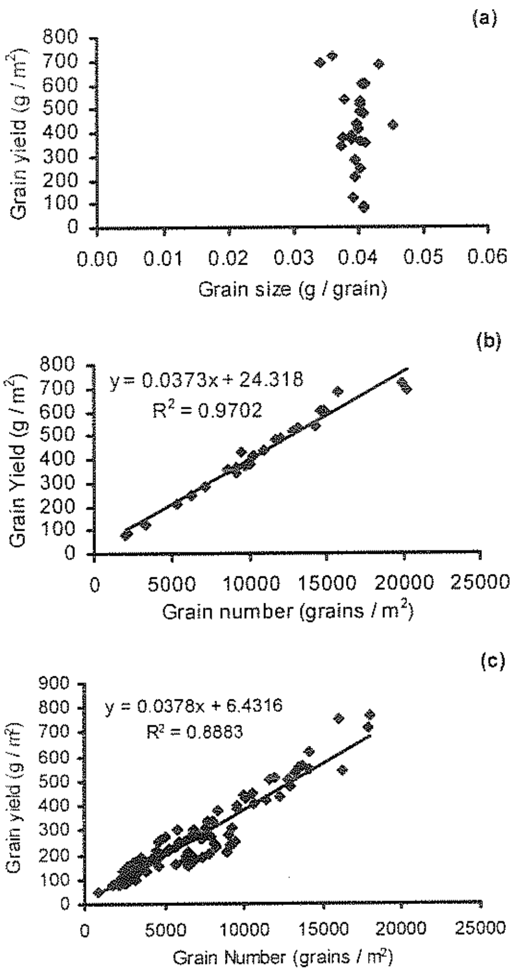

Figure 2. Relationship between grain yield and grain size or grain number. (a) and (b) data for wheat cv. Hartog from 3 experiments conducted in South East Queensland combining various N, water and residue treatments [Meinke et al., 1997; Keating et al, unpublished data]. (c) The simulated relationship between wheat yield and grain number in Queensland using APSIM-Wheat.

4.2 Evaluation of Genetic Traits to Support Breeding Program

The separation of model parameters from source code and the ability to reset these parameters of GCROP create great flexibility for evaluating genetic traits for the purpose of crop improvement. Many constants/parameters in the crop parameter file represent important physiological traits. Their values can be easily modified to conduct simulation runs under various environments. Thus the impact of these changes can be assessed.

Simulation analysis using APSIM-Sunflower [Wang et al., 2001a] and 100 years weather data from NSW and central Queensland identified six major types of water stress patterns. The most common stress pattern was the terminal stress pattern where little or no rainfall was received after sowing. These simulations indicated that a 10% increase in transpiration efficiency (TE) of the crop could result in a 12-14% increase in sunflower yield [Chapman et al., 1999]. This finding led to a revised breeding effort by using the carbon-isotope discrimination (delta) method to find molecular markers linked to low delta or high TE. Three RFLP markers have so far been identified and tests of the new hybrids under drought conditions showed that the low delta (high TE) pool significantly out-yielded the high delta (low TE) pool in two droughted locations by 35% [Lambrides et al., 2001]. Once these new hybrids become available, their performance under various conditions can be easily assessed using simulation. This reduces the need for expensive and time-consuming experiments.

4.3 Factorial Evaluation of Management Alternatives

The flexible specification of management regimes by the APSIM-Manager module allows the user to easily investigate a range of management options like sowing time, cultivar choice, fertiliser rate etc. APSIM also allows simulation runs to be fully automated by generating simulation control files that cover all permutations of full factorial combinations, eg, 2 crops, 3 soil types, 3 starting soil moistures, 4 sowing dates, 2 densities, 3 cultivars and 100 years of weather data. APSIM can then import the results of these simulation runs into an Access database and graphically display them. Generalised crop module outputs by GCROP make such simulation scenarios crop-type independent.

An example of an evaluation of management options is given in Figure 3. This shows the simulated responses of wheat grain yield to different sowing dates (a), maturity types (b) and N fertiliser rates (c). The results indicate that, on average, wheat yield decreases with delaying sowing dates. It further demonstrates that the high yield potential of early sowing can never be achieved with late sowing even under optimal growing conditions. The performance of different maturity types and the impact of various N rates on yield can be easily analysed using such simulations.

The Whopper Cropper team in ASPRU has established simulation databases with various crops, soils and possible management options [Hammer et al., 1996]. These simulation results can be used to evaluate a range of management options and to optimise these options in the context of climate variability.

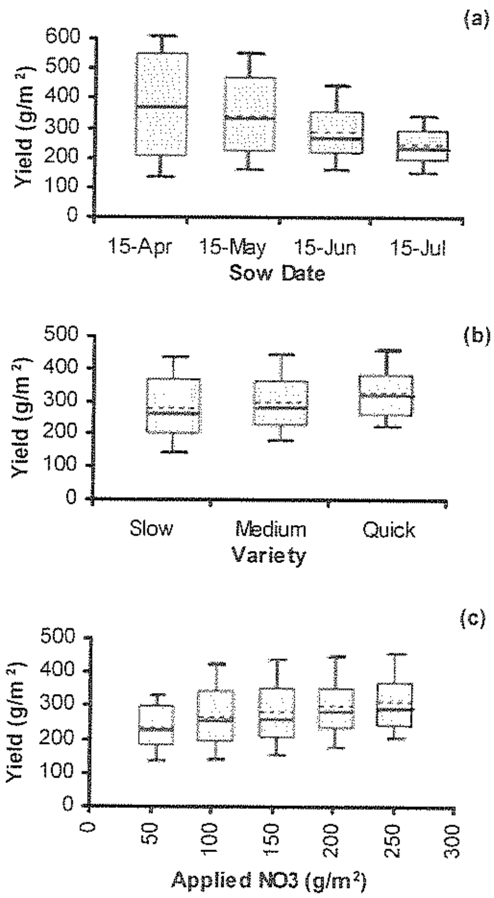

Figure 3. Simulated wheat yield response to different sowing dates, varieties and N rates at Goondiwindi, South East Qld. On each box bar from the bottom to top lines indicate the 10, 25, 50, 75 and 90 percentiles. Dotted lines indicate the average yield over the whole period. Simulations assumed that a medium variety was planted on a grey vertosol with plant available soil water 170mm. Fixed sowing dates were used with a plant density of 100 plants/m^2 and soil profile 2/3 full. For (a) 150 kgN/ha was applied at sowing. For (b) and (c) a fixed sowing date on 15 June was used.

5 DISCUSSION AND CONCLUSION

Agricultural systems models require high modularity, flexibility and sound component science. A focus of predictive ability and high usability must also be maintained. This can be achieved through combining sound software engineering with scientific rigour. The additional tools in APSIM package give the user vast opportunities to use the model to do various virtual experiments and address much more cross scale issues than what would be feasible with field experiments alone.

The development of the generic crop template (GCROP) presents a new challenge. It has the potential to enhance our understanding, promotes rapid scientific advance and provides a framework for testing useful ideas. Very often in the past, if a model performed worse under a given situation or it did not fit a specific framework, the whole model was rejected and many useful ideas in such a model were lost. GCROP enables interchange of different modelling approaches from a wide community of scientists, providing an objective assessment of these approaches by using well-defined goals. It allows APSIM crop modules to be configured using approaches with various levels of detail. It can also serve as a useful tool for gene function research by connecting the disciplines of genetic engineering, plant breeding and crop physiology.

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