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APSIM – Evolution towards a new generation of agricultural systems simulation

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A B S T R A C T

Agricultural systems models worldwide are increasingly being used to explore options and solutions for the food security, climate change adaptation and mitigation and carbon trading problem domains. APSIM (Agricultural Production Systems sIMulator) is one such model that continues to be applied and adapted to this challenging research agenda. From its inception twenty years ago, APSIM has evolved into a framework containing many of the key models required to explore changes in agricultural landscapes with capability ranging from simulation of gene expression through to multi-field farms and beyond.

Keating et al. (2003) described many of the fundamental attributes of APSIM in detail. Much has changed in the last decade, and the APSIM community has been exploring novel scientific domains and utilising software developments in social media, web and mobile applications to provide simulation tools adapted to new demands.

This paper updates the earlier work by Keating et al. (2003) and chronicles the changing external challenges and opportunities being placed on APSIM during the last decade. It also explores and discusses how APSIM has been evolving to a "next generation" framework with improved features and capabilities that allow its use in many diverse topics.

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Software availability

Name: Agricultural Production Systems Simulator (APSIM)
Developer: APSIM Initiative, Email: apsim@daff.qld.gov.au, T: +61746881596
Year first available: 1994
Hardware required: Any recent PC with a minimum of 2 Gb of RAM, 32 or 64 bit.
Software required: Microsoft Windows XP, Vista, Windows 7 or Windows 8. The model (not the user interface) will run on LINUX.
Availability: www.apsim.info
Cost: free for non-commercial use.

1. Introduction

Agricultural simulation models have an important role in informing farmer practice (Hochman et al., 2009b), breeding strategies (Cooper et al., 2009) and government policy (Bezlepkina et al., 2010) that aim at addressing challenges such as food security and climate mitigation and adaptation. The demand for tools that can assist in the analysis of complex problems are more pronounced than ever. The evidence for this can be seen by examining the papers in the Special Issue "Modelling Cropping Systems: Science, Software and Applications" of which the Keating et al. (2003) paper was one article. The overview paper for the Special Issue (van Ittersum and Donatelli, 2003) outlined how "model use is no longer exclusively driven by researchers" and went on to list "management of production systems" and "exploring options at farm and regional scale" as two dominant model applications in the Special Issue. While food security and climate mitigation and adaptation are no doubt implicitly part of these application domains, no mention is made of how models can inform plant breeding and government policy. Jones et al. (2003), in the same Issue, table a list of DSSAT applications where climate change and variability account for 25% of all applications; food security <2%. Stöckle et al. (2003) and Brisson et al. (2003) both describe how the models CropSyst and STICS, respectively, were used to explore the impact of climate change scenarios on cropping systems. No mention was made of the other drivers of change. A decade on and a trend is emerging where agricultural models need to be broader in scope and cover new and wider domains (Holzworth et al., 2014). The models also need to be able to simulate scenarios that include mixes of gene and trait effects, crop and pasture production, livestock performance.

The social setting where agricultural models are used has also changed dramatically in the past ten years. Social media, internet and mobile applications that are spatially aware, for example Google Maps/Earth, have exploded in popularity with a consequent impact on the scientific community. The world is a much more connected and open place than it was ten years ago. Many researchers use tablets and other mobile devices, using and building apps in their problem domains. Open source, freely available software is routinely used (e.g. R, GFortran, MapWindow) and many expect agricultural models to be the same. Open source encourages collaboration and provides a degree of transparency that is not possible with closed arrangements.

The Agricultural Production Systems sIMulator (APSIM) is a farming systems modelling framework that has evolved significantly due to these external pressures. It contains interconnected models to simulate systems comprising soil, crop, tree, pasture and livestock biophysical processes. It is used extensively by researchers to assess on-farm management practices, climate risk/change adaptation strategies, mixed pasture/livestock strategies, agroforestry resource competition, nutrient leaching under various conditions, gene trait expression and many other applications. The literature contains numerous papers outlining the many uses of APSIM applied to diverse problem domains. In particular, McCown et al. (1995, 1996), Wang et al. (2002) and Keating et al. (2003) have described earlier versions of APSIM in detail, outlining the key APSIM crop and soil process models and presenting some examples of the capabilities of APSIM. However, given the most recent of these publications is now ten years old and how much APSIM has evolved, an updated paper describing current capabilities is warranted.

The purpose of this paper is to describe the evolution of APSIM since its description by Keating et al. (2003) and to describe the directions in which it is likely to continue to develop in the future. It outlines the modifications that have been made to the content and scope of the APSIM modules, infrastructure, user and developer support, training and the legal/IP arrangements. The reader will discover how APSIM is being used in a diverse range of problem domains, how the community of users and developers has evolved and how APSIM is being redeveloped into a "next generation" agroecosystem model. Simulation models provide great benefit to agricultural science when they are extensively used by a wide-ranging community of agricultural scientists. Much of the development surrounding APSIM has been aimed at achieving this – through a variety of means including expanding the 'science base' of the model and through more flexible IP arrangements. We will not present a detailed description of the individual sub-models that make up APSIM here, as the earlier overview papers cover this topic adequately and most are still relevant.

2. A description of APSIM

Work on building the APSIM framework began in the early 1990s. A key and novel design concept was a focus on cropping systems as distinct from individual crops. The dynamics of the soil and system management over crop seasons became central. It seems simple now, but the statement below transformed how APSIM was designed from both science and software engineering perspectives.

"Crops come and go, each finding the soil in a particular state and leaving it in an altered state." (McCown, 1995)

The early inclusion of a highly flexible manager module was also critical to achieving this novel farming systems modelling capacity. A key design specification was that the simulator needed to be capable of robustly representing farm management specifications that went well beyond ourcurrent imagination, so a truly generic manager design was needed.

Existing knowledge from the literature and models available at the time, both from participants and other groups, were utilised as a starting point. A further key and novel design concept was the modular software framework developed to support close connection with scientific innovation in modelling crop and soil processes. Fig. 1 shows how initially APSIM inherited much of the science and knowledge built into AUSIM and PERFECT and how both of these precursors had incorporated developments from other groups. The initial version has been enhanced continuously and substantially via both in-house research and development and integration of relevant models and scientific knowledge from other groups (Table 1, Fig. 1). Facilitating this on-going software and science improvement is a conceptual and critical design feature of APSIM and continues to this day.

For the first decade, the focus was on construction of the software infrastructure required to implement a cropping systems model in a modular fashion and on scientific development of simulation models for the broad acre crops important for Australian

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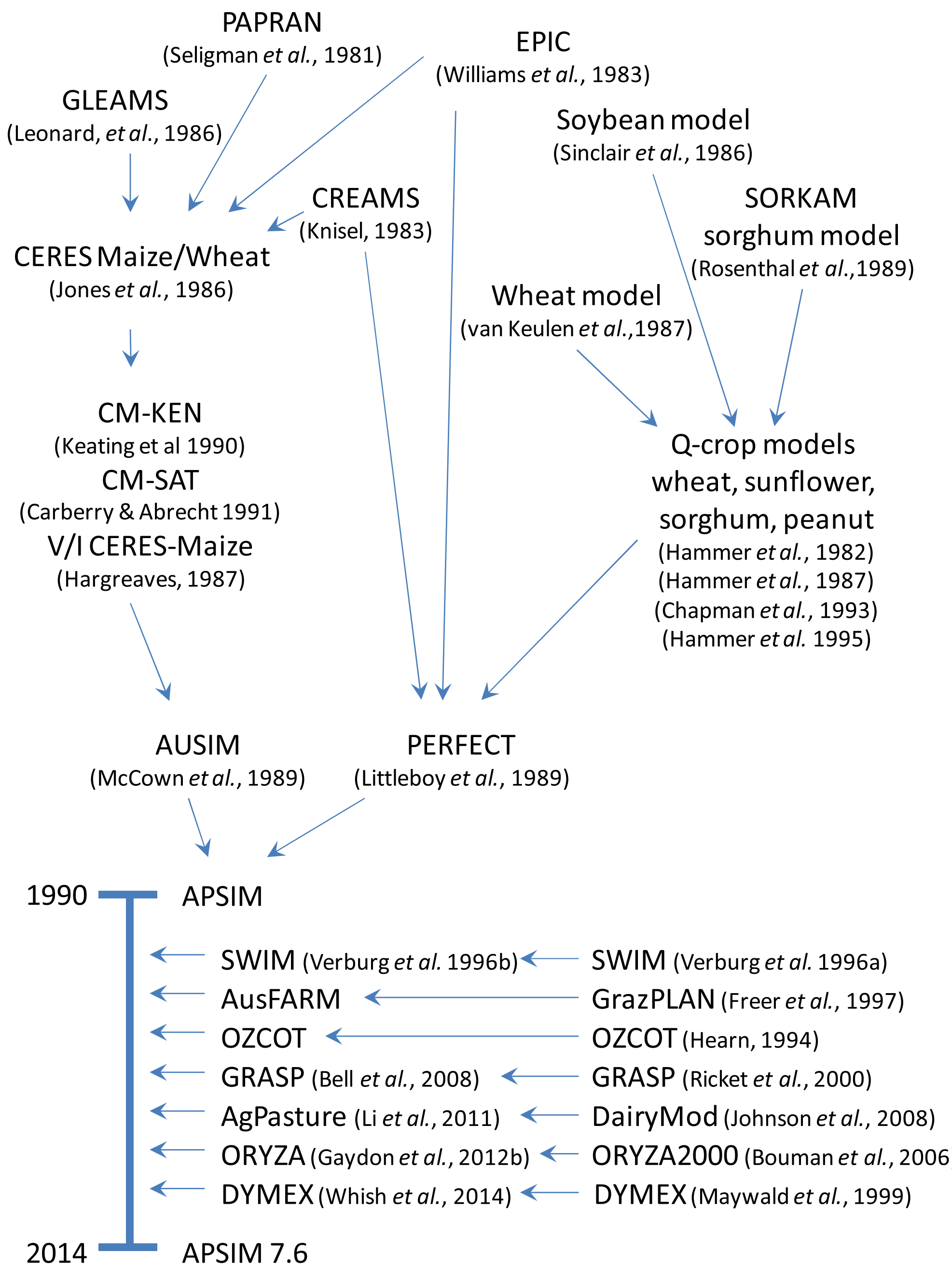

Fig. 1. This figure shows the model pedigree of APSIM, the models that have influenced APSIM's inception and the external models that have been incorporated into APSIM, post 1990. It does not show the numerous models that have been built in APSIM.

farmers. This model building phase represented a way of capturing the modeller's knowledge of the farming system. The software development processes in the first half of that decade were relatively informal but was acceptable at the time because the team was small and co-located. During the latter part of that decade, considerable time was invested in determining whether tools like APSIM could be beneficial to consultants and farmers (Carberry et al., 2002). The decade following 2003, the focus for this manuscript, was primarily devoted to deepening our systems thinking through applying and extending APSIM to new problems, new fields of research and new scenarios, leading to new capabilities being added. This section presents a brief overview of APSIM with a focus on the new capability that has been added during this period of model development and application.

APSIM is comprised of 1) a set of biophysical models that capture the *science* and management of the system being modelled, 2) a *software* framework that allows these models to be coupled together to facilitate data exchange between the models, 3) a *community* of developers and users who work together, to share ideas, data and source code, 4) a *data* platform to enable this sharing and 5) a *user interface* to make it accessible to a broad range of users.

A model is defined as a unit of computation and in APSIM this represents a collection of processes. For example, a crop or water balance is considered a model whereas photosynthesis or runoff is considered a process. These process based models interact with each other on a daily timestep. Table 1 provides a list of the biophysical models available in APSIM and specifies the key

Table 1
The plant, soil, animal and climate models are listed with key references describing the development and testing of each model.

APSIM model	Origin/references	APSIM model	Origin/references
Plants		Sorghum	(Hammer et al., 2010)
AgPasture	(Li et al., 2011a)		(Whish et al., 2005)
Bambatsi		Soybean	(Robertson and Carberry, 1998)
Barley	(Manschadi et al., 2006)	Stylo	(Carberry et al., 1996c)
Broccoli	(Huth et al., 2009)	Sugarcane	(Keating et al., 1999)
Butterfly pea		Sunflower	(Chapman et al., 1993)
Canola	(Robertson et al., 1999)	Sweet corn	(Henderson et al., 2011)
Centro		Sweet Sorghum	
Chickpea	(Robertson et al., 2002)	Vine	
Cotton	OZCOT:	Weed	
	(Hearn, 1994)	Wheat	(Brown et al., 2014)
Cowpea	(Adiku et al., 1993)		Wheat (Wang et al., 2003)
			NWheat (Keating et al., 2001)
Fababean	(Turpin et al., 2003)		I_Wheat (Meinke et al., 1998)
Field pea	(Chen et al., 2008a)		Nwheats (Asseng et al., 1998)
	(Robertson et al., 2002)	*Soil*	
French bean	(Henderson et al., 2011)	DCD	(Cichota et al., 2010)
GRASP	(Bell et al., 2008)	Erosion	(Freebairn et al., 1989; Littleboy et al., 1992)
	(Rickert et al., 2000)	Nitrogen (SoilN)	(Probert et al., 1998a)
Growth	*Eucalyptus* species	Phosphorus	(Delve et al., 2009)
	(Huth et al., 2002)	Pond	(Gaydon et al., 2012c)
Lablab	(Hill et al., 2006)	Solute	(Paydar et al., 2005)
Lucerne	(Dolling et al., 2005)		(Poulton et al., 2005)
	(Probert et al., 1998b)	Surface	(Connolly et al., 2001)
	(Verburg et al., 2007)	Surface OM	(Probert et al., 1998a)
Lupin	(Farré et al., 2004)		
Maize	Origin: AUSIM-maize	SWIM	(Huth et al., 2012)
	(Carberry and Abrecht, 1991a,b)		(Connolly et al., 2002)
Millet	(van Oosterom et al., 2001)		(Verberg et al., 1996a,b)
Mucuna	(Robertson et al., 2005)	Temperature	(Campbell, 1985)
Mungbean	(Robertson et al., 2002)	Water (SoilWat)	(Probert et al., 1998a)
Navybean	(Robertson et al., 2002)		(Verberg and Bond, 2003)
Oats	(Peake et al., 2008)	Water Supply	(Gaydon and Lisson, 2005)
Oil Mallee		*Animal*	
Oil Palm	(Huth et al., 2014)	DDRules	
Pasture	(Moore et al., 1997)	Graz	(Owens et al., 2009)
Peanut	(Hammer et al., 1995)	Stock	(Freer et al., 1997)
	(Robertson et al., 2001c)	Supplement	
Pigeonpea	(Robertson et al., 2001b)	*Climate*	
Potato	(Brown et al., 2011a)	Canopy	(Carberry et al., 1996b)
Rice	ORYZA:	E0	(Meinke et al., 2002)
	(Bouman and van Laar, 2006)	MicroClimate	(Snow and Huth, 2004)
	(Gaydon et al., 2012b)		

reference(s) for each. They are categorized into plant, soil, animal and climate models. As the models function in a similar way as described by Keating et al. (2003), only a short summary of the plant, soil and animal models is provided, with some highlights on the new developments that have occurred in the last ten years.

2.1. Plant models

The plant models simulate the key physiological processes, including phenology, organ (leaf, stem, root, and grain) development, water and nutrient uptake, carbon assimilation, biomass and nitrogen partitioning between organs, and responses to abiotic stresses. These processes are described extensively in the literature (see Table 1). Many of the crop models reuse the same source code base with an external file used to specify which processes to use and parameterisation. This generic crop template work, pioneered by Wang et al. (2002), was combined with the work by Robertson et al. (2002) to create a generic PLANT model which has now been applied to simulating 30 different plant species. Around the same time, a generic cereal template was incorporated into APSIM that simulates sorghum and maize (Hammer et al., 2010). Recently, an approach was developed by Brown et al. (2014) to evolve both approaches into a single, unified code base capable of simulating all species of plant. Named the ‘Plant Modelling Framework’, this new framework provides a library of plant organ and process submodels that can be coupled, at runtime, to construct a model in much the same way that models can be coupled to construct a simulation. This means that dynamic composition of lower level process and organ classes (e.g. photosynthesis, leaf) into larger constructions (e.g. wheat, sorghum) can be achieved by the model developer without additional coding. This approach takes advantage of the most advanced science in a given species, while minimising the maintenance of many code bases. Hence, all plant models communicate with other models in the same way. For example, they all provide potential uptake values for soil water, nitrate and ammonium-N to the soil models in a consistent manner. Likewise they communicate with MicroMet for light arbitration, with the animal models for grazing, and with the soil organic matter model for return of biomass to the soil surface at harvest or following a cutting event. This consistent approach to inter-model communication allows models to be swapped at will, not just for the plant models but also for many other models in APSIM. This realises the intent of the original crop template work begun over a decade ago.

Modelling of crop response to increased atmospheric CO_2 has grown in importance with growing interest in analyses of climate change scenarios and so plant CO_2 responses have been incorporated into most crops via the generic crop template (Wang et al., 2002). Increased atmospheric CO_2 concentration impacts upon simulated crop growth and resource use via changes to radiation use efficiency (RUE), transpiration efficiency (TE) and the critical nitrogen concentration (CNC) for crop growth (Reyenga et al., 1999a). Testing of simulated responses to increasing atmospheric CO_2 has been published for predecessors of the current APSIM Wheat model (Asseng et al., 2004; Reyenga et al., 1999a).

A rice modelling capability is a new addition to APSIM with the ORYZA2000 rice model (Bouman and van Laar, 2006) incorporated into the APSIM framework. The soil water routines within the original ORYZA2000 model were replaced by APSIM's soil water balance modules, while routines to describe realistic soil water, carbon and nitrogen dynamics in rice-based cropping systems were incorporated within the APSIM soil modules (Gaydon et al., 2012b) to replace the previously ‘dryland-specific’ ones. Various new chemical and biological processes that occur in long-term ponded water (such as algal biomass production and N fixation – critical to the performance of rice cropping systems) were also added to APSIM's simulation capability via the APSIM-Pond module and subsequently validated against long-term cropping experiments and fertility trials (Gaydon et al., 2012c). The new modelling framework is often referred to as APSIM-Oryza and is increasingly used by scientists throughout the rice-growing world (Brown et al., 2011b; Heinemann et al., 2012; Liu et al., 2013b). A similar arrangement provides APSIM users access to the OZCOT cotton model (Hearn, 1994).

APSIM is no longer just a cropping systems model but can also simulate the growth of a range of pastures and forages. The range of pastures and forage models available in APSIM has grown significantly over the past decade and now includes several annual forages (e.g. forage oats and sorghum, *Lablab purpureus* and *Centrosema* spp.). The lucerne model has been used and validated in a wider range of environments and systems (Chen et al., 2008b; Dolling et al., 2005; Teixeira et al., 2009; Verburg et al., 2007). Several models for domesticated tropical grasses have also been developed although none of these have been widely validated, e.g. *Panicum coloratum var. makarikariense* (Paydar et al., 2005) and Rhodes grass (Lawes and Robertson, 2008). Linkages of APSIM with other animal-pasture models have also brought the capacity to simulate native or unimproved pastures using GRASP (Bell et al., 2008; Rickert et al., 2000) perennial ryegrass/white clover using AgPasture (Li et al., 2011b) and a range of improved and native temperate pastures via the GRAZPLAN pasture growth model (Moore et al., 1997). Incorporating the GRAZPLAN model into APSIM has been done in much the same way as ORYZA and OZCOT; to some extent, therefore, the reduction in the size of the APSIM code base through the use of the Plant Modelling Framework has been balanced by the addition of new code that has been incorporated. Integration of a multi-species pasture module into APSIM allows modelling temperate pasture systems (Li et al., 2011a,b). The plant production response to CO_2 in the newly integrated pasture model was modelled by incorporating the CO_2 effects on plant photosynthesis, nitrogen demand and stomatal conductance (Li et al., 2013).

Large scale oil palm (*Elaeis guineensis*) development around the globe has led to interest in an agricultural systems model for these systems. Development of the APSIM Oil Palm model (Huth et al., 2014) has grown out of experience in modelling other agroforestry systems (Huth et al., 2002) and the development of the new generic plant modelling framework (Brown et al., 2014). Current development and testing of the model is being undertaken in Papua New Guinea and South East Asia for the purpose of exploring sustainability indicators for yield, fertiliser management and greenhouse gas emissions.

The performance of the plant models in APSIM has been widely reported in the literature (Table 1). Most of the references in Table 1 compare simulated outcomes against experimental measurements, this being the traditional validation technique. Carberry et al. (2009) were interested in how the APSIM plant models compare to farmer grown crops. This is important for farmers and consultants gaining credibility in APSIM's ability to simulate their crops. They describe the performance of a number of APSIM crop models and conclude that APSIM is relevant to the real world, provided soil properties are well characterised. More recently, Pembleton et al. (2013) compared APSIM predictions of forage crops to farmer records and found that although biomass was relatively well-predicted, additional work was required on the prediction of the nutritive value of the crops.

2.2. Soil models

The soil models simulate the relevant processes occurring on and in the soil profile; this includes water infiltration and movement, evaporation, runoff and drainage, temperature variations, the cycling of nitrate, ammonium and other solutes, and soil organic matter decomposition (Table 1). Two models of water and solute transport are provided: a simple one using a “tipping bucket” approach (SOILWAT: (Probert et al., 1998a)) and another using a numerical solution of the Richard's equation (SWIM: (Verberg et al., 1996a,b)). Although they are quite different, both approaches are interchangeable and work with all plant models. Over time, the SWIM module has been developed to improve its numerical stability and simplify parameterisation of soil hydraulic properties (Huth et al., 2012). There have also been developments in models of other soil processes. The Surface Organic Matter module has a revised function describing the decomposition of thick layers of crop residues on the soil surface (Thorburn et al., 2001b). The SoilN module, which has always simulated the processes of nitrification and denitrification, has been modified to include emissions of N_2O during nitrification, and partition N gasses emitted during denitrification into N_2 and N_2O (Thorburn et al., 2010).

The soil phosphorus model simulates crop response to added P fertilisers under different soil conditions (Delve et al., 2009). A new development included the effect of root citrate efflux on P availability in soil, crop P uptake and growth (Wang et al., 2013a). This has enabled the model to be used to simulate the long-term impact of root citrate across soil and climatic conditions. The enhanced model can be used to simulate a wide range of combinations of Genotype by Environment by Management (GxExM) scenarios to address knowledge gaps, and to assist in design of field testing for validating the performance of new wheat varieties (with enhanced citrate efflux from roots) across environments. The simulation results formed the basis of a life cycle assessment of phosphorus use for wheat grown in Australia (Ridoutt et al., 2013).

Urease and nitrification inhibitors are increasingly being used to increase the retention of N added to the soil (e.g. in fertilizer, urine, manure, etc.) and so reduce losses to the environment through leaching or gaseous (N_2O, NH_3) emissions. Simulation models such as APSIM can play an important role in the investigation of likely benefits of these inhibitors as well as investigating, *in silico*, possible solutions to technological challenges. One current example is the increasing use of the nitrification inhibitor DCD in grazed dairy farming systems in New Zealand and a generalised inhibitor model is currently under development using DCD as a template (Cichota et al., 2010).

2.3. Animal models

Several options exist for simulating cattle and sheep in agricultural systems, including their effects on crops and soils. For analyses where livestock production outcomes are of interest, the GRAZPLAN ruminant biology model (Freer et al., 1997) can be

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coupled to an APSIM simulation. This model is conceptualized at a similar level of physiological detail to the plant models in APSIM. It can be used to model a wide variety of sheep and cattle genotypes and of flock or herd structures, through the use of management events that cover trading, reproductive management and grazing management of animals. Grazing of grain crops, both during the growing season (Moore, 2009) and as residues (Lilley and Moore, 2009), can be modelled. A separate model handles storage and supply of supplementary feeds, including conserved forage, to livestock. Return of nutrients to the soil as urine and faeces is modelled explicitly. Lastly, where animals are of interest only insofar as they remove forage and recycle nutrients, then these processes can be mimicked using simple management scripts where biomass removal by livestock is equated to cutting. However, this mechanism will omit several processes known to be important to the behaviour of grazed systems (Snow et al., 2014).

2.4. Software

A simulation (defined as a configuration of APSIM) is constructed by coupling models together to form larger “models” and then configuring each by specifying its input parameter values. Fig. 2 represents models as jigsaw pieces. A large set of toolboxes of biophysical and infrastructure models provide the necessary pieces to construct a representation of a single point in space. This single soil/climate/management construct has traditionally represented a field on a farm that has a uniform soil and management. In the past decade, this capability has been expanded to allow multiple constructs or fields with an overarching controlling construct that could represent a whole farm. This top level construct can contain any combination of models but usually incorporates a climate provider model and a management model that specifies the interactions between the fields. This multi-point capability can be used for many other scenarios, for example, simulating a field with variable soil types or urine patches within a field. Section 3 outlines several other uses of this capability. At run-time, a set of common software interfaces, known as the “common modelling protocol (CMP)” (Moore et al., 2007), are used to control the computation of the simulation and to convey information between the component models/modules.

One aspect that sets APSIM apart from most other agricultural models is its ability to allow users to describe management interventions via scripting languages. Scripting languages have provided the user with a mechanism to precisely describe on-farm management interventions using rules without needing to modify the source code (Moore et al., in this issue). Over the past decade, the number of languages supported has grown from a single, in house built, FORTRAN style language to include C#, VB.NET, TCL and R. These languages allow the user to precisely specify management of all APSIM models by a) inspecting and setting the values of model variables, b) sending events to the models and c) receiving events from them. APSIM utilises the features of the CMP, where an event is defined as an instruction (e.g. sow, harvest, fertilise, irrigate) that can be sent to a model or is a notification that something is occurring (sowing, flowering, harvesting). The interactions between the models can be quite complex in multi-point simulations, hence the need for building in full scripting capabilities. For example, pastoral, dairy and mixed crop/livestock farms with many possible management interventions present significant challenges to the process-based simulation modeller. To overcome the problem of trying to foresee all possible management interventions, scripting languages have been employed, allowing the modeller to custom build the required functionality.

Every APSIM simulation must be represented as an XML document before it can be executed (Moore et al., 2007). There are multiple ways of building this document. The most common is via a graphical user interface that allows models to be chosen from a set of toolboxes. The models listed in Table 1 can all be found in toolboxes along with many infrastructure models for reading and writing data, scripting and graphing results. A separate “Management” toolbox contains many user built management scripts to control one or more models. These scripts (complete with their own user interface) have been collected over the past decade and provide an immense array of functionality to the APSIM community

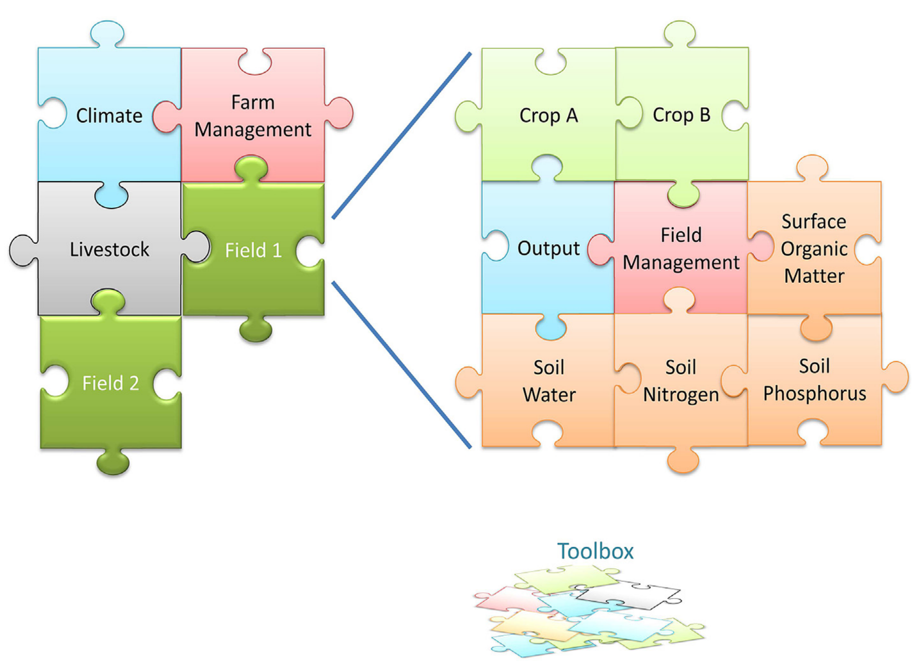

Fig. 2. This conceptual representation of an APSIM simulation shows a “top level” farm (with climate, farm management and livestock) and two fields. The farm and each field are built from a combination of models found in the toolbox. The APSIM infrastructure connects all selected model pieces together to form a coherent simulation.

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of users. Other XML files are used extensively by the user interface to represent toolboxes, model configuration files and the simulation file itself. These text based files are also very easy to construct or modify outside the user interface. When coupled with the ability to run APSIM from a command line, this document-based approach provides a capability to run batches of APSIM simulations on a single computer or a cluster of computers. This capability has been used by many to simulate large factorials of simulations (Cichota et al., 2012; Hayman et al., 2010) or large spatial areas.

The way software is created and tested by software developers has changed significantly over the last decade. In general, the software industry has moved away from heavy, top-down, waterfall methods of development to adaptive and incremental methods. Often called Agile Software Development (http://agilemanifesto.org/), the emphasis is on individuals and interactions, working software, customer collaboration and responding to changing requirements. APSIM's style of development has been profoundly and positively influenced by the Agile style of development. Rather than adopting a prescriptive style of development, many Agile techniques have been adopted by the APSIM software team. Holzworth et al. (2011) describe how version control, continuous integration, defect tracking and automated testing have been combined to improve APSIM's stability and robustness. When a change is submitted for inclusion in the next software release, it is automatically compiled and run against a large test suite. Only when the output from this run is deemed to be correct are the changes committed to version control and released in the next version. This level of rigour is critical to maintaining the integrity and performance of APSIM, particularly given APSIM's open source nature and geographical spread (multiple sites in Australia, New Zealand and Europe) of developers.

In the last decade, programming languages have evolved, bringing the ability for the code to examine itself and extract metadata inserted by the programmer. Reflection, as it is called, provides the ability to write lightweight models that are more transparent and easier to understand than models with a lot of infrastructure code (David et al., 2013; Rahman et al., 2004). These techniques have been used in APSIM to explore simpler ways to create generic and flexible plant models and user interfaces (Holzworth et al., 2010). Indeed, many users use the scripting capability of APSIM to build complex models for quick prototyping needs. This is in stark contrast to the technology of APSIM's inception where model developers were faced with a multitude of hurdles to produce the simplest of components. At that time, developers had to contend with multiple compilers, builders, protocols and programming interfaces. New programming languages, primarily C# and VB.NET, and scripting have made this much simpler.

The expansion of the software and hardware platforms that APSIM can utilise includes the addition of a version of APSIM that can run on most LINUX systems. This has been made possible by using GNU FORTRAN, GNU C++ and the MONO framework for the .NET languages. Interoperability between models written in different languages is facilitated by the generic nature of the CMP (Moore et al., 2007). This support for LINUX platforms has allowed APSIM to be executed on science grid infrastructures and computer clusters. This enables large scale, gridded applications to be developed (Elliot et al., 2014; Hammer et al., 2014; Zhao et al., 2013a) at the regional, country, continental and global scale.

2.5. The APSIM community

In 2007, the APSIM Initiative (AI; www.apsim.info/AboutUs.aspx) was established to promote the development and use of APSIM. All development, maintenance and commercialisation activities are now the responsibility of the AI. Previously, the research-oriented Agricultural Production Systems Research Unit (APSRU) managed both the application and development of APSIM and its related science. After many years of successful collaboration among several institutions, APSRU continues as an informal collaborative arrangement between interested parties based out of Toowoomba, Australia. The foundation members of the AI are CSIRO, the State of Queensland (through its Department of Agriculture, Fisheries and Forestry) and the University of Queensland with other institutions encouraged to join the Initiative. The AI is managed by a Steering Committee, with a Reference Panel providing advice on matters relating to APSIM development, in particular science quality and software development.

The change in governance arrangements for APSIM was paralleled by a distinct shift in the focus of how it is managed. Previously, APSIM users were required to pay a licence fee; APSIM is now released under a modified open source arrangement, is freely available for non-commercial use and can be downloaded from the APSIM website (www.apsim.info). An open-source licence was developed that satisfied the three organisations of the APSIM Initiative; adopting a generic GNU type license was not an option due to the need for commercial use clauses. This open approach to development and licensing has led to an explosion of APSIM usage worldwide with approximately 100 downloads per month. Fig. 3a shows a map of downloads, which is one indicator of APSIM usage. The map clearly shows that APSIM has been noticed outside of its Australian home base. Perhaps a better measure of usage is via journal article citation. Fig. 3b shows Web Of Science citation statistics. 6852 journal articles have cited one or more of the 551 articles that have APSIM as a topic. This level of citation increased markedly in 2009, following a two year lead time from the inception of the AI and its more open policy for development and licensing.

The openness and internationalization has also seen a much broader pool of developers contributing to the development of APSIM. To maintain and enhance the quality of science and software, the AI has created a process for reviewing all major changes to the source code. Run similarly to an editorial board at a journal, the AI asks members of the APSIM community to perform a review of the change and make recommendations for enhancing the science or software.

2.6. Data platform

As the APSIM community has broadened, there has been an increase in the demand for sharing of model configurations, soil and weather files and data needed to parameterize the models. Within Australia, simulation modellers are fortunate to have access to a comprehensive collection of climate (Jeffrey et al., 2001) and soil data (Dalgliesh et al., 2009). In todays connected, cloud based world, users expect easy access to such data. For countries without similar data availability or services, the needs are great and to this end, the AI is exploring options for building a linking network that connects users to APSIM data. With a working name of The Stack (http://www.apsim.info/TheStack), the Google Earth based product allows users to share one or more of their DropBox™ folders with The Stack. The Stack crawler then indexes the files found in the folders and creates a Google Earth KMZ file, allowing Google Earth to show the locations of the files (Fig. 4). The Stack already indexes various online databases such as APSoil in Australia (Dalgliesh et al., 2012), the WISE soils database (Romero et al., 2012) and the Watch Forcing Dataset (Weedon et al., 2011).

The AI also collects and stores the calibration and validation data that is used to build and test a model's performance. A generic database (REMS) has been developed for storing experimental data (McLean and Doherty, 2004). It has proved useful for storing a considerable amount of data for a number of experiments. Recently, we have begun exploring using The Stack as a storage repository for

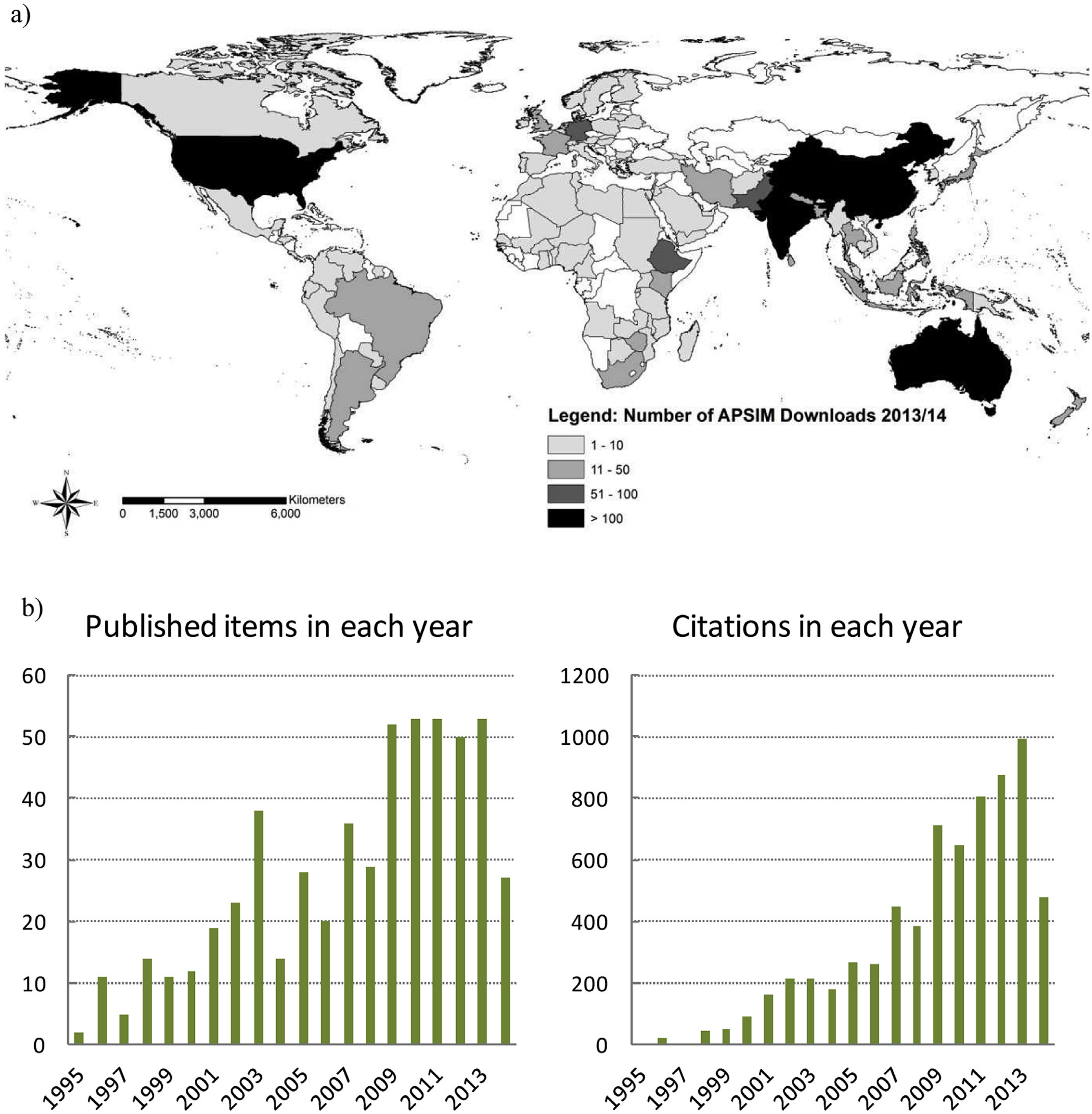

Fig. 3. a) The map shows APSIM downloads by country for July 2013 through to June 2014. The shading indicates the number of downloads. b) These two graphs show citation statistics from Web Of Science on the number of journal articles that have APSIM as a topic (as at the end of June 2014) and the number of citations of those articles per year. Other statistics include the number of articles (551), total number of times cited (6852), number of citing articles (3612), average citations per article (12.44) and an overall h-index (40).

this type of data which would allow users to easily view the validation graphs and download the model configurations and outputs. While the issue of data ownership and intellectual property inevitably arises, the approach being adopted thus far is to only publish data that are in the public domain or where we have the required permission. This issue remains unresolved and is one that the agricultural modelling community needs to address. Furthermore, the issues around how to acknowledge, store and access scientific data is a global issue facing all science disciplines. Many initiatives are being formed to explore options and provide guidance for scientists, for example the Australian National Data Service (website at www.ands.org.au. Accessed 29 August 2013).

3. APSIM's broader scope and scale

Much of APSIM's impact is achieved through its use in achieving a deeper understanding of the problem domain, its application to analysing real world problems and to providing options to farmers,

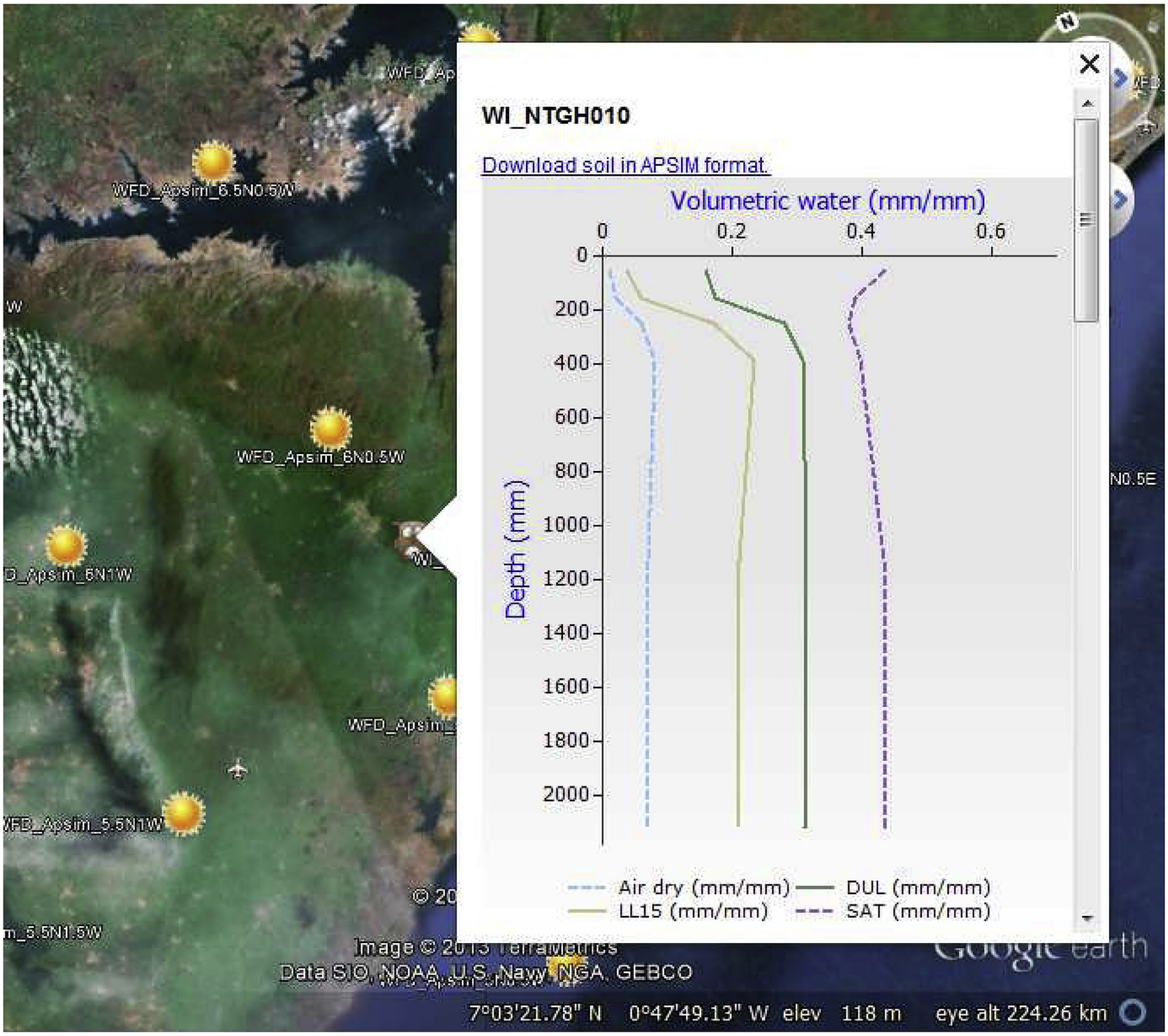

Fig. 4. This screenshot of the integration of The Stack in Google Earth shows a graph of the soil water profile for a soil from the WISE database.

consultants, plant breeders and other end users. In the past decade, the types of problems being addressed by APSIM have significantly broadened in both scope (livestock, environmental outcomes, pests and diseases) and scale (gene expression effects through to whole farm). No longer just a cropping systems model, APSIM has evolved into a legitimate agricultural systems model. This section explores the domains within APSIM's reach and provides a snapshot of new applications that were not possible a decade ago.

3.1. Delivering outcomes directly to consultants and farmers

Typically, commercial farmers manage their agronomy, marketing, and finance in regards to profitability and risks. This complex mix of activities is made more difficult by Australia's variable and changing climate. As APSIM can clearly help with some of these, a simplified commercial online tool, Yield Prophet® was developed to suit farmer and consultant needs. Developed through a partnership between CSIRO and BCG (The Birchip Cropping Group, a not for profit farmer-driven research organisation), it provides a simplified Internet enabled user interface to APSIM (Hochman et al., 2009b). Consultants and their farmer clients use Yield Prophet® to help them think through the matching of crop inputs (e.g. nitrogen fertiliser) to potential yield in a given season. This is achieved by a combination of virtual monitoring of crops and their soil resources (Fig. 5) and scenario analyses in which the effects of alternative management options on crop yield and potential profitability can be assessed.

Yield Prophet® provides production risk assessments that are timely and relevant to farm management through various simulation reports allowing farmers and advisers to manage a) climate risk, b) forecast yield, c) make informed decisions about nitrogen applications, d) match various other inputs to the yield potential of their crop, e) assess the effect of changed sowing dates or varieties and f) assess the possible effects of climate change. By matching crop inputs with potential yield in a given season, Yield Prophet® subscribers can avoid over- or under-investing in their crop.

From 2003 to 2012, Yield Prophet® was used by over 2000 innovative grain growers (568 fields were subscribed in 2012) supported by their consultants and farming groups, in a wide range of agro-climatic environments throughout the Australian wheat

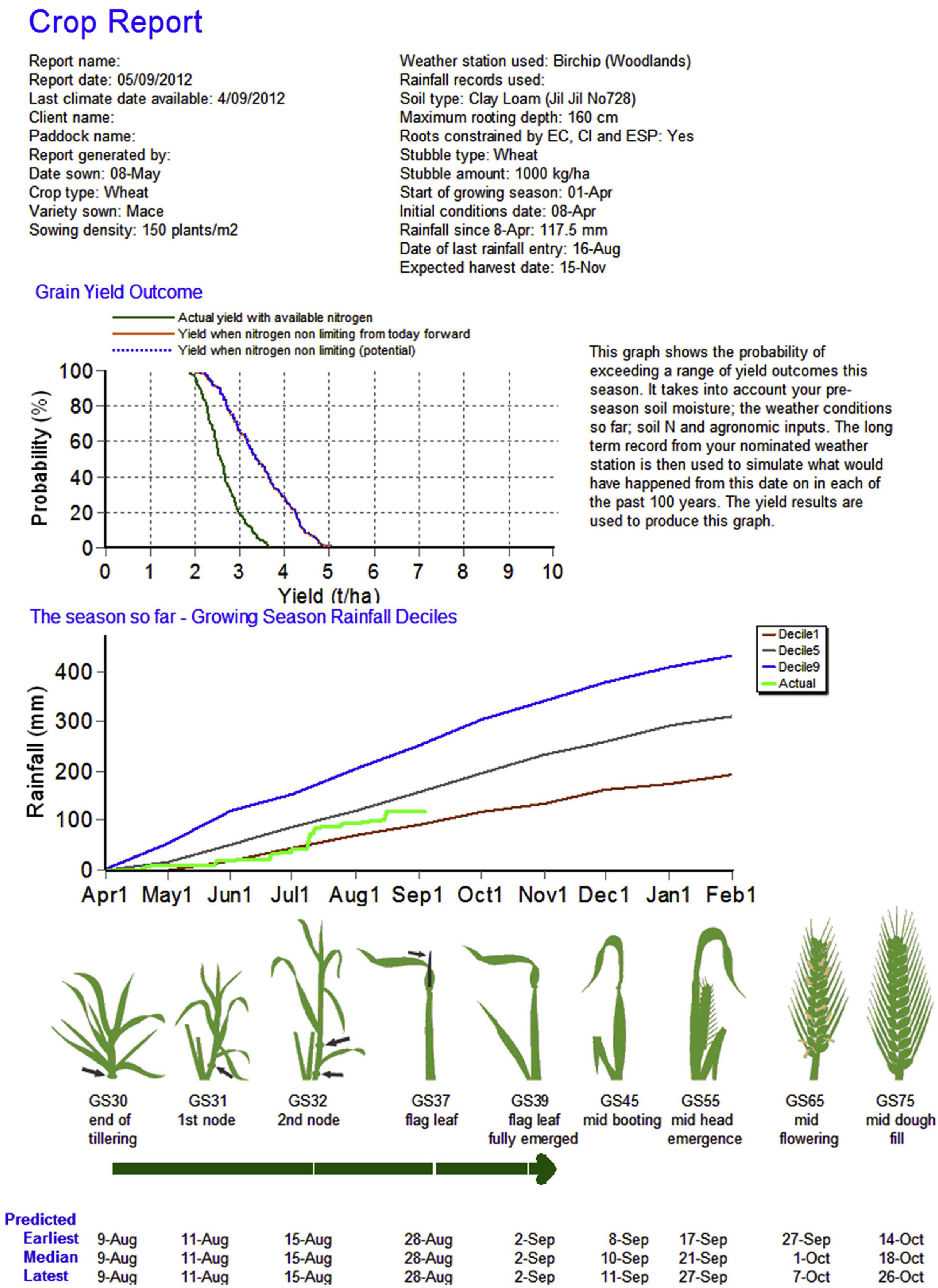

Fig. 5. This figure shows segments of a Yield Prophet® crop report generated on the 4th of September 2012 for a property in the southern Australian wheat zone. The report shows probability based prediction of grain yield outcomes comparing current management with N unlimited management and the current growth stage.

zone. Yield Prophet® is well-established in the major rainfed grain cropping regions of Australia where it has become the most widely recognised decision support system (DSS) in the grains industry. With subscribers including consultants, government agencies, researchers, and farming systems groups, the actual number of farmers benefiting from the program is far greater than those who subscribe directly. In addition, a significant number of agricultural organisations regularly publish outputs from Yield Prophet® in their newsletters and extension material.

Every simulation report generated since 2004 and all field data entered have been retained in a Yield Prophet® database. These data have proven to be a rich vein for research in the investigation of water use efficiency (Hochman et al., 2009a), nitrogen use efficiency (Hochman et al., 2013), yield gap analysis (Hochman et al., 2012; van Ittersum et al., 2013) and eco-efficiency frontier analysis (Carberry et al., 2013).

An alternative approach to delivering APSIM to farmers and consultants, with similar objectives, is the WhopperCropper (Nelson et al., 2002) simulation-aided discussion tool. This application was designed primarily to analyse the long-term impacts of different varieties, soil resources, and management options (e.g. quantity of stored soil water and nitrogen at planting, fertiliser applications) on projected yield outcomes given different climate scenarios. Based on a database of pre-run simulations for 100-year climate records, WhopperCropper comprises 'point and click' operations with immediate feed-back to users. In the seven years following its development, 675 agronomists and farmers were trained and supplied with the program. WhopperCropper is also used for training in agronomy by Australian universities and high schools. Its ongoing demand has prompted a planned move to a web-based product.

The development and application of these tools to help management has also been accompanied by in-depth analysis of the interactions between scientists and farmers (Jakku and Thorburn, 2010; Thorburn et al., 2011b). A useful concept to emerge from this work is the degree to which modelling enables co-learning between scientists and farmers, and the recognition of the value of this co-learning in its own right, rather than defining success through model development use.

3.2. Whole farm modelling

APSIM's new multi-point capability has led to a number of new scenarios, one of which is whole farm modelling. One embodiment of this is APSFarm (Rodriguez et al., 2011), a configuration of APSIM that allows users to simulate the impacts (economic, financial, environmental) of the alternative allocation of limited production resources (e.g. land, labour, time, irrigation water, livestock, machinery, and finance) across a number of alternative farm enterprises at the whole farm level (Power et al., 2011; Rodriguez et al., 2014, 2011).

Modelling resource allocation questions at the farm scale brings increased complexity and has required a change from fixed, calendar driven management rules to dynamic sets of rules that operate across the whole spectrum of farm activity (e.g. land, labour, water, livestock and machinery). The introduction of high level scripting languages into APSIM allowed APSFarm developers to simulate the management of the farming system as a set of state and transition networks (a finite state automata), allowing rules for the management of the farm to be studied in detail without affecting higher level function. The use of scripting languages allows the user to very precisely, at run-time, describe the transition between states (the rules), mimicking, as close as possible, the real management of the farming system being studied. In APSFarm, each field has a current state (e.g. fallow, wheat, sorghum), and 'rules' that allow the transitions between adjacent states. These rules represent the capacity (e.g. availability of machinery, land and labour), capability (e.g. agronomic and technical skills) and preferences (e.g. farm business

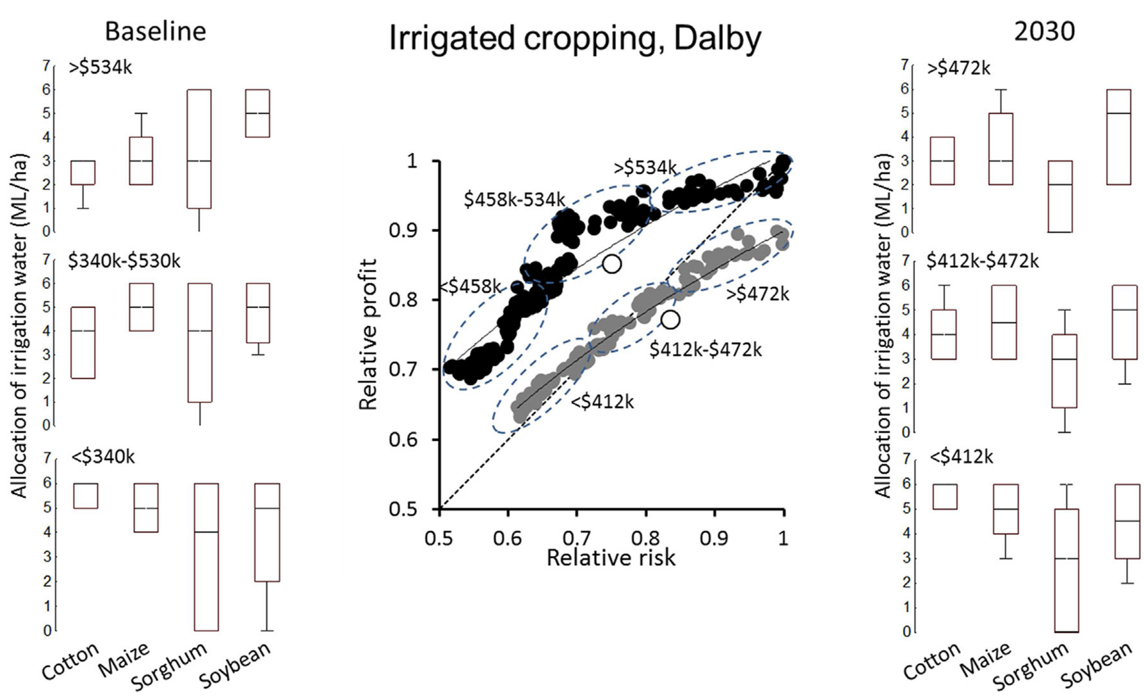

Fig. 6. This figure shows the relationship between profits and risks (relative to the farming system having the highest profits) for an irrigated cropping case study from Dalby, Queensland, Australia. The two simulated scenarios include a Baseline (1961–2010) (black circles), and a 2030 climate change scenario i.e. A1FI emissions scenario, and MRI-GCM232 model (grey circles). Only farming systems within the top 10th percentile of the Pareto rank are shown. The profits for the top, middle and bottom terciles are shown with the dashed envelopes, and the performance of the present farm management is represented by an empty circle. The boxplots show the changes within each profit range for the allocation of irrigation water across alternative enterprises. Taken from Rodriguez et al. (2014).

strategies, risk attitude) of the farm manager. Rules can be expressed as a boolean value (true for feasible, false for otherwise) or a floating point number representing the desirability of a particular action. Each day, the model examines all paths leading away from the current state to adjacent states and if the product of all rules associated with a path is non-zero, it becomes a candidate for action. The highest-ranking path is taken, and the process repeats until nothing more can be done for that day. Rules can represent farm level criteria (e.g. sowing windows for each crop, temporal definitions of "season break" such as rainfall amount over a defined period of time), physical limitations of farm components (e.g. machinery operation) and preferential behaviour (e.g. the maximum farm area that could be sown to each crop).

The results from actions having economic implications (e.g. variable costs from the use of fertilisers, the need for seeds to plant a crop, or the profits from harvesting a crop), are calculated based on a list of expected costs and prices provided by the participating farmers (see Fig. 6 for an example). Fixed farm operational costs are also obtained from the participating farmer and used in the calculation of farm profits (i.e. before tax). Therefore, outputs from APSFarm include, but are not limited to, production measures (yields and crop areas), economic measures (e.g. production costs, crop gross margins, economic risk and farm annual profit), efficiency measures (e.g. crop and whole farm water use efficiency) and environmental measures (e.g. deep drainage, runoff, and erosion). Fig. 6 shows the types of outputs possible from APSFarm. Tradeoffs between profit and risk for multiple options can be analysed.

3.3. Modelling crop and livestock interactions

APSIM is one of the few models that dynamically simulate interactions between crop and livestock systems. As described above, this major development in APSIM's capability over the past decade resulted from linking the strong animal-pasture systems modelling capability of GRAZPLAN (Freer et al., 1997; Moore et al., 1997) to APSIM and through diversifying the range of pasture and forages available. The major driver has been a need to capture material flows such as forage or nutrient between crop and livestock activities that occur on mixed farms (e.g. forage from cropping to livestock, nutrients from grazed pastures in rotations with crops). This capability has been used to explore the implications for system productivity, risk and natural resource management of practices such as ley pastures, grazing crops, diversified feed systems or land use changes on mixed farms.

With the diverse range of crop and pasture models now available, systems that involve a diverse feedbase can now be analysed.

Table 2
A range of pasture/forage models can simulate variability in annual forage growth. For a diverse range of mixed feed systems at Roma, Queensland simulated forage growth was compared against livestock demand in a breeding cow-calf system with a mean annual stocking rate of 1.4 Dry Sheep Equivalent (DSE) per ha to estimate mean annual utilization (livestock demand/forage grown) and the frequency that monthly forage growth was inadequate to meet livestock demand.

Feedbase systems	CV in annual feed supply	Mean utilization (demand/forage grown)	% months when monthly ME supply < demand
100% GRASP Buffel pasture	49	29	46
80% GRASP Buffel pasture			
+20% Lablab	48	21	42
+20% Forage sorghum	40	14	38
+20% Lucerne	47	17	21
+20% Oats	34	14	17
+20% annual medic (GRAZPLAN)	47	21	28

Source: Bell et al. (2008).

This is particularly relevant in mixed farming regions where livestock requirements are met by a diverse range of feed sources including a range of pastures (domesticated and native), annual forage crops, crop residues or dual-purpose crops. This has enabled greater quantification of the size and frequency of feed gaps (periods when feed supply and quality are insufficient to meet livestock demands) across a range of crop and livestock systems (McCormick et al., 2011; Moore et al., 2009). As the range of forage options that can be simulated has increased, APSIM has been utilized to explore tactical and strategic responses to improve the performance of livestock feed systems (Bell et al., 2008). For example, Table 2 shows how growth of a range of forages can be predicted in a common simulation environment and how this can be used to assess the performance of different feed systems. The wider variety of pastures and forages has also enabled better quantification of climate related production variability captured in other whole-farm bio-economic (e.g. MIDAS, IAT, NABSA) or decision support tools (Bell et al., 2008; Lisson et al., 2010; Robertson et al., 2009).

In many mixed farming systems, grain crops are an important forage source. As described above, it is now possible to simulate livestock performance while grazing grain crops or crop residues by linking the GRAZPLAN ruminant biology model to the APSIM crop models. This development required adding new forage quality parameters for crop components (leaf, stem, grain) and associating changes in these with crop phenological development. At this time, it has only been comprehensively validated in wheat (Bell et al., 2009). This has enabled APSIM to provide predictions of potential and variability in grazing from dual-purpose use of wheat and canola (i.e. grazing during their vegetative stage and allowed to regrow to produce grain) across a range of environments in Australia's cropping zone (Moore, 2009). Fig. 7 demonstrates the capacity to simulate the range of possible livestock production from winter and spring wheat varieties sown in different windows at two locations in southern Australia. In many mixed farming regions, grain crops are sometimes also sacrificed for grazing when grain yield prospects are low. APSIM has been used to identify the frequency and circumstances under which it is more profitable to sacrifice a crop to grazing than to harvest it for grain and to investigate tradeoffs between timing and intensity of grazing of a wheat crop (Bell et al., 2009). The implications of grazing crops or crop residues on the livestock system as a whole have also been examined. For example, whole-farm simulations that allow crops to be grazed as part of a broader farm feedbase have been used to quantify the value of wheat stubbles and dual-purpose crops on livestock productivity and the frequency of feed gaps and supplementary feeding (Thomas et al., 2012, 2010). Most analyses todate have explored the potential of crops to provide forage, but further development is required for the model to capture crop regrowth after grazing, impacts on crop phenology, allocation of resources and nutrient partitioning. Comparison with farmer records suggests that more attention to the simulation of nutritive value is needed (Pembleton et al., 2013).

The incorporation of complex livestock systems models, which require complex management routines and spatial interactions at multiple points, has also enhanced APSIM's ability to capture and isolate several whole-of-farm interactions and relationships that occur in mixed farming systems. For example, Bell and Moore (2012) utilized a combination of APSIM and GRAZPLAN modules to demonstrate the production and economic risk mitigation benefits that arise from operating a mix of crop and livestock systems. Further interactions such as nutrient and forage transfers that occur in integrated crop-livestock systems can also be isolated and examined using simulation models under common climatic, soil

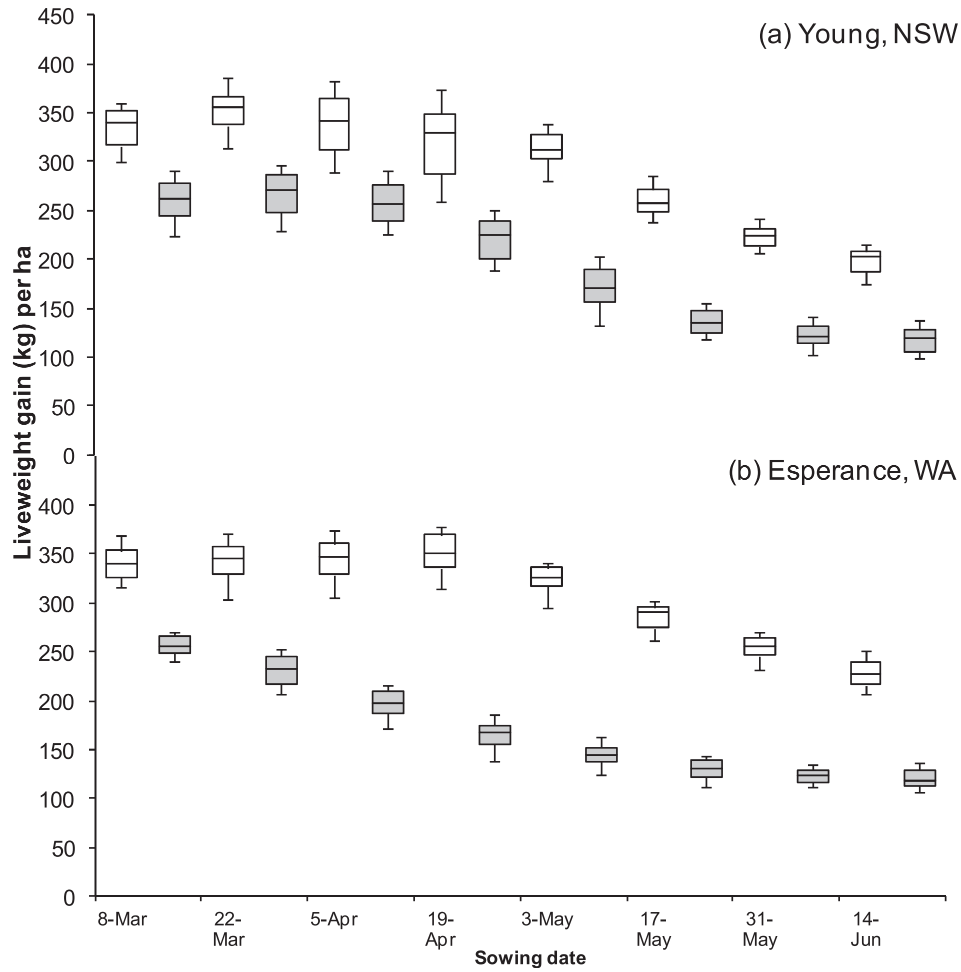

Fig. 7. Simulated sheep liveweight gain when grazing winter (white) and spring (grey) wheat during its vegetative period when sown at different times at two locations in Australia's mixed crop-livestock zone.

and management inputs. This integrated modelling can also be used to quantify trade-offs between natural resource management and production or land use practices. For example, Lilley and Moore (2009) examined modifying stock and crop management practices and trade-offs between farm productivity (grain, meat and wool) and ground cover levels. Robertson et al. (2009) also used a combination of APSIM and GRAZPLAN crop and pasture models to derive long-term relationships between farm land use and several NRM indicators (deep drainage, nitrate leaching change in soil carbon, ground cover) and use this as input into static bio-economic models to examine concurrently the profit and NRM implications of a range of land use changes.

3.4. Genotype × environment × management landscape and gene-to-phenotype modelling

Selection for yield gains in crop improvement programs is hampered by genotype × environment × management (G × E × M) interactions. While breeders are taking advantage of molecular technologies to develop empirical genetic models for traits and predict gene–phenotype relationships, genetic and environmental context dependencies cause complexities in these gene–phenotype relationships. Theoretical studies have suggested that the efficiencies of crop improvement programs could be accelerated if these empirical genetic models were incorporated into biologically dynamic crop models like APSIM that could capture context dependencies due to G × E × M interactions (Cooper et al., 2009; Messina et al., 2011). A core requirement for application of gene-to-phenotype models in crop improvement is to link the phenotype of a trait to its underpinning genetic control in a way that will reproduce observed G × E × M interactions and provide predictive capability in untested parts of the G × E × M landscape (Chenu et al., 2009; Hammer et al., 2006).

Most agronomically relevant traits are complex in nature, as their phenotypic expression is determined by multiple genes that often exhibit small individual effects and significant G × G and G × E × M interactions (Mace et al., 2013). Such interactions or context dependencies make it impossible to directly parameterise these complex traits in a model. A solution is to dissect complex traits into simpler, underlying component traits that have a physiological basis and are environmentally stable. In such an approach, complex traits thus become emergent properties of the interactions among underpinning component traits, the environment, and the management system (Fig. 8). The value of this approach was illustrated in APSIM-sorghum (Hammer et al., 2010), when incorporation of a model for nitrogen dynamics allowed simulation of genotypic differences in stay-green (leaf area senescence during grain filling) as an emergent property of genotypic differences in biomass partitioning and radiation use efficiency due to plant height. Trait dissection thus implements a level of biological functionality into a model where physiological insights help understand

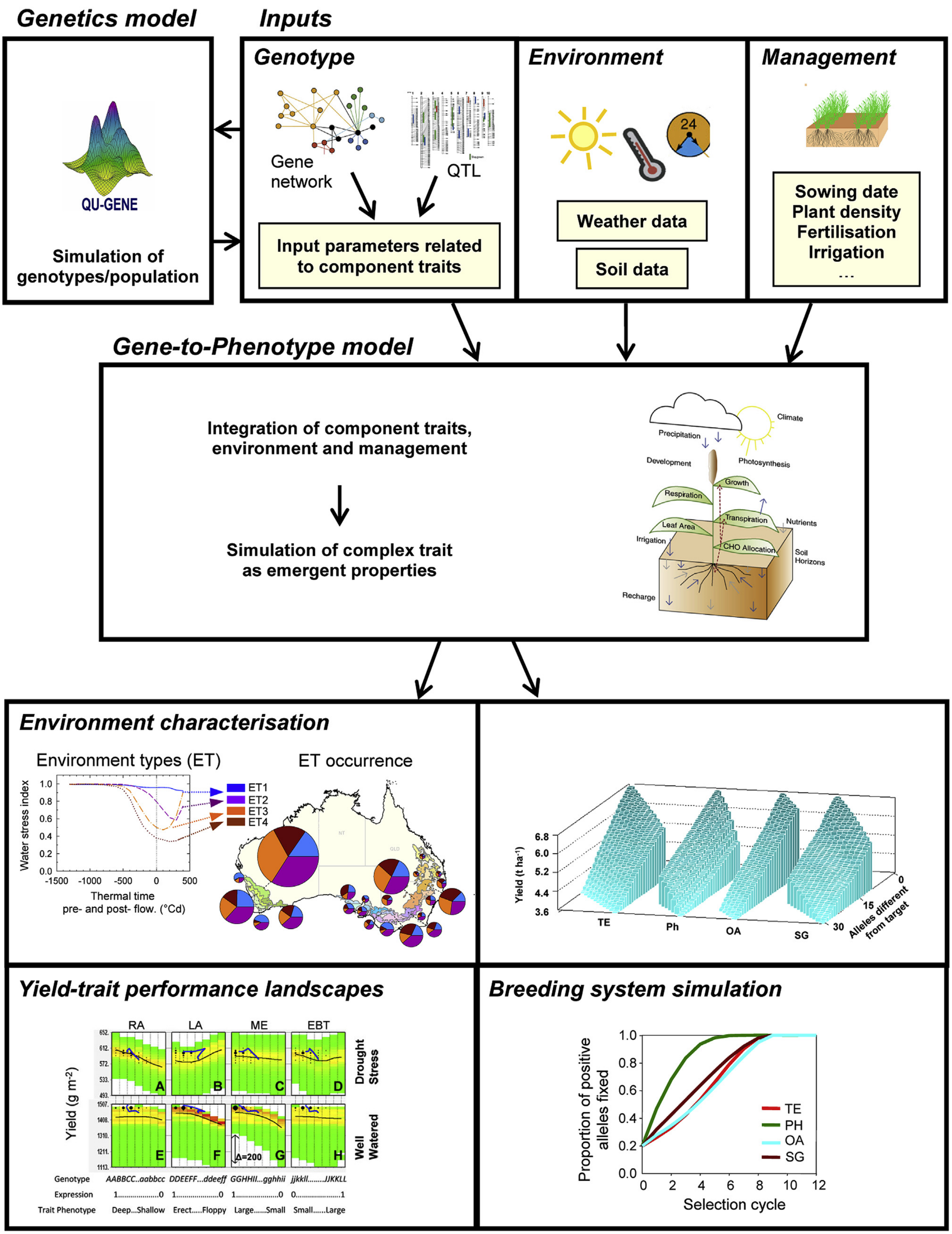

Fig. 8. This schematic representation of Gene-to-Phenotype modelling includes the genotype, environment, and management inputs and some outputs that have potential application in crop improvement. In the phenotypic outputs, abbreviations correspond to individual traits. Source: Data and figures from Chapman et al. (2003); Hammer et al. (2005); Messina et al. (2011); Chenu et al. (2013a,b).

the phenotypes of complex traits as emergent consequences of G × E × M interactions.

A central paradigm of trait dissection in modelling is that the absence of context dependency of component traits implies relatively simple and environmentally-stable genetic control. This enables the incorporation of genetic effects (Quantitative Trait Loci (QTL) or genes) as influences on the input parameters of gene–-phenotype relationships associated to component traits in APSIM crop models. An example is leaf elongation rate responses to temperature, water deficit, and evaporative demand in maize. These responses are under environmentally-stable genetic control and incorporation of their underpinning genetics into a gene-to-phenotype version of APSIM-maize allowed quantification of QTL effects on yield (Chenu et al., 2009). Examples are rare where our knowledge is sufficiently advanced to map genetic effects to input parameters of crop models. However, trait dissection provides models with the biological functionality required to properly integrate genetic variability. Genotypic values of input parameters are then the representations of alleles for those traits in that genotype. Although this represents a simplification of reality, it allows hypothesis testing of the gene–phenotype relationships in an iterative process of knowledge generation, where data collection in breeding programs informs trait simulation and vice versa (Hammer et al., 2005; Messina et al., 2011). Trait dissection thus helps understand and predict gene–phenotype relationships of complex traits and provides predictive capabilities in parts of the G × E × M landscape where the model has not yet been validated, while not compromising performance in known parts of the landscape (Hammer et al., 2006).

A first step in the application of models in plant breeding is to characterize the environment that crops experience. Quantification of the main abiotic stress patterns can be performed by simulations over long-term periods and across multiple locations to define the type of environments a crop is likely to experience in the target population of environments (Fig. 8). Such characterisation of the target population of environments has been performed using APSIM for crops such as sorghum, maize, wheat, and field pea, grown in drought prone environments in Australia, Europe, and India (Chapman et al., 2000; Chenu et al., 2011, 2013a; Kholova et al., 2013; Sadras et al., 2012). When applied to breeding trials, environment characterisation has been demonstrated as helpful to unravel some of the G × E × M interactions observed across experiments (Chapman, 2008; Chapman et al., 2000; Chenu et al., 2011). Such characterisation also enables breeders to weight trials and genotypes within trials based on how well they represent the target population of environments (Podlich et al., 1999). Recently, dynamic modelling of environment characterisation has been used in pre-breeding programs to assist managed-environment trials target specific environment types and thus improve the relevance of field phenotyping (Chenu et al., 2013b).

Once a gene-to-phenotype model has been developed, it can be used to create yield-trait performance landscapes that provide the basis for applications of such models in crop improvement programs (Messina et al., 2011). Trait-yield performance landscapes can also be used to improve selection methods in breeding programs. A rugged yield-trait adaptation landscape indicates complex G × E × M interactions, but combining biologically functional crop models in APSIM with the quantitative genetics simulation model QU-GENE (Podlich and Cooper, 1998) has allowed identification of promising breeding strategies that enable navigation towards peaks in such complex adaptation landscapes where grain yields are high (Chapman et al., 2003; Chenu et al., 2009; Hammer et al., 2005; Messina et al., 2011).

Applications to breeding are broad, as the described approaches can be applied to various systems, including for testing of potential benefits of new genetic expressions, new environments and/or alternative management systems. In particular, recent studies have focused on the effects of future climatic scenarios on crop environment (Potgieter et al., 2013), crop responses (Lobell et al., 2013), and on breeding solutions for future crop adaptation (Zheng et al., 2012).

3.5. Biotic constraints in APSIM

An increasing understanding of farming systems has evoked new questions concerning utilisation of water and the value of fallows for replenishing soil water reserves and the cost of poor weed control for its loss. Analysing the cost of weeds within a crop has been a feature in APSIM via intercropping (Carberry et al., 1996a), with specific weed modules being developed based on competition studies (Deen et al., 2003; Robertson et al., 2001a). Initially, the seed bank model was created in APSIM's manager language (Grenz et al., 2006), but as the problem space became more complex alternatives were investigated.

A seed bank model was developed (Robertson et al., 2001a; Smith et al., 2005) using the visual modelling framework Vensim™, which enables researchers, without the ability to write code, to easily construct their own models via an icon based approach. Linking processes in APSIM allowed this model to interact and share variables with other APSIM models. Initially developed to evaluate farm management strategies to reduce weed seed banks (Robertson et al., 2001a; Smith et al., 2005), the seed bank model allowed investigation of the development of weed resistance in Australian rain-fed farming systems (Thornby et al., 2010; Thornby and Walker, 2009). However, the underlying structure of the icon based seed bank model became a limitation due to the complexity of modelling multiple weed cohorts with different genetic heritages positioned at different layers within the soil, so an alternative approach was needed.

An increased capability to model biotic stresses has arisen from the union between APSIM and DYMEX (Maywald et al., 1999), a detailed climate-driven process-based population cohort model, which simulates biotic constrains within the agro-ecosystem, specifically insects, diseases, and weed populations. The APSIM-DYMEX link provides the means to efficiently integrate multiple population models with minimal transaction costs. A wrapper was built around the DYMEX simulator so that the model could run as a *normal* APSIM model (Whish et al., 2014). While having complex population models running in tandem with a system model is still being realised, this new capability will also allow increased understanding of the biotic constraints within the farming system. This offers a symbiosis for many population models previously built in DYMEX, to move beyond simple single season outcomes, based around simple water balance and crop phenology models, to outcomes from a more dynamic farming system model. This union of models shifts the APSIM framework towards being a true agro-ecosystem framework.

3.6. Climate change adaptation and mitigation research

In the last decade, APSIM has increasingly been applied to assess the impacts of climate change on agriculture, as well as adaptation and mitigation strategies. Applications range from local to multi-site assessments, including recent national scale studies in Australia and New Zealand (Lieffering et al., 2012; Teixeira et al., 2012b), and multi-site and regional scale assessments in China (Liu et al., 2013a, 2010, 2012; Wang et al., 2013b) and South Asia (Gaydon et al., in press; Roth and Grünbühel, 2012).

The model has been most commonly applied to identify the effects of changes in atmospheric CO_2 concentration, temperature and/or precipitation patterns for different emission scenarios (Ludwig and Asseng, 2006; van Ittersum et al., 2003; Wang et al., 2011, 2009). These studies identified the most critical factors determining climate change impacts for particular region and crop combinations (Luo et al., 2005a; Reyenga et al., 2001, 1999b), and to derive probabilistic crop response surfaces for multiple environmental factors (Luo et al., 2005c). More subtle impacts of El Niño Southern Oscillation (ENSO) events or climatic change on crops, such as from extreme temperature events during sensitive stages of crop growth, have also been studied with APSIM (Asseng et al., 2011; Hayman et al., 2010). These studies enable identification of the plant physiological mechanisms that are most affected under contrasting climates, e.g. phenological development rates in response to temperature (Sadras and Monzon, 2006) and the efficiency of solar radiation and water use in response to CO_2 concentrations (Asseng et al., 2004; Bassu et al., 2011; Li et al., 2013). More recently, analyses of climate change impacts have extended beyond crop productivity to address quality components of produce, e.g. protein content of wheat grains (Asseng et al., 2004; Ludwig and Asseng, 2006; Luo et al., 2005b). Analyses have also extended beyond solely focussing on attributes of crop production to consider environmental indicators of cropping systems. Indictors have included soil water balances (Wang et al., 2011, 2009) and nutrient loads to ground and surface water (Biggs et al., 2014; Webster et al., 2009), with the latter work looking at the relative responses of loads to climate change compared with improved management (fertiliser application, tillage and fallow management).

An important application of APSIM on climate change research has been the study of crop performance under recent weather variability of past decades (Chen et al., 2013; Gaydon et al., 2012a; Sadras and Monzon, 2006). This type of study enables evaluating key climate components affecting historical yields (Ludwig et al., 2009), the effectiveness of recent management adaptation (Chen et al., 2010; Liu et al., 2010) and to explain current yield-gaps (Liu et al., 2012). This deeper understanding of the impacts of a changing climate has led to the development and testing of various adaptation strategies. Options include changing sowing dates, using alternative genotypes and altering times and rates of irrigation and fertiliser application (Liu et al., 2010; Luo et al., 2009; Teixeira et al., 2012a). As another example, APSIM modelling combined with analysis of historical crop data showed that cultivar selections in the past three decades have reversed the negative impact of climate warming in China (Liu et al., 2013b, 2010, 2012; Wang et al., 2013b). Another model application is the testing of different physiological traits to increase plant adaptive capacity for new climatic conditions. These include earlier flowering, deeper roots, faster rates of root growth and carbohydrate remobilisation to grains and contrasting photoperiod and vernalisation sensitivity (Bassu et al., 2011; Ludwig and Asseng, 2010; Luo et al., 2009). When coupled with the new developments outlined in Section 3.4 (gene-to-phenotype modelling), this type of application can support breeding strategies for improved adaptive capacity under future climates and management systems.

In addition to the more common analysis of climate change on single-crop responses, APSIM has also been used for multi-crop and farm business studies. These include quantifying the complex trade-offs that occur in crop rotation systems under climate change. For example, in New Zealand the early maturity of annual crops in response to higher temperatures enables a longer growth period for winter forage crops, indicating the need to consider the entire rotation period for this multi-crop system. Similarly, climate adaptation studies considering “whole-farms” (Section 3.2) show the importance of taking into account economic and social aspects of production systems with complementary activities (e.g. cropping and livestock). APSIM has also been used to explore opportunities of expanding cropping areas in response to climatic changes (Asseng et al., 2013b; Nidumolu et al., 2012). This type of analysis enables assessing different aspects of land suitability, including climate factors, management and soil characteristics.

APSIM's well developed representation of soil processes has allowed it to be used to explore abatement of greenhouse gas (GHG) emissions from farming systems, through either reducing N_2O emissions of increasing soil organic sequestration. Investigating these issues has led to testing of nitrification and denitrification processes in APSIM (Meier et al., 2006; Thorburn et al., 2010; Vogeler et al., 2013), as well as addition of N_2O emissions from these processes (Thorburn et al., 2010). It has also led to extended validation and further development of APSIM for the simulation of long-term soil carbon dynamics in response to management changes across climatic regions in Australia (Huth et al., 2010; Luo et al., 2011; Thorburn et al., 1999) and South Africa (Thorburn et al., 2002). N_2O emissions from soils in Australia's crop lands vary widely, including some of the lowest (wheat in Western Australia) and highest (sugarcane in north-eastern Australia) N_2O emissions recorded from cropping systems (Thorburn et al., 2012). These high emissions are of concern, and modelling studies have shown they are caused by (1) the warm and moist environment where sugarcane is grown, (2) high rates of N fertiliser applications traditionally applied to these crops and, (3) in some places, high soil C (Thorburn et al., 2010, 2013). Avoiding over-application of N fertilisers will be the primary means of mitigating these emissions. In grain production systems, legumes in rotations are an important source of N that lessen the need for N fertiliser. However, including legumes in cereal crop rotations is also likely to increase N_2O emissions (Huth et al., 2010), and mitigating N_2O emissions in these cropping systems will be more difficult. Other agricultural systems with high N_2O emissions are intensive pastoral systems (Vogeler et al., 2013), and the nitrification inhibitor dicyandiamide (DCD) has been proposed as a means of mitigating emissions from these systems. However, simulation studies have shown that the mobility of DCD in the soil solution poses a substantial limit to its efficacy (Cichota et al., 2013). Another practice to abate GHG emissions from cropping land is sequestration of organic C in the soil. Simulation studies have defined soil organic C sequestration potential in Australian grain growing regions (Luo et al., 2013; Zhao et al., 2013b), and highlighted that potential is greatest in cooler areas, in soils with initially low C, where crop residues were conserved and 50 kg ha^{-1} of N fertiliser was added.

An interesting concept to emerge with the agricultural climate change community is the use of ensemble modelling of climate change impacts to better characterise uncertainty (Rosenzweig et al., 2013). A recent study comparing a large number of wheat models over a wide range of environments found that, while individual crop models could simulate yields accurately with sufficient input information, the median of all model predictions was close to measured yields in all environments even in the absence of detailed input information (Asseng et al., 2013a).

3.7. Effects of agriculture on water quality

Exports of sediments and chemicals from agricultural lands degrade the quality of surface and ground waters (Parfitt et al., 2006; Thorburn et al., 2014). Understanding the causes and management of these problems is often difficult using empirical data alone, as they often emerge on sufficiently large space and time scales where robust measurements are difficult within reasonable time frames and budgets. Thus, simulation modelling has a strong role to play. In the past, there has been a substantial focus on understanding and reducing N leaching from cropping systems (Sharp et al., 2011; Stewart et al., 2006; Thorburn et al., 2001a, 2011b, 2005; Verburg et al., 1998). However, more recent focus has expanded to include assessments of more general water and N efficiency of intensive agricultural systems, such as dairy pastures (Cichota et al., 2013; Snow and White, 2013; Vogeler et al., 2013; White and Snow, 2012) and sugarcane production systems (Biggs et al., 2014; Thorburn et al., 2011a). APSIM has also been applied within catchment-scale water quality frameworks (Carroll et al., 2012).

Implementation of environmental policy is often progressed through application of empirical models, e.g. Overseer in NZ (Wheeler et al., 2006), to calculate nutrient balances for whole farms for fertilizer recommendations. However, the development/parameterization of empirical models is usually constrained by the availability of reliable experimental data from a sufficiently diverse range of conditions. This is particularly the case when new mitigation techniques or management systems are adopted on commercial farms; often there is simply not sufficient data to support the inclusion of these systems in the empirical model. Here, process-based models have a role to play. Simulation models are normally too complex to be used directly but, when appropriately validated for certain processes, they do have a valuable role to play in adding to the database that can be used to parameterize the nutrient balance model. One example of this is where APSIM was used to develop and parameterize a leaching model for Overseer (Cichota et al., 2012). This approach to the work allowed the Overseer developers to retain the best experimental data for validation purposes.

3.8. *Small holder (interactions with models at other scales)*

Smallholder farming systems support much of the food and fibre needs of developing economies, but regional shortfalls are common and smallholder families and communities face many challenges and risks for securing and enhancing their livelihoods. In the face of increasing pressure on food stocks from global population growth, economic growth and climate induced yield variability, these challenges remain acute and significant attempts are being made to address them through R4D and associated aid programs (Winter and Doyle, 2008).

As is the case for developed agricultural systems, simulation modelling offers considerable scope for exploring constraints and opportunities for increasing the performance of smallholder production systems. These systems are typically characterised by a mix of subsistence and cash crops, forage crops and locally sourced feedstuffs, and a variety of small and large livestock types. Smallholder households also rely on access to various forms of non-farm employment activities to secure their livelihood needs. The systemic interconnectedness between the different farm and non-farm activities, whereby resources of land, labour, animal power, residues, and cash pass between the activities as inputs and outputs, is well recognised, as is the challenge created by surpluses and deficits of these resources and especially at critical times of the production cycle (MacLeod et al., 2007).

The challenge of addressing the complexities of smallholder farming systems within the context of seeking cost-effective crop, forage and livestock management options for raising household welfare standards has been the focus of much work undertaken by CSIRO and partner agencies in Eastern Indonesia (Lisson et al., 2011) and southern Africa (Whitbread et al., 2010). These initiatives have applied farming systems research principles (including on-farm, on-station experimentation, participatory techniques), and applied simulation (i) to mimic the production and home consumption performance of a smallholder household for rapidly screening technical options for potential application in the target communities on the islands of Lombok, Sumbawa and South Sulawesi (McDonald et al., 2004); (ii) to add value to field experimentation and demonstration; (iii) in direct engagement with farmers; (iv) to explore key system constraints and opportunities with researchers and extension agencies; and (v) in the generation of information for policy makers, bankers and insurance institutions (Whitbread et al., 2010).

The IAT (Integrated Analysis Tool) is a decision support tool, written in Microsoft© Excel, for smallholders and their supporting agencies to screen various options for potential application. It is designed to help analyse the impact of a wide range of intervention strategies on a smallholder farm. The IAT integrates on-farm crop, pasture and animal production activities, non-farm employment opportunities with associated labour, land, draught and cash requirements, accounts for revenue streams and costs, and evaluates these against existing land, labour and financial resources. The extent to which the different activities augment scarce resources or contribute to household food security and cash resources is also registered. The IAT is not an optimising tool (contains no optimising algorithm), but rather is used to explore the direction and magnitude of changes in a variety of physical and financial performance indicators as alternative options are introduced to the household activity mix or various technical and financial co-efficients are changed. In this sense it approaches the logic of creep budgeting and approximates the iterative approach to decision making that is employed by many farm managers (Makeham and Malcolm, 1981).

The key link to APSIM is through the central structure of the IAT which links a user interface to a crop and pasture yield database, a process model for predicting animal growth, reproduction, lactation and mortality, and an economic model of the household

Table 3
Model output from baseline and various intervention strategies in Binh Dinh, run over a 10 year period (Parsons et al., 2011). Final cash balance values are the balance at the end of 10 years.

Cut & feed kg/day	Animals sold over 10 years	Cattle sale weight (kg)	Fodder surplus (kg/month)	Gross Margin (M VND/year)[a]	Final cash balance (M VND)
Scenario 1. Baseline: 0.2 ha rice (3 crops); 0.1 ha cassava on upland; 0.2 ha peanut on upland; 1 cow; fed cut & carry of 20 kg/day plus supplements; 90% retention of rice and peanut straw.					
20	5–6	200	−1600	10	48
Scenario 2. Grow 0.1 ha grass on upland, plus 0.1 ha in backyard; increase cut & carry to 25 kg/day					
25	5–6	225	0	10	51
Scenario 3. As above, and grow 100 m of tree legume					
25	7–8	300	4000	10–15	79
Scenario 4. As above with seasonal mating and early weaning					
25	8–9	350	3500	10–20	95
Scenario 5. As above, increase number of cows to 2, cut & carry to 35 kg					
35	14–15	300	−1500	15–20	154

[a] 1 AUD = approximately 22,000 VND (June 2011).

economy and labour resources. The crop and pasture yield database is populated with pre-run output from APSIM simulations of a range of crops and forage types in use in the existing farming systems of the target regions or which may be under consideration for introduction to those systems. This allows the many complex management and climatic options that can be modelled in APSIM to be included for whole farm comparisons in the IAT by simply including the APSIM output in the crop and forage databases of the IAT, along with different livestock management options (see example output from Vietnam in Table 3).

Although it was initially developed for application in Eastern Indonesia, the IAT has received a widening level of interest and has been applied to smallholder farming system improvement studies in south central Vietnam (Parsons et al., 2011), livestock-lucerne integration in western China (Komarek et al., 2012), and milk production in Pakistan (Shafiullah, 2012), and is currently being applied to smallholder farming systems in Zimbabwe, Burkina Faso, Niger, Mali and Senegal, as well as for evaluating adaptation to climate change in Laos. This expansion in the geographical scope of the application of the IAT has led to several modifications to the model to meet some specific local circumstances such as broadening the type of livestock simulated, allowing multiple livestock types at one time, allowing multiple land types on the one farm, and specifying feeding restrictions on crop residues and forages (Parsons et al., 2011).

A variant of the IAT, the North Australian Beef Systems Analyser (NABSA) model, was developed in 2012 to explore the opportunity for future research and development investments to raise the productivity and economic performance of beef cattle herds run under extensive grazing conditions in northern Australia (Hunt et al., 2013). This derivative model is fundamentally similar to the root smallholder model with several modifications to more closely capture the dynamics of the larger herds of animals typically carried in Australian rangelands and to broaden the forage base to dynamically capture the growth of the native pasture communities on which they graze.

4. Discussion

As illustrated in the previous sections, APSIM has evolved from a cropping systems model into an agro-ecosystem model. This has been driven by new pressures being placed on the farming community (climate change, food security concerns, changing environmental policies) and on the research community (interest from the plant breeding community, the AgMIP community). Farmers are looking to become more productive through better land and resource management, all within a changing world. Funding bodies in Australia have responded to this by allocating significant funds to provide research opportunities to deliver these outcomes through targeted projects. This funding though doesn't directly support model development, so the challenge has been to find ways to do this in a funding framework that focuses on outcomes, not development of new science or models. Despite this, new developments have been significant over the past decade with new capabilities being continually added. This is likely to continue into the future with plans to;

a) Improve the modelling of competition for resources (light, water, nutrients) over time, spatially and between species, particularly below-ground. Spatial heterogeneity of root systems and soil properties are important components to achieving this.
b) Improve the modelling of physiological traits, develop gene-to-phenotype modelling, and extend G $\times$ E $\times$ M capabilities.
c) Improve the modelling of soil processes (evaporation, wind erosion, soil carbon and nitrogen dynamics, GHG emissions, water logging, water tables, potassium, phosphorus response in crops, volatilisation).
d) Extend the forage quality parameterisations.
e) Improve the modelling of stock/plant/soil interactions (grazing, excreta return, compaction, dairy, feedlot slurry).
f) Fully incorporate population dynamics (pests, diseases, weeds, pastures) and soil pathogens.
g) Develop new crop models (chicory, kale, oil palm, triticale, white clover, red clover, plantain, carrot, onion) and varieties.

Each of these broadens APSIM's *scope* and ability to better simulate agricultural systems. APSIM's ability to simulate at multiple *scales* will likewise extend into larger spatial scenarios with millions of "points" being simulated for continental sized simulations. This is already beginning to happen with several groups modelling Australian grain regions (Bryan et al., 2010a, 2010b; Luo et al., 2013; Zhao et al., 2013b). Mostly these points will be independent of each other but it is theoretically possible for data flows to occur spatially. For example, movement of populations (like the spread of disease, the patch dynamics and pollen distribution of resistant weeds or within paddock movement of pathogens by machinery) requires a spatial understanding. While theoretically possible in the current framework, the software team plan to improve the efficiency and design of APSIM to better facilitate this type of simulation.

The challenge remains how to develop these new capabilities in a project driven environment with tight deadlines and limited resources, where science and software development are often not valued *per se* by funding entities. Projects that permit newly-developed capabilities to be both fully validated and documented are rare. This in turn leads to premature releases of science with users applying incomplete models to real world scenarios, something that risks incorrect analysis. The APSIM Initiative is employing various strategies (science and software peer reviews, automated testing, continuous integration, training users to undertake "due diligence") to safeguard against this possibility.

This new science capability is also being developed in an increasingly inter-connected and open environment. Access to the internet, social media and mobile devices has exploded in popularity, leading to a new way of living and working. There is increasing demand for interconnected, up to date, mobile information and tools that are relevant to farmers, consultants and researchers. APSIM is not immune to these changes. APSIM has transitioned from a desktop-only simulation tool to one that is capable of being run on computer clusters and behind web pages. The Yield Prophet® online crop simulation service is one such example among many. While farmers and consultants are accessing these tools on their iPads via a web browser, many have enquired about dedicated apps. They expect their simulation reports, soil analyses, weather forecasts to be accessible from their mobile devices. Like the requirement for better spatial capabilities in APSIM, the software team is transitioning APSIM to accommodate this by evolving the software to a "run anywhere" philosophy.

The move to an open source development framework has also presented challenges in the way this new science is developed. Development of APSIM is no longer centred on one location in Australia (Toowoomba, Queensland); development is instead distributed across multiple locations in multiple time zones. The number of developers of new science in APSIM has exploded (for example, 15 different individuals committed a change to the model code between January and July of 2013). So too has the number of users of the model. The benefits include many new collaborations globally, presenting many new opportunities and spreading the development and maintenance across multiple organizations and individuals. While these are all positive outcomes, there are challenges. Despite an increased investment of time in scientific quality assurance by the AI Reference Panel, it has become increasingly difficult to maintain a high level overview of all new science and software developments to ensure that they are robust, stable and of a sufficient high quality. We still have much to learn from the open source community.

As we begin a third decade of working with APSIM, the software team is evolving APSIM to a more modern, multi-platform, source code base, based on the .NET framework. With a working name of ApsimX (final name is still to be determined), this new software will allow users to run simulations and the user interface on Windows, Linux and Macintosh, via the Mono implementation of .NET. The model shall also run behind web pages, on Android, and on IOS devices (iPad, iPhone), albeit with a custom user interface. ApsimX will be significantly faster, smaller and very lightweight. Early prototypes suggest that the runtime speed of ApsimX will be at least five times quicker than the current APSIM; a one hundred year simulation with wheat grown every year will take seconds in ApsimX as compared to 40 s in the current APSIM. This will present a host of new opportunities for new problem domains and their analysis and will help alleviate the increasing need for improved simulation throughput. New tools and interfaces will be built to support the aggregation and summarization of large output datasets allowing for a new era where genomics, phenotyping and global modelling are increasingly required.

Finally, as the APSIM community more broadly engages with the international modelling community, the issue of model support becomes more important. The APSIM Initiative is currently exploring ways to support scientists trying to use APSIM, developers who wish to add new capabilities to APSIM and modellers who are trying make sense of the output of the models. Each of these is made more difficult with limited resources. A solution may be to open-source the support burden by using on-line forums, creating alliances with other modelling groups and creating a global network of APSIM 'experts'. This process has already begun with our involvement in international projects like AgMIP.

5. Conclusions

The paper by Keating et al. (2003), written by the founders of APSIM, described in detail the science and software at the end of the first decade of APSIM development. Since then, the farming system and modelling community has changed significantly as outlined in this paper. It is interesting to compare the authorship of that paper with this one. While many authors of the first paper remain within the APSIM community as mentors, in large part the custodianship and leadership of APSIM has been passed on to a second generation that is far more geographically dispersed. This has been a significant achievement. This longevity is largely due to the community of people surrounding APSIM as can be seen in the large number of contributing authors for this paper. There are many dozens more individuals that have influenced the direction that APSIM has taken and it is this community that has driven the significant changes to APSIM.

To conclude, we pose a question: "Why are we seeing greater collaboration, trust and contribution to APSIM from various groups internationally?" We believe it is a combination of the increased openness of APSIM, the commitment of members of the first generation to an outward focus and the inherent flexibility of the framework to allow researchers to adapt it to their specific needs. Organisations find the APSIM community an attractive way to collaborate, to leverage scientific investment by others and share the development of a large framework that is too large for a single organization to maintain and develop.

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