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REVIEW ARTICLE

APSIM's origins and the forces shaping its first 30 years of evolution: A review and reflections

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Abstract
Simulation models have co-evolved with agricultural research methods over the last 60 years and they are now a widely accepted and deployed component of agricultural research and development. Modelling supports research in a very diverse range of disciplines and situations, but nowhere more so than in farming systems research. The complex interactions in space and time in the face of climate variability and change that characterise contemporary farming systems research create a situation in which farming systems models are vital tools in interpreting and generalising research results. This review examines the evolution of one of the most widely used farming systems modelling platforms, the Agricultural Production Systems Simulator (APSIM). The review sets the scene for APSIM development with an account of research approaches in agronomy during the 1960s and 1970s. The early innovations in crop and soil modelling in the 1980s are covered briefly and a more explicit history of APSIM development is reported from the 1990s. Reports of APSIM use and impact are reviewed over the 2000s and 2010s. The review concludes with reflections on the forces that have shaped and enabled this more than 30-year history of APSIM development and use, together with a look forward to future challenges. Recent developments in proximal and remote sensing together with advances in the power of empirical models arising from machine learning are not seen as threats but more so opportunities for sound bio-physical models to be deployed with greater effect.

Keywords Farming systems models · APSIM

Contents

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1 Introduction

The Agricultural Production Systems Simulator (APSIM) model first emerged under that name in the early 1990s (McCown et al. 1996) and since that time the APSIM platform has been at the forefront of model development and application philosophy, model structure (modularity) and software quality (Keating et al. 2003; Holzworth et al. 2014, 2018). This review focuses on the forces that led to APSIM's development and evolution over the 1980–2010 period. The aim is to record the early history and reflect on the factors that have contributed to APSIM's ever-growing contribution and endurance. All history is seen through individual eyes and this account is no different—it reflects the author's personal experience and recollections. Others who were also there will have additional perspectives that will be equally legitimate.

As APSIM evolved within the Australian agricultural R&D system, these reflections will inevitably be "Australian centric". Jones et al. (2017) and Keating and Thorburn (2018) provide the wider global context for this narrative.

2 Some background—Australian agronomy in the 1970s

My contention is that agronomy was not seen as the cutting edge of agricultural science in Australia during the 1970s. A number of terms were often raised that implied agronomy was more of an empirical art rather than scientific endeavour. Notions such as "rates and dates" and "spray and pray" are examples. The earliest references I could find to the term "white peg agronomy" come from Angus et al. (1974) and Nix (1980). This term describes an agronomic method based on empirical observations of experimental plots bounded by "white pegs". The Angus et al. (1974) and Nix (1980) publications are largely inaccessible and uncited, yet with the benefit of hindsight one sees they forecast the developments in quantitative agronomy that we have seen unfold over the last 40 years.

Agronomy's core method when I was an undergraduate student in the early 1970s went as follows:

- Pose some questions on crop, pasture or livestock management
- Select some treatments and set out a replicated experiment (with the proverbial white pegs and sign-off from your biometrician)
- Record observations on the influence of the treatments for a few years
- Use ANOVA to determine if any of the treatment means were significantly different

These experimental results were generally highly conditional on site and seasonal factors and the experimental and analytical methods had very limited capacity to address those drivers. The idea that there was a probabilistic base to interventions in dryland agriculture was (almost) nowhere to be seen and there were no methods available to agronomists to deal with the riskiness of farm management at that time. It would be another 10 years before French and Schultz (1984) would provide us with a simple quantitative foundation to explore water supply and crop yield under Australia's variable climate. Some agricultural economists (most notably from University of New England) were starting to develop theory and methods to explore agricultural decision-making under risk (Anderson et al. 1977), but it would be some time before agronomists took any note of that work.

3 1950s and 1960s—the science foundations (at home and abroad)

Advances in understanding crop-soil-environment interactions steadily accumulated during the 1950s and 1960s and it is important to recognise that these developments were foundational to the model development activities that followed. The first numerical models started to appear in the Netherlands and the USA during the 1950s and 1960s (e.g. van Bavel 1953; Duncan et al. 1967; Brouwer and De Wit 1968). In Australia, an early focus on land evaluation led to developments in water balance modelling (Slatyer 1960; Fitzpatrick and Arnold 1964; Fitzpatrick 1969; Keig and McAlpine 1969; McAlpine 1970).

4 1970s and 1980s—crop and soil simulation models emerge

Interest in model development and application was growing rapidly in the 1970s. W.G. Duncan was a pioneer when he outlined a vision for model use in agronomy:

> … "one can predict maize yields by correlation methods if sufficient past yield and weather history is available, but this gives little information about why yields varied. A simulation model should predict grain yields, given the same weather information, but in addition it should describe the state of the plant at any date of the growing season. … One could predict the consequences of earlier or later planting, or of irrigation at any time, or of the use of a variety with different characteristics. An important use of almost any simulator is to answer the question "what would result if …?" - "With the simulator and historical weather records one can learn what would have resulted over past years from the use of new practices or varieties, thus accumulating valuable experience without loss of time" …. W.G. Duncan (1975).

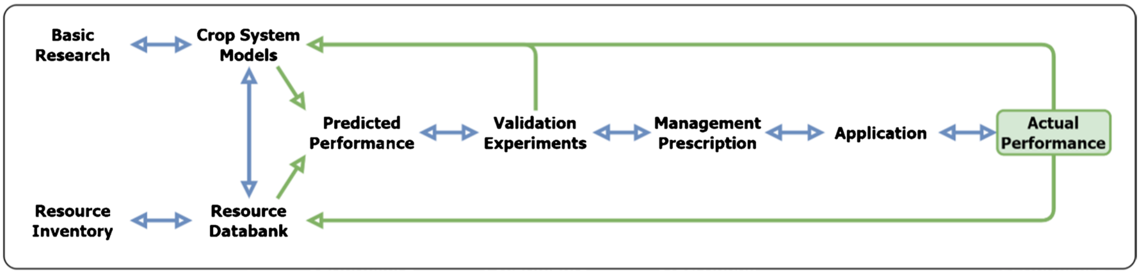

Fig. 1 Components of a systems research strategy as devised by (Nix 1985), figure adapted from Keating and Thorburn (2018).

Much of the early crop model development activity in that time can be traced back to central Texas (an agro-environment not dissimilar to southern Queensland). Joe Ritchie was an agricultural engineer and he started building component models of the water balance of row crops (Ritchie 1972) and with others such as Jerry Arkin and Richard Vanderlip, a full crop growth, development and yield model was produced called SORGF model (Arkin et al. 1976). This generation of models were neither fully mechanistic nor fully empirical. They were structured around the key mechanisms understood to drive plant development, growth and yield and key processes understood to be important in soils (initially soil water and later soil nitrogen balance).

Australian crop physiologists and agronomists were also active at this time. The focus was generally on model development and included work with potato (Moorby and Milthorpe 1980), sunflower (Smith et al. 1978; Hammer et al. 1982) and wheat (Hammer and McKeon 1983; Stapper 1984). Work on cotton (Hearn et al. 1981) was an exception with a focus on model deployment in a computer-based decision support system.

The modelling effort that had one of the most significant impacts globally over this period started with the umbrella name of CERES—the "Crop Environment Resource Synthesis". CERES-Maize and CERES-Wheat (Godwin et al. 1983; Jones and Kiniry 1986) emerged from these efforts in the early to mid-1980s. A critical achievement of the CERES effort was to link up comprehensive models of plant growth and development with a similar level of functional detail and explanatory power in the soil water and nitrogen balance.

At around the same time these crop-soil models were being published and released to the public domain, USAID had funded a project on agro-technology transfer called IBSNAT (International Benchmark Sites Network for Agro-technology Transfer) (Silva and Uehara 1985). IBSNAT promoted the development of minimum data sets for model development and testing (Nix 1983) and the extensive training program in model application associated with the CERES and GRO modelling efforts (later linked under the Decision Support System Agrotechnology Transfer package (DSSAT). The Australian, Henry Nix, was active in IBSNAT, and in the late 1970s, he proposed (Nix 1985) a "systems research strategy" (Fig. 1) that placed "crop system models" and resource databanks as key tools in framing research activity and interpretation.

5 1980s—simulation modelling meets farming systems research

Farming systems research (FSR) emerged in the late 1970s and early 1980s with strong Australian links (e.g. Dillon 1976) in response to a growing view that agricultural research was not relevant to the needs of "real-world" farmers. This was a movement most strongly seen within the CGIAR with its focus on smallholder farmers in developing countries. (Collinson 1982) set the template for FSR with his famous "Figure of Eight" diagram on "on-station" and "on-farm" research cycles.

The FSR approach did generate new and improved insights into the real-world constraints under which farmers operate, both biophysical and socio-economic. It took previously research station-bound researchers out onto farms and into dialogue with farm households. Problems arose, however, with how to interpret the on-farm experiments established under FSR programs given the large number of controlled and uncontrolled variables interacting. Problems also arose in generalising the results across seasons and soils. The early proponents of FSR were aware of these potential challenges and (Dillon and Virmani 1985) wrote:

> The newly evolving field of dynamic systems models would seem to have great potential for handling the complex interaction that characterise on-farm production. If this is so, such models should help in over-coming the problem of location specificity. Data collected from multi-disciplinary investigations across different agro-climatological zones could be used effectively in the development of 'weather-driven' crop production models which would provide a vehicle for guidelines for system manipulation and appraisal under varying locales.

This proposition put forward by Dillion and Virmani in 1985, and broadly in line with the systems research strategy of Henry Nix, was explored by the Australia-Kenya Dryland Farming Systems project from 1985 to 1992 (McCown et al. 1992). The newly released CERES-Maize was tested on maize growth and development data collected under a very broad range of crop management, water and nitrogen regimes.

The approach to combining a crop-soil simulator with the Collinson FSR methodology was summarised by McCown et al. (1994) in Fig. 2.

The Kenya work produced new insights into the opportunities to use modest nutrient inputs and adapted agronomic practices to move a low-yield subsistence farming system towards a more productive and sustainable state (Keating et al. 1991). These ideas evolved in partnerships with ICRISAT in Southern Africa and the notion of "micro-dosing" emerged (Twomlow et al. 2010) and got taken up in food security interventions.

An international symposium in Brisbane, Australia, in 1990 showcased these emerging applications of crop-soil models, stimulated in large part by the modelling work in Kenya and companion programs in northern Australia (Carberry and Abrecht 1991). Titled "Climatic Risk in Crop Production—Models and Management for the semiarid tropics and subtropics" (Muchow and Bellamy 1991), this meeting was a turning point. All the discussion of the potential for crop modelling in the 1980s was replaced by tangible evidence from around the world on the insights that were being generated—particularly in situations where agriculture operated under highly variable climates.

Beyond Kenya, these participative action research (PAR) approaches involving on-farm research aided by crop-soil simulation modelling gained wider application during the 1990s and 2000s in India (Dimes and Revanuru 2004) and Southern Africa (Whitbread et al. 2010). In more recent years, we see examples of this approach all over the world—including in developed agricultural systems as has proved to be the case in Australia (FARMSCAPE—Carberry et al. 2002).

6 1990s—APSRU and APSIM emerge

The establishment of the Agricultural Production Systems Research Unit (APSRU) in 1990 was a significant development in this narrative. APSRU was the inspired solution hit upon by two senior managers of agricultural research in northern Australia when faced with fierce competition between their staff aspiring for leadership in crop/soil

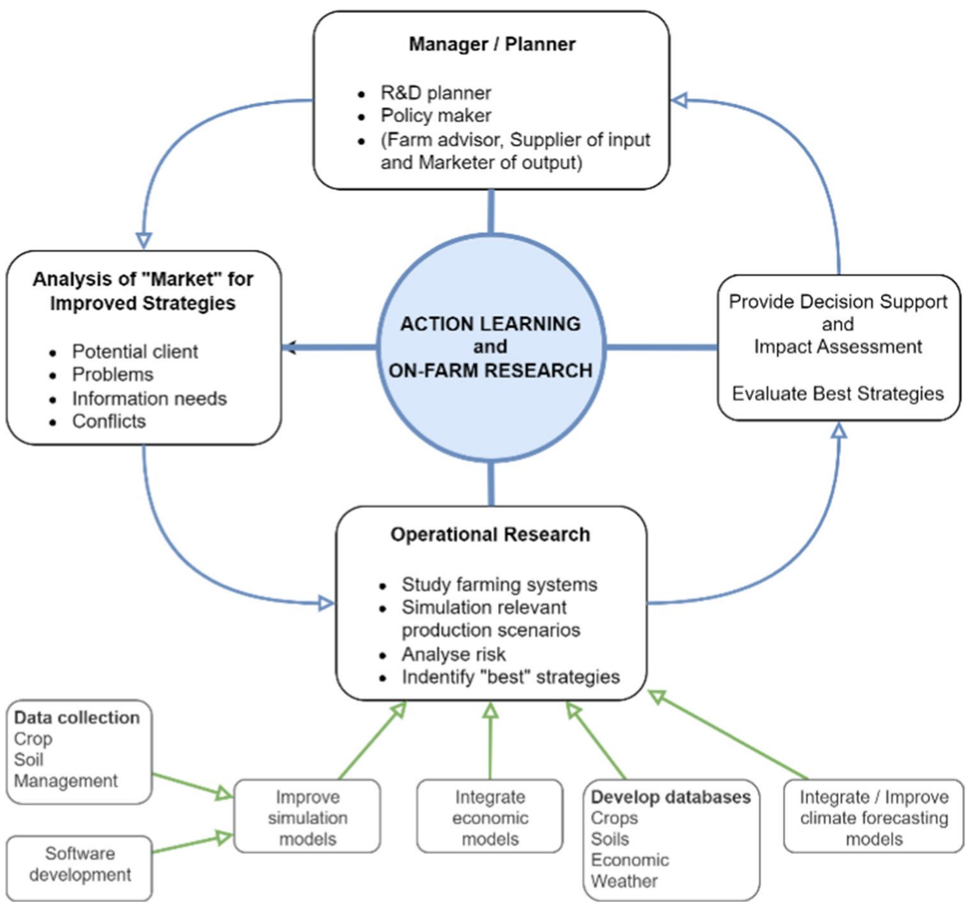

Fig. 2 The systems research framework that builds crop-soil modelling into a farming systems research paradigm (from McCown et al. 1994). Note: "Operational research" in this figure replaces the "On Station Technical Research" in the original (Collinson 1982) "Figure 8 diagram". Figure adapted from Keating and Thorburn (2018).

modelling and DSS development, i.e. John Leslie of the Queensland Department of Primary Industries (QDPI) and Bob Clements of CSIRO Tropical Crops and Pastures. Their solution was to "put them together" in a joint unit in Toowoomba and see what emerged. There were certainly plenty of fireworks as APSRU went through a decade or more of "forming, storming and ultimately performing" (not sure APSRU ever "normed"). The APSIM model including the approaches adopted to software engineering and model applications emerged as the key outcome from the APSRU venture.

6.1 AUSIM

AUSIM emerged in 1989 (McCown and Williams 1989) as a model concept—strongly influenced by experience with the limitations of crop-soil models (e.g. CERES-Maize) whose architecture was not well suited to farm systems simulation. Adaptations of CERES-Maize emerged from experience with low-input farming systems in Kenya (Keating et al. 1992) and maize legume rotations and intercrops in the semi-arid tropics of Australia (Carberry et al. 1989). These adaptations saw "systems capabilities" being super-imposed on the CERES-Maize model structure. By 1990, it had become increasingly obvious to all involved that the "spaghetti FORTRAN" code had become too complex and unstable to provide a long-term foundation for a cropping systems simulator. Most importantly, it became evident that the entire approach to model conceptualisation and software architecture needed to be reconsidered. That is what the AUSIM concept sought to do.

It seems obvious now looking back, but the critical "mind-set" change needed was for crop modelers to adopt a "soil-centric" approach to model architecture. Instead of trying to link up different crop-soil models such as was done in the early DDSAT, a robust and capable systems model needed to start with a soil simulation and build from there. There were other "land systems" models available at the time with this same "soil-centric" view, such as EPIC (Williams et al. 1984), NTRM (Shaffer and Larson 1987) and PERFECT (Littleboy et al. 1992), but none dealt with the crop components in an adequately yield-sensitive and management-responsive way, like that which was established in the CERES approach.

The initial blueprint was called AUSIM (the Australian Simulator), a modular agricultural systems simulator with the soil modules as central for crop and pasture modules that could "come and go" (Fig. 3).

6.2 APSIM

One of the first big battles within APSRU was what to do with the existing crop-soil modelling investments. QDPI came to APSRU with PERFECT (Productivity, Erosion and Runoff Functions to Evaluate Conservation Techniques) from their Soil Conservation team and SORGF/QSORG, QSUN from their crop agronomists. CSIRO had embarked on AUSIM but there was a long road of model development ahead. Were we to combine these efforts or continue down the existing pathways? To cut a long story short, PERFECT, as a land systems model had many attractive systems features, but it did not meet the needs of crop agronomists or breeders for yield prediction. Agreement was reached to jointly develop a new platform, to be called APSIM.

The original structure of the APSIM model as published in 1996 is reproduced in Fig. 4. The influence of the hand-drawn diagram that first conceptualised AUSIM (Fig. 3) is clear.

Key (and still largely unique) features of APSIM include abilities in the simulation of intercrops, weeds, biotic constraints, crop-livestock interactions, manure and phosphorous in low-input farming systems, multi-field situations with complex crop rotations, erosion-productivity interactions, greenhouse gas and water quality impacts, elaborate crop-surface water storage simulations, forest and agro-forestry configurations. APSIM's flexibility always resided in its core architecture:

> "Crops [and animals and trees and weeds and seasons and managers] come and go, each finding the soil in a particular state and leaving it in an altered state" (McCown et al. 1996 with bracketed text coming from Keating et al. 2003).

The conceptualisation of the MANAGER facility in APSIM proved to be critical to the platform's utility. Put simply, we wanted the model user to be able to explore management issues with the same flexibility as a real-world farmer who every day makes choices about what they do on their farm. As there was no way we could predict what future users might want to explore in their simulations, we sought to avoid any strait-jackets in how we specified the management parameters. The specification for the MANAGER boiled down to a capability to *initiate any action* at *any time* based on the *status of any variable* in the simulation. Over time, the software team came up with a powerful means of achieving that specification via a MANAGER Module driven by a script language. This approach has continued to evolve over the last 30 years and continues to deliver great utility to the present day.

6.3 Software engineering

From the outset, there was a recognition that long-term success was dependent on the quality of the software engineering that went into APSIM's design, construction, testing and documentation. John Hargraves and Brian Wall were

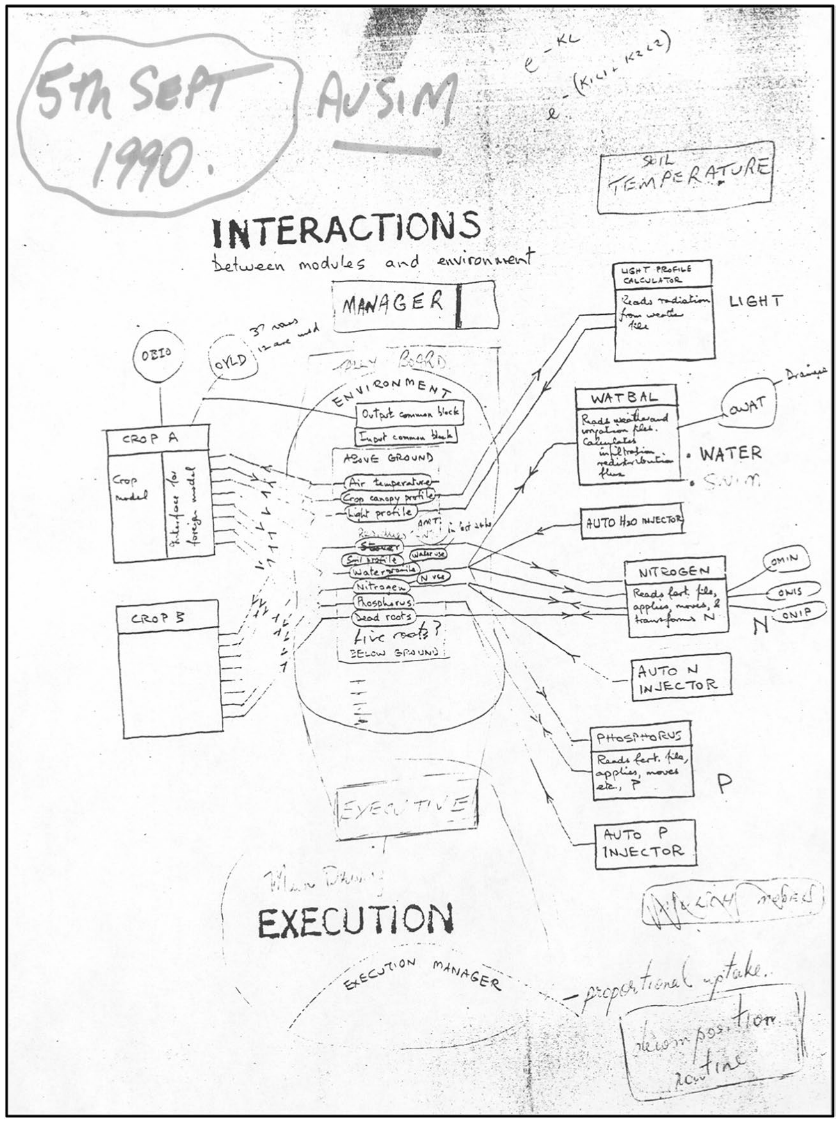

Fig. 3 The oldest surviving record of APSIM's origin. This was an image from a whiteboard used at a meeting at CSIRO Davies Laboratory Townsville on 5th September 1990.

the strongest initial advocates of attention to good software design and testing. In 1995, an independent review of APSIM software practice was commissioned of Prof. Ray Offen, Macquarie University. The finding was essentially that whilst there was good intent on achieving quality in software practices, an effort of the scale that we were attempting would require a more significant software engineering investment to succeed in the longer term. Bob McCown, one of the founders of APSRU and APSIM, was never one to hold back and his personal papers from 2010 describe this review as "devastatingly critical". Fortuitously, in a separate initiative, CSIRO had recognised an organisation-wide need for better software practice across its activities and new funding became available in 1996/1997 for a cross-CSIRO project called the Software Engineering Initiative (SEI). This resulted in two software engineers being based with APSRU in Toowoomba (Sid Wright and Val Veraart) for 2 years and together with the existing team led by this time by Dean Holzworth, they were able to forge a Software Engineering Group (SEG) for APSIM whose influence is still strong today.

7 2000s—model capability, availability and use grow nationally and internationally

By 2000, 10 years into the APSIM development journey, there was strong evidence that a model-augmented FSR approach was generating strong interest at home and abroad. The international engagement continued with the support of the Australian Centre for International Agricultural Research (ACIAR), extending from eastern Africa to Southern Africa and over to South Asia. Partnerships with the CGIAR

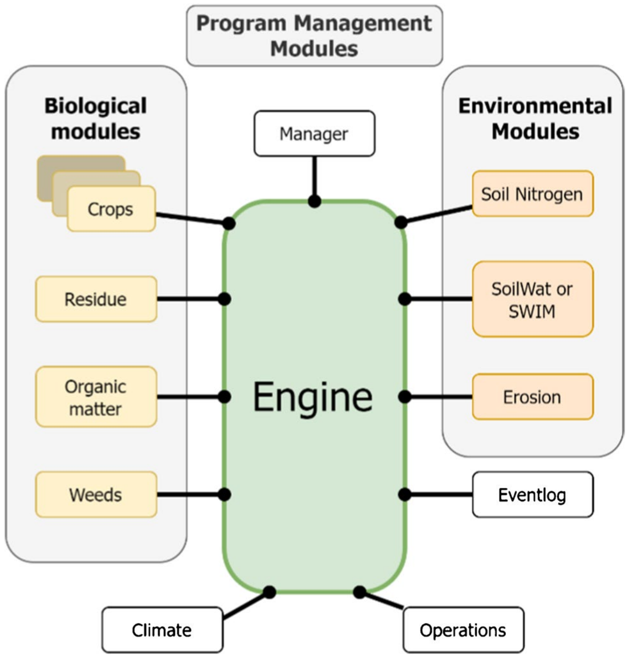

Fig. 4 Structure of APSIM based on McCown et al. (1996).

Centres were established. At home, however, we had a situation where Australia's most powerful "systems agronomy" capability was constrained to an area, the north-eastern grains production regions, that produced less than 10% of the nation's cereal crops. The mandate for the Queensland Government and CSIRO Tropical Crops and Pastures teams was geographically limited and this threatened the longer-term sustainability of the overall effort. To address this challenge, we set out on a multi-faceted "partnerships" strategy, to both underpin the capability of what was emerging in Qld and broaden its impact. Over the decade from 2000, we had effectively established a critical mass of national collaboration within CSIRO, with most State Departments, many Universities and with many leading farmer groups. Some key enablers of this transformation included the following:

- The commitment of CSIRO Soils researchers to the vision of a "soil-centric" farming systems simulator remained strong. John Williams (to later become Chief of the *CSIRO Division of Soils and CSIRO Division of Land & Water*) shared this initial AUSIM vision with Bob McCown (one of the founders of APSRU) in 1989 and many staff in *CSIRO Division of Soils* (and later *Land and Water*) made major contributions including Merv Probert, Kirsten Verburg, Val Snow, Warren Bond, Chris Smith and Keith Bristow. Access to major national research programs within CSIRO and the Australian Government helped the Toowoomba-based team with entry to the national stage.
- In the year 2000, moves to reorganise CSIRO Divisions led to the recognition that the "systems research" teams in CSIRO were a national asset that could be lost if split up. A solution was found via the creation of a new *Division of Sustainable Ecosystems* including ecologists and systems researchers. This put agriculturalists and ecologists, together with economists and sociologists, into a unique mission-focused division in CSIRO. An unexpected benefit of this change was it gave our farming systems research team a national platform and staff were relocated or recruited to most major research centres in southern Australia and able to engage locally, often in partnership with State Dept researchers, Universities and/or farming systems groups.
- The partnership with Australia's leading farming systems group[1], the Birchip Cropping Group (BCG) (including with Harm van Rees, the BCG agronomist at the time), was particularly effective in establishing a systems agronomy platform in the State of Victoria. BCG's national leadership was such that benefits spilled over to collaboration with other farming systems groups nationally.
- In 2006/2007, CSIRO established the *Sustainable Agriculture Flagship* as a national program with integrated funding for agronomy, entomology, soils, ecology, forestry, livestock and related bio-statistics and ICT disciplines. Systems modelling tools featured prominently in the research investments and APSIM efforts got a major boost, including more seamless integration of all of CSIRO's farm-relevant modelling (including GRAZPLAN and AusFARM from CSIRO Plant Industry) effort via the "Common Modelling Protocol" (Moore et al. 2007).
- APSIM IP management was initially quite restrictive requiring collaborative agreements for APSIM access and limited access to APSIM source code. In 2006/2007, after the 3rd term review of APSRU, a new more open multi-party platform was established to provide inputs and governance to APSIM development and use. The source code was transferred to an "open source" domain and a strong oversight of software version control and performance testing was maintained. The significance of this change in approach to source code access and governance cannot be over-stated and it is likely to have laid the foundation for

[1] Farming Systems Groups are groups of farmers with common interests in a particular geographical region and farming activity. They started to emerge in Australia around 2000 and were stimulated by a gradual withdrawal of government agencies providing direct agricultural extension and services. Many grew into larger "not for profit" entities that would conduct translational R&D as well as extension like activities. They generally employed staff and secured competitive funding. They continue to act as "knowledge brokers" linking Government, Academic and Private Industry R&D to farming practitioners.

the significant increase in APSIM-based collaboration and use around the world since 2006/2007.

8 2010s—leadership passes to the next generation

It is rare for scientific endeavours to last as long as has been the case for APSRU and APSIM. APSRU ceased as a formal entity in 2007 and the continuing focus shifted to the "APSIM Initiative" with more open and collaborative governance arrangements. The software itself has evolved enormously over the last 32 years. The 2014 reference paper for APSIM (Holzworth et al. 2014) is the best source of information on APSIM's software engineering and capabilities still in active use under APSIM ver 7.x. (Holzworth et al. 2018) explain the more recent efforts to capture APSIM's historical strengths but transform the software to meet future needs via what is called "APSIM-Next-Generation". The foundation members of the APSIM Initiative (when it replaced APSRU in 2007) were CSIRO, the State of Queensland and The University of Queensland. AgResearch Ltd., New Zealand, became a party in 2015 followed by the University of Southern Queensland in 2017. In March 2020, Iowa State University, US, became a member. Most recently, Plant & Food Research (NZ), joined in 2021.

9 Reflections on APSIM use and impact

In this section, I gather the data on APSIM usage and try to assess what difference it has made.

9.1 APSIM use—globally

For the 2020/2021 year, there were *4863 non-commercial licenced users* registered (up from 4002 in 2019/2020). This resulted in some *5861 downloads* of APSIM (all versions as some users download older versions or use multiple versions). In 2019/2020, APSIM was being *used in 132 countries*. In Australia, there were 604 users (23% APSIM Next Gen). In New Zealand, there were 93 users (36% APSIM Next Gen) and 255 users in the United States of America (17% APSIM Next Gen).

The second most cited paper in the ISI-WoS database for all papers ever published in agronomy or multi-disciplinary agriculture with at least one Australian-based author (a total of 31,338 papers) is one of the three commonly used citations for the APSIM farm systems model (Keating et al. 2003). If all three APSIM source papers were considered in aggregate (Fig. 5), they would be Australia's most cited agronomy paper of all time.

Globally in 2021, there were 0.75 million agronomy or agriculture multi-disciplinary papers listed in the Web of Science (WoS) database and the Keating et al. (2003) APSIM paper is ranked number 31. So clearly these statistics suggest something has been happening in agronomic model building and application in Australia of global significance.

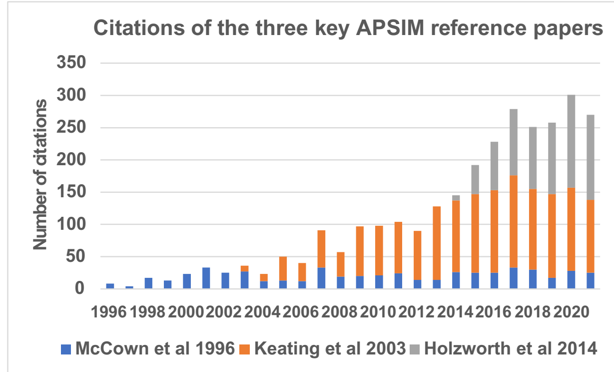

Fig. 5 Citations per year since 1996 for the three standard APSIM reference papers as captured in the WoS database. (Note, some papers may cite more than one of these key reference papers at the same time).

Not surprisingly, Australia is the most significant "country of use" for APSIM over the 2000–2020 period based on WoS data (36%) followed by China (15%) with Brazil, USA, India and New Zealand significant users each at 3–4%. Overall, there are APSIM papers originating from 39 different countries or regions (Fig. 6).

Figure 7 shows 22 different domains of application identified in the 5 "deep dive" years spanning 2000–2020. Agronomic investigations are strongly represented along with climate change investigations (many of which will have an agronomic focus) making up 61% of all papers in 2020.

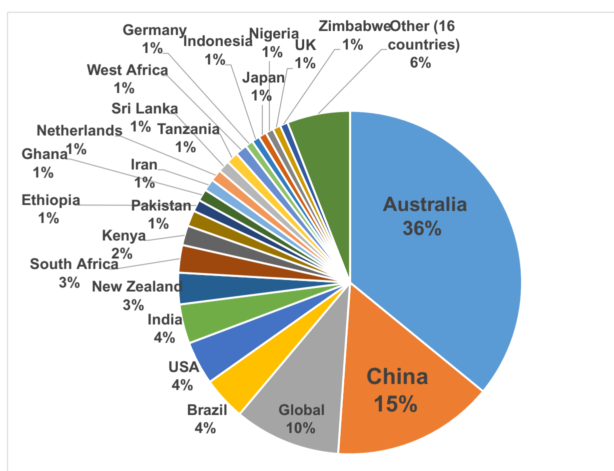

Fig. 6 Country of use data derived from on WoS papers that identify APSIM as a Topic (based on a sample of 5 years of publication, namely 2000, 2005, 2010, 2015 and 2020, $n = 270$).

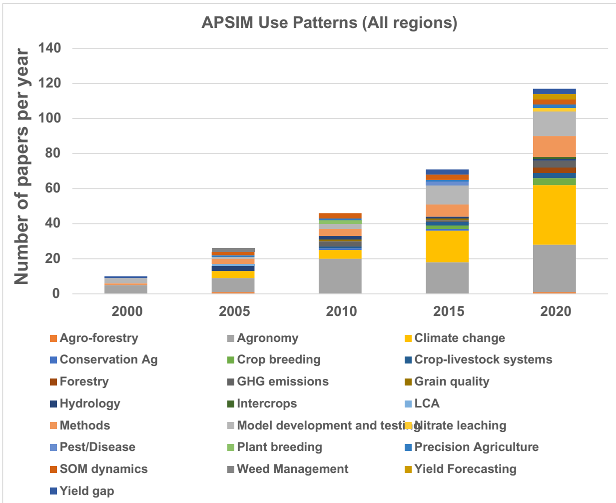

Fig. 7 Estimates of the purpose of APSIM use based on papers with APSIM as a Topic in the WoS database for 2000, 2005, 2010, 2015 and 2020 years of publication.

Beyond those topics, almost every conceivable topic has been subject to some APSIM-related investigation at some point.

9.2 APSIM impact—has APSIM changed Australian agronomy?

We will look to answer this question separately in each of four application domains (impact pathways). That is (i) use in research, with indirect influence on farmers and advisers), (ii) use in government or industry policy, (iii) use in plant breeding and finally, (iv) use directly by farmers and advisers.

9.2.1 Model use in research agronomy

There appears to be strong evidence to support the contention that APSIM has been immensely influential on agronomists and agronomic research in Australia. Robertson et al. (2015) reviewed the simulation model used in the Australian grains industry using stakeholder surveys and literature search techniques. APSIM was the dominant tool in use at that time, representing 95% of all model applications. These authors estimated that there were around 100 active and independent model users, 15 model developers and 10 post-graduate students at any one time. Around 15% of papers at Australian Agronomy Conferences in the 2000s made use of simulation models. This compares with around 3% in the early 1990s when the APSIM effort began.

Hochman and Lilley (2019) reviewed the application of APSIM simulation methods and simulation-based decision support systems (DSS) in Australia. They identified 18 different issues where they saw evidence for simulation-based studies being successfully combined with field-based agronomic knowledge to advance farming systems profitability and sustainability. This inventory of impacts is organised in terms of the following:

- Managing crops in a variable and changing climate
- Crop-genotype improvement and trait value propositions
- Industry scale predictions, quantifying and diagnosing wheat yield gaps
- Scaling up to crop sequences
- Balancing production and environmental goals

This list built up by Hochman and Lilley (2019), impressive as it is, misses much of what was achieved before 2008. Keating et al. (2003) provide a report of APSIM application over the 1996 to 2001 period which identified some additional foci for APSIM application including the following:

- An extensive body of work on the water balance of Australia's farming systems in the context of the challenges of dryland salinity
- The extensive body of work on irrigation and nitrogen management in sugarcane
- Considerations of soil acidification under farming practice
- Consideration of windbreak effects and other issues relating to trees on farms
- Investigations into the potential for expansion of cropping into new regions of northern Australia
- An extensive body of work looks at the potential to sequester soil carbon in Australia's farming systems
- Evaluation of the greenhouse gas footprint of cereal-based farm systems and exploration of mitigation options
- Evaluation of climate change impacts on Australia's farming systems and exploration of adaptation opportunities
- The influence on Australian agronomists as they engage internationally in Research for Development (R4D) activities in Africa, South Asia, South-East Asia and the Pacific

In summary, there is a strong body of evidence that simulation modelling has empowered Australian research agronomists via the following:

- Interpretation of experimental results
- Extrapolation of these results to account for seasonal variability and assessing risk
- Extrapolation of results to other soils and climate regions
- Exploring the potential for farming systems modification in silico as a lead into experimentation in the field

9.2.2 Model use in government and industry policy

Deployment of simulation models in government policy making or policy implementation domains has always been seen as a challenging path to impact. One challenge is it is difficult to accommodate all of the political nuances that influence government policy making when a deterministic model is centre stage. Another is the potential for someone adversely impacted by a policy outcome to pursue legal challenges and the mis-match between model input and output uncertainties and the legal process. The NZ experience with the "Overseer" model for managing nutrient loads on ground and surface waters has thrown up many challenges (MPI 2021) and there are important lessons there for anyone hoping to deploy a biophysical model in a contentious policy domain. One current use of APSIM that appears to be gaining traction is in the Australian and Queensland Governments' Paddock to Reef Integrated Monitoring, Modelling and Reporting Program aimed at improving Great Barrier Reef water quality (Carroll et al. 2012). The nitrogen balance capability of APSIM-Sugarcane (Biggs and Thorburn 2016) with some recent enhancements (Vilas et al. 2022) are used as an integral part of this Program.

In terms of "industry" policy, the scope includes any industry participant in the agri-food value chain. APSRU staff had some early experience as witnesses in court battles over crop insurance claims and there remains potential for APSIM use in the insurance domain (Thorburn et al. 2020), a big driver of model use in the USA. There has also been interest over the years in input and output logistics (e.g. forecasting fertiliser volumes or crop volumes by region) but it appears none of those applications have evolved into a sustained pathway to impact for APSIM at this time. More customised tools have been developed which use APSIM as one element of the tool. Graincast™ is a good example (Lawes et al. 2022). It combines a broad suite of satellite-based crop mapping, crop modelling and data delivery techniques to create an integrated analytics system that covers the Australian cropping landscape. APSIM is used to give growers an estimate of yield potential and soil water in return for data on what they have planted which is in turn used with remote sensing for wide area production forecasts in the Graincast™ system.

One of the most powerful means by which APSIM can influence industry policy is via its deployment by R&D funding bodies, either as a pre-investment analysis tool to determine the potential returns from a proposed research program or as a scaling out tool across regions and across the value chain to maximise the returns from past research. Feedback from the Grains Research and Development Corporation (GRDC) suggests APSIM "is extensively used to provide situation analysis and business case justification for GRDC investments that underpin grain production". For instance, the use of APSIM to quantify yield gaps in Australian agriculture (Hochman and Horan 2018) has been highly influential in shaping GRDC's current RDE Plan 2018–2023 which specifically targets closing significant yield gaps as one of the largest investment priorities (P.S. Carberry, pers. comm. 2022).

9.2.3 APSIM use in crop improvement and breeding

Whilst CSIRO members of APSRU placed a major emphasis on APSIM use in agronomic research (discussed above) and in decision-making on-farm (discussed below), our State Government colleagues (at the time in the Queensland Department of Primary Industry, (QDPI) and latter in partnership with the University of Queensland via Queensland Alliance on Agricultural and Food Innovation, QAAFI) became pioneers in simulation model use in crop improvement. Graeme Hammer provided the initial leadership in that domain which places considerable demands on "parsimonious, biologically credible modelling to enhance the capability for modelling the physiology and genetics of complex adaptive traits in crops as a means to advance G-to-P prediction capacity". (Hammer et al 2010). In particular, the focus here has been to identify and assess impactful genomic regions and traits in target environments (Chenu et al 2009; Casadebaig et al 2016; Hammer et al 2020) and to develop meaningful phenotyping approaches (Chenu et al 2018).

One key application in this domain is "environmental characterisation" to help interpret genotype-environmental interactions for complex traits such as drought resistance (Chenu et al 2011). More recently, deeper long-term partnerships with commercial plant breeding efforts have demonstrated how physiologically sound crop models with "gene to phenotype" capabilities can be deployed to improve the efficiency and effectiveness of quantitative genomics approaches to plant breeding efforts (Cooper et al 2020). This remains in 2024 a very active field of APSIM deployment.

9.2.4 APSIM use in decision-making by farmers and advisors

Much of the early excitement researchers had for simulation modelling was driven by the idea that they would be used to develop model-based Decision Support Systems (mbDSS) for use by farmers and farm advisors. This was part of the rationale for APSRU's formation in 1990 and early success with DSS tools like "Wheatman" (Woodruff 1992) and SIRATAC (Hearn et al. 1981) was encouraging research managers to see value in such investments. If we look back to Nix's "systems research strategy" of the early 1980s (Fig. 4), we see "Management Prescriptions" identified as a key output of the process. Nix was not alone. This idea that models could be used to identify the best decisions for farmers permeated the thinking of most scientists in the 1980s and has survived for many till the current day. But there is a dearth of evidence to support this notion in practice. APSRU researchers were always a little more circumspect about the prospects for DSS tools (we would often redefine that as Discussion Support Systems (see Nelson et al 2002)). The circumstances under which models could be useful in informing farmer practice ended up as a major line of research for my CSIRO colleagues in APSRU.

One early foray into this space was *Whopper Cropper* developed during the 1990s (Nelson et al. 2002), a massive database of predefined APSIM output covering management options, soils classes and weather sites for a target farmer population. The idea was to convey risk-based insights into the value of a range of management options (including seasonal forecasts coming from newly emerging indices based on SOI). This activity was certainly of value to researchers and it did serve to promote new concepts such as the use of SOI-based seasonal forecasts in decision-making. However, there is no evidence there was sustained interest from farmers or advisers or a strong impact on farm decision-making. One interpretation is that farmers are interested in analyses that apply to their own *specific* situations (soils, weather, field history and management options). Generic "prescriptions or even discussions" are of less interest and certainly of no sustained value beyond some initial exposure.

FARMSCAPE was a 17-year investigation into the place for science-based models in real-world farm decision-making (Carberry et al. 2002). Bob McCown was always one for acronyms and the FARMSCAPE acronym was one of his more ambitious—but it is explanatory in terms of what FARMSCAPE was all about, i.e. *F*armers, *A*dvisors, *R*esearchers, *M*onitoring, *S*imulation, *C*ommunication *a*nd *P*erformance *E*valuation. A related investment was *Yield Prophet*, a partnership between APSRU/CSIRO and the Birchip Cropping Group (BCG) which sought to take the power of the simulation models and combine that with the lessons from FARMSCAPE as to what might be useful in terms of decision-making support for farmers and advisors, and package these two things in a "DSS-like" web-based service.

My reflections from observing FARMSCAPE and Yield Prophet over the years can be summarised along the following lines:

- Even experienced farmers can get significant value from engagement with well-adapted simulation models that let them explore the risk-based consequences of the choices they face in tactical and strategic farm management (the analogy with a flight simulator used by experienced pilots).
- This value, however, only comes once trust has been established that the model can provide relevant insights to farmer circumstances. Farmers are well-tuned into situations when a model is not capturing reality, but they are also well-placed to interpret a situation when factors outside the model cause deviations between predictions and observations.
- Benchmarking performance within and across farms and exploring opportunities to close "yield gaps" (or even better, "profit gaps") can be of great benefit to farmers and their advisory agronomists.
- These model-based "WiFADS" (What If Analysis and Discussion Sessions) need to be customised to farmers' specific real-world circumstances (soils, climate and farm management systems). (It is interesting to note the first use of the "what if" notion in model application came from W.G. Duncan (1975) as outlined earlier).
- Whilst not the only option, generally, these engagements have worked best when an experienced advisory agronomist supports a group of farmers in the model setup and use.
- The development of "easy to use" tools that reduce the complexity of model use and reduce the chances of model misuse is useful for wider uptake in circumstances where the model developers or experts cannot be directly engaged (e.g. Yield Prophet is an example).
- Farmers and advisors DO NOT appear to look to these tools for a "management prescription". They are more likely to see them as they would see a "research agronomist" whom, once trust has been built up, has some insights to offer on their circumstances that can then be factored into the wider decision-making process.
- Intuition plays a key role in shaping farmer decisions and actions in the face of uncertainty (McCown 2012). Models are most useful when they are used to "nudge" farmer intuition through virtual experience in ways that is not easily achieved through "real-world" experience.
- Farmers and advisors who have got value from an intensive model-based engagement with researchers or a sustained period of use of a tool such as Yield Prophet, do not generally remain users indefinitely. This can be interpreted as an internalisation of the value the model was giving and translation into some internal heuristics or "rules of thumb" (i.e. nudging intuition). This phenomenon is not necessarily a bad thing. The test is when circumstances change, do the models come back into the picture for another more intensive period of use? There is some evidence of this in our recent survey of farmers associated with the BCG but I suspect we need to say the "jury is still out" on that at this point.

Bob McCown spent the last 20 years of his career seeking to answer the question: "Can science-based models that arise from the world of theory be useful to farmers and advisors in their world of practice?" McCown (2012) explores the theoretical basis to this question in terms of a cognitive framework model with links to both the farm production system and an analytical information system (the decision tools) and McCown et al. (2012) test this theory against the FARMSCAPE evaluation data. These were McCown's last two papers. They do not make easy reading but they make an important contribution in drawing together various bodies of theory to explain the circumstances in which science-based analytical information can add value to farm decision-making.

9.3 Why did this effort originate in Queensland/Australia?

One can postulate why a development as significant as APSIM might have emerged from Australia in general and more specifically from a small research collaboration in south-east Queensland.

9.3.1 Bio-physical factors

Australia as a whole experiences a high level of rainfall variability (e.g. a national annual coefficient of variability of around 18% compared to 9% for India and less than 6% for the USA) (Love 2005). The subtropical cropping systems of southern and central Queensland experience very high levels of climate variability even by Australian standards (e.g. coefficients of variability of annual rain totals in the order of 28 to 38%). Farming systems in this region are also very diverse given they are made up of both tropical summer crops and pastures and temperate winter crops and pastures. Planting opportunities are driven by episodic rainfall events and there are crop or forage species options available for every month of the year. The capability to store water in the deep clay soils of the region also adds additional flexibility and complexity to the farm system. Along with water supply, nitrogen supply from mineralisation and past crop or pasture sequences and from fertiliser inputs dominates cropping productivity. All these factors together mean that a simulation approach to farming systems agronomy fell on "fertile ground" in this region.

9.3.2 Institutional factors

Australia was also a natural place for simulation-based systems agronomy to gain strong traction. The initial impetus came from assessing the agricultural potential of regions that had no agricultural track record and models were drawn into this process in the early 1960s (Slatyer 1960; Fitzpatrick and Arnold 1964). Over time, the continuing focus on the trading of un-subsidised agricultural commodities on world markets meant a continuing focus on efficiency in the use of farm inputs as a critical driver of global competitiveness. The dry and variable climate also means farmers are looking to operate on the high-efficiency slopes of production curves rather than be on the plateaux with excess inputs (Keating and Carberry 2010). All these factors mean that simulation of response functions in relation to climate variability was quickly embraced by systems agronomists. Another institutional factor that was critical for APSIM's emergence in the early 1990s was the productive competitiveness of State and Federal research bodies. The Qld State Government researchers and the national researchers from CSIRO were able to achieve more together than either would have achieved in isolation.

Australia's rural R&D system with industry levies and government co-contributions also proved to be an essential means of linking APSIM development and application to real-world farm situations. The GRDC, Land and Water Resources and Development Corporation (LWRRDC) and Rural Industries Research and Development Corporation (RIRDC) all made significant contributions in this regard. Finally, the Australian Government's sustained support for international agricultural research partnerships through ACIAR was also a major factor sustaining both the pace and breadth of APSIM development from 1990 to 2010.

This concept of comparative advantage was born from a mix of healthy competition and productive differentiation. No one institution in Australia could have achieved what has been achieved with APSIM. Collaboration between State and Federal institutions got APSIM underway initially and collaborations and shared projects with most State agencies, many Universities, most RDC funders, ACIAR, CGIAR Centres and many farming systems groups have been critical. There has been a healthy two-way flow of ideas and tools with like-minded groups internationally, in particular the USA, Netherlands and New Zealand.

10 Conclusions

A key ingredient to APSIM's success is that there was always a healthy balance of influence amongst the team of agronomists/farming systems researchers and software development professionals. Importantly, we were blessed with a few individuals who could cross over both domains. This meant the scientific and utility specifications remained centre stage within strong governance of software design and quality. Of course, 32 years is a long time to carry forward legacy issues in a software platform and the initiation of "APSIM Next Generation" in parallel with APSIM 7.x in 2018 is a measured move to transform for the future whilst not losing the gains of the past.

At the 2019 Australian Agronomy Conference, Hunt et al. (2019) put out the call for more "transformational agronomy" given what they saw as a marginalization of agronomy to some of the "M" issues in a wider GxExM dynamic (what they call the "left-over bits"). They called for agronomists to be the "directors and integrators of multidisciplinary research teams" and to "oversee and optimise the G x E x M system". They map out a vision for what this "transformational agronomy" entails and farming systems models are identified as central to the approach—in pre-experimental and post-experimental modes of use.

The Hunt et al. (2019) paper gives me some confidence that current and future leaders in Australian agronomy are going to make use of the systems modelling developments that have been discussed in this review. The "transformational agronomy" framework has much in common with the framework first proposed by McCown et al. (1994). Such frameworks have deep roots in a body of theory and practice arising from a long history of farming systems research (FSR), participatory action research (PAR), operations research (OR) and more recently innovation systems approaches. Current leaders would do well to get better acquainted with such history. Knowing where we (as agronomists) have come from is vital to inform where we are going.

We are about to see a plethora of corporate agronomic offerings under the banner of "digital agriculture", building on networks of proximal and remote sensing, the "internet of things", machine learning and perhaps the simulation models I have been discussing today. I am pleased to see these efforts to offer integrated services, often involving cashed-up private sector entities. I wish them well and certainly hope the best efforts find a market niche. I would suggest that they will encounter the same issue we model-building scientists have encountered over the last 50 years—that is the human elements of farming do not necessarily want to become just another circuit in a cybernetic world. In other words, new approaches in "digital agronomy" ignore the human dimension of farming at their peril.

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References

Anderson JR, Dillon JL, Hardaker JB (1977) Agricultural decision analysis. Iowa State University Press

Angus JF, Basinski JJ, Nix HA (1974) Weather analysis and its application to production strategy in areas of climatic instability. Food and Agriculture Organization of the United Nations, Hyderabad Khon Kaen, Kuala Lumpur, p 29

Arkin GF, Vanderlip RL, Ritchie JT (1976) A dynamic grain sorghum growth model. T ASAE 19:622–626. https://doi.org/10.13031/2013.36082

Biggs JS, Thorburn P (2016) Sugarcane crop, soil loss and dissolved inorganic nitrogen modelling (APSIM). In: Shaw M, Silburn M (eds) Modelling changes in pollutant loads due to improved management practices in the Great Barrier Reef catchments - Paddock Modelling, Technical Report - Report Cards 2010 to 2013. Queensland Department of Natural Resources and Mines, Brisbane, Queensland, pp 41–63

Brouwer R, De Wit CT (1968) A simulation model of plant growth with special attention to root growth and its consequences. In: Whittington WJ (ed) Proceedings of the 15th Eastern School in Agricultural Science. University of Nottingham, pp 224–242

Carberry PS, Muchow RC, McCown RL (1989) Testing the CERES-maize simulation model in a semi-arid tropical environment. Field Crop Res 20:297–315. https://doi.org/10.1016/0378-4290(89)90072-5

Carberry PS, Hochman Z, McCown RL et al (2002) The FARMSCAPE approach to decision support: farmers', advisers', researchers' monitoring, simulation, communication and performance evaluation. Agric Syst 74:141–177. https://doi.org/10.1016/S0308-521X(02)00025-2

Carberry PS, Abrecht DG (1991) Tailoring crop models to the semiarid tropics. In: Muchow RC, Bellamy JA (eds) Climatic risk in crop production: models and management for the semi-arid tropics and subtropics. CAB International, Wallingford, UK, pp 157–182

Carroll C, Waters D, Vardy S et al (2012) A paddock to reef monitoring and modelling framework for the Great Barrier Reef: paddock and catchment component. Mar Pollut Bull 65:136–149. https://doi.org/10.1016/j.marpolbul.2011.11.022
Casadebaig P, Zheng BY, Chapman S, Huth N, Faivre R, Chenu K (2016) Assessment of the potential impacts of wheat plant traits across environments by combining crop modeling and global sensitivity analysis. PLoS ONE 11:1–27
Chenu K, Chapman SC, Tardieu F, McLean G, Welcker C, Hammer GL (2009) Simulating the yield impacts of organ-level quantitative trait loci associated with drought response in maize: a "gene-to-phenotype" modeling approach. Genetics 183:1507–1523
Chenu K, Cooper M, Hammer GL, Mathews KL, Dreccer MF, Chapman SC (2011) Environment characterization as an aid to wheat improvement: interpreting genotype-environment interactions by modelling water-deficit patterns in North-Eastern Australia. J Exp Bot 62:1743–1755
Chenu K, Van Oosterom EJ, McLean G, Deifel KS, Fletcher A, Geetika G, Tirfessa A, Mace ES, Jordan DR, Sulman R, Hammer GL (2018) Integrating modelling and phenotyping approaches to identify and screen complex traits: transpiration efficiency in cereals. J Exp Bot 69:3181–3194
Collinson MP (1982) Farming systems research in Eastern Africa: the experience of CIMMYT and some national agricultural research services, 1976-81. MSU International Development Papers
Cooper M, Powell O, Voss-Fels KP, Messina CD, Gho C, Podlich DW, Technow F, Chapman SC, Beveridge CA, Ortiz-Barrientos D, Hammer GL (2020) Modelling selection response in plant-breeding programs using crop models as mechanistic gene-to-phenotype (CGM-G2P) multi-trait link functions. In Silico Plants 3(1):1–21
Dillon JL (1976) The economics of systems research. Agric Syst 1:5–22. https://doi.org/10.1016/0308-521X(76)90018-4
Dillon JL, Virmani SM (1985) In: Muchow RC (ed) Agro-research for the semi-arid tropics; North-West Australia. University of Queensland Press, St. Lucia, pp 507–532
Dimes JP, Revanuru S (2004) Evaluation of APSIM to simulate plant growth response to applications of organic and inorganic N and P on an alfisol and vertisol in India. In: Delve RJ, Probert ME (eds) Modelling nutrient management in tropical cropping systems. Australian Centre for International Agricultural Research, Canberra, pp 118–125
Duncan WG, Loomis RS, Williams WA, Hanau R (1967) A model for simulating photosynthesis in plant communities. Hilgardia 38:181–205. https://doi.org/10.3733/HILG.V38N04P181
Fitzpatrick EA, Arnold JM (1964) Climate of the West Kimberley area. CSIRO, Australia
Fitzpatrick EA (1969) Instructions for preparing decks for a computer program to carry out variable forms of weekly water balance accounting. CSIRO, Australia
French RJ, Schultz JE (1984) Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. Aust J Agric Res 35:743–764. https://doi.org/10.1071/ar9840743
Godwin DC, Jones CA, Ritchie JT et al (1983) The water and nitrogen components of the CERES models. In: Krumble V (ed) Proceedings of the International Symposium on Minimum Data Sets for Agrotechnology Transfer. ICRISAT, Patancheru, A.P. 502 324, India, pp 101–106
Hammer GL, Goyne PJ, Woodruff DR (1982) Phenology of sunflower cultivars. III. Models for prediction in field environments. Aust J Agric Res 33:263–274. https://doi.org/10.1071/ar9820263
Hammer GL, van Oosterom E, McLean G, Chapman SC, Broad I, Harland P, Muchow RC (2010) Adapting APSIM to model the physiology and genetics of complex adaptive traits in field crops. J Exp Bot 61(8):2185–2202
Hammer GL, McLean G, van Oosterom E, Chapman S, Zheng B, Wu A, Doherty A, Jordan D (2020) Designing crops for adaptation to the drought and high-temperature risks anticipated in future climates. Crop Sci 60:605–621
Hammer GL, McKeon GM (1983) Evaluating the effect of climatic variability on management of dryland agricultural systems in northeastern Australia. In: Fitzpatrick EA, Kalma JD (eds) Need for climatic and hydrologic data in agriculture in southeast Asia. Proceedings of a United Nations University workshop held at the Canberra College of Advanced Education. Belconnen, ACT
Hearn AB, Ives PM, Room PM et al (1981) Computer-based cotton pest management in Australia. Field Crop Res 4:321–332. https://doi.org/10.1016/0378-4290(81)90082-4
Hochman Z, Horan H (2018) Causes of wheat yield gaps and opportunities to advance the water-limited yield frontier in Australia. Field Crops Res 228:20–30
Hochman Z, Lilley J (2019) Impact of simulation and decision support systems on sustainable agriculture. In: Pratley J, Kirkegaard J (eds) Australian agriculture in 2020: from conservation to automation. Agronomy Australia and Charles Sturt University, Wagga Wagga, pp 337–356
Holzworth DP, Huth NI, deVoil PG et al (2014) APSIM - evolution towards a new generation of agricultural systems simulation. Environ Modell Softw 62:327–350. https://doi.org/10.1016/j.envsoft.2014.07.009
Holzworth D, Huth NI, Fainges J et al (2018) APSIM next generation: overcoming challenges in modernising a farming systems model. Environ Modell Softw 103:43–51. https://doi.org/10.1016/j.envsoft.2018.02.002
Hunt J, Kirkegaard J, Celestina C, Porker K (2019) Transformational agronomy: restoring the role of agronomy in modern agricultural research. In: Pratley J, Kirkegaard J (eds) Australian agriculture in 2020: from conservation to automation. Australian Society of Agronomy, Wagga Wagga, Australia, pp 373–388
Jones JW, Antle JM, Basso B et al (2017) Brief history of agricultural systems modeling. Agric Syst 155:240–254. https://doi.org/10.1016/j.agsy.2016.05.014
Jones CA, Kiniry JR (eds) (1986) CERES-maize: a simulation model of maize growth and development. Texas A&M University Press, College Station
Keating BA, Carberry PS (2010) Emerging opportunities and challenges for Australian broadacre agriculture. Crop Pasture Sci 61:269–278. https://doi.org/10.1071/CP09282
Keating BA, Thorburn PJ (2018) Modelling crops and cropping systems—evolving purpose, practice and prospects. Eur J Agron 100:163–176. https://doi.org/10.1016/j.eja.2018.04.007
Keating BA, Carberry PS, Hammer GL et al (2003) An overview of APSIM, a model designed for farming systems simulation. Eur J Agron 18:267–288. https://doi.org/10.1016/S1161-0301(02)00108-9
Keating BA, Godwin DC, Watiki JM (1991) Optimization of nitrogen inputs under climatic risk. In: Muchow RC, Bellamy JA (eds) Climatic risk in crop production: models and management for the semiarid tropics and subtropics. CAB International, Wallingford, UK, pp 329–357
Keating BA, Wafulu BM, Watiki JM (1992) Development of a modelling capability for maize in semi-arid eastern Kenya. In: Probert ME (ed) A search for strategies for sustainable dryland cropping in semi-arid Eastern Kenya. Australian Centre for International Agricultural Research Proceedings. Australian Centre for International Agricultural Research, pp 26–33
Keig G, Mcalpine JR (1969) Watbal: a computer system for the estimation and analysis of soil moisture regimes from simple climatic data. CSIRO
Lawes R, Hochman Z, Jakku E et al (2022) Graincast^{TM}: monitoring crop production across the Australian grainbelt. Crop Pasture Sci. https://doi.org/10.1071/CP21386

Littleboy M, Silburn D, Freebairn D et al (1992) Impact of soil erosion on production in cropping systems .I. Development and validation of a simulation model. Soil Res 30:757. 10.1071/SR9920757

Love G (2005) Impacts of climate variability on regional Australia. In: Nelson R, Love G (eds) Proceedings of outlook conference, climate session papers. ABARE, Canberra

McAlpine JR (1970) Estimating pasture growth periods and droughts from simple water balance models. Proceedings 11th International Grassland Congress 484–7

McCown RL (2012) A cognitive systems framework to inform delivery of analytic support for farmers' intuitive management under seasonal climatic variability. Agric Syst 105:7–20. https://doi.org/10.1016/j.agsy.2011.08.005

McCown RL, Hammer GL, Hargreaves JNG et al (1996) APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. Agric Syst 50:255–271. https://doi.org/10.1016/0308-521X(94)00055-V

McCown RL, Carberry PS, Dalgliesh NP et al (2012) Farmers use intuition to reinvent analytic decision support for managing seasonal climatic variability. Agric Syst 106:33–45. https://doi.org/10.1016/j.agsy.2011.10.005

McCown RL, Williams J (1989) AUSIM: a cropping systems model for operational research. In: Proceedings of eighth biennial conference on modelling and simulation, Australian National University. Australian National University, Canberra, pp 25–27

McCown RL, Keating BA, Probert ME, Jones RK (1992) Strategies for sustainable crop production in semi-arid Africa. In: Outlook on Agriculture, pp 21–31

McCown RL, Cox PG, Keating BA et al (1994) The development of strategies for improved agricultural systems and land-use management. In: Goldsworthy P, De Vries FP (eds) Opportunities, use, and transfer of systems research methods in agriculture to developing countries: proceedings of an international workshop on systems research methods in agriculture in developing countries, 22–24 November 1993, ISNAR, The Hague. Springer Netherlands, Dordrecht, pp 81–96

Moorby J, Milthorpe FL (1980) Potato. In: Evans LT (ed) Crop physiology ; some case histories. Cambridge University Press, London, pp 225–258

Moore AD, Holzworth DP, Herrmann NI et al (2007) The common modelling protocol: a hierarchical framework for simulation of agricultural and environmental systems. Agric Syst 95:37–48. https://doi.org/10.1016/j.agsy.2007.03.006

MPI (2021) Overseer whole-model review - assessment of the model approach. Ministry for Primary Industries and the Ministry for the Environment by the Science Advisory Panel. Ministry Primary Industry MPI Technical Paper 2021/12 p 118

Muchow RC, Bellamy JA (1991) Climatic risk in crop production: models and management for the semiarid tropics and subtropics. CAB International, United Kingdom

Nelson RA, Holzworth DP, Hammer GL, Hayman PT (2002) Infusing the use of seasonal climate forecasting into crop management practice in North East Australia using discussion support software. Agric Syst 74:393–414. https://doi.org/10.1016/S0308-521X(02)00047-1

Nix HA (1980) Strategies for crop research. In: Proceedings of the Agronomy Society of New Zealand. 1980, Paper 27 pp 107–110. https://www.agronomysociety.org.nz/1980-journal-papers

Nix HA (1983) Minimum data sets for agrotechnology transfer. In: Proceedings of the International Symposium on Minimum Data Sets for Agrotechnology Transfer. ICRISAT, Patancheru, India, pp 101–108

Nix H (1985) Improving research efficiency. In: Muchow RC (ed) Agro-Research for the Semi-Arid Tropics: North-west Australia. University of Queensland Press, St. Lucia, QLD

Ritchie JT (1972) Model for predicting evaporation from a row crop with incomplete cover. Water Resour Res 8:1204–1213. https://doi.org/10.1029/WR008i005p01204

Robertson MJ, Rebetzke GJ, Norton RM (2015) Assessing the place and role of crop simulation modelling in Australia. Crop Pasture Sci 66:877–893. https://doi.org/10.1071/CP14361

Shaffer MJ, Larson WE (1987) NTRM, a soil-crop simulation model for nitrogen, tillage, and crop residue management. United States Department of Agriculture, Agricultural Research Service

Silva JA, Uehara G (1985) Transfer of agrotechnology. In: Silva JA (ed) Soil-based agrotechnology transfer. Department of Agronomy and Soil Science, Hawaii Institute of Tropical Agriculture, University of Hawaii, p 292

Slatyer RO (1960) Agricultural climatology of the Yass Valley. CSIRO, Commonwealth Scientific and Industrial Research Organization

Smith RCG, Anderson WK, Harris HC (1978) A systems approach to the adaptation of sunflower to new environments III. Yield predictions for continental Australia. Field Crop Res 1:215–228. https://doi.org/10.1016/0378-4290(78)90027-8

Stapper M (1984) SIMTAG: a simulation model of wheat genotypes. University of New England. Department of Agronomy and Soil Science and …, Armidale

Thorburn P, Biggs JS, McMillan L et al (2020) Innovative economic levers: a system for underwriting risk of practice change in cane-farming. Reef and Rainforest Research Centre Limited, Cairns

Twomlow S, Rohrbach D, Dimes J et al (2010) Micro-dosing as a pathway to Africa's Green Revolution: evidence from broad-scale on-farm trials. Nutr Cycl Agroecosyst 88:1101–1113. https://doi.org/10.1007/s10705-008-9200-4

van Bavel CHM (1953) A drought criterion and its application in evaluating drought incidence and hazard. Agron J 45:167–172. https://doi.org/10.2134/agronj1953.00021962004500040009x

Vilas MP, Shaw M, Rohde K et al (2022) Ten years of monitoring dissolved inorganic nitrogen in runoff from sugarcane informs development of a modelling algorithm to prioritise organic and inorganic nutrient management. Sci Total Environ 803:150019. https://doi.org/10.1016/j.scitotenv.2021.150019

Whitbread AM, Robertson MJ, Carberry PS, Dimes JP (2010) How farming systems simulation can aid the development of more sustainable smallholder farming systems in Southern Africa. Eur J Agron 32:51–58. https://doi.org/10.1016/j.eja.2009.05.004

Williams JR, Jones CA, Dyke PT (1984) A modeling approach to determining the relationship between erosion and soil productivity. T ASAE 27:0129–0144. https://doi.org/10.13031/2013.32748

Woodruff DR (1992) "WHEATMAN" a decision support system for wheat management in subtropical Australia. Aust J Agric Res 43:1483–1499. https://doi.org/10.1071/ar9921483