From white pegs to silicon chips: Fifty years (1973-2022) of Australian agronomy.

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> *"The prevailing, conventional, 'white-peg' agronomy is a deeply entrenched component of crop research strategy. …… Statistical differentiation of treatment effects in situations where site x season interactions may account for the major share of total variance, is not conducive to understanding nor to development of general functional relationships."*
>
> Henry Nix, 1980

Preamble

Those of you who are old enough can take your minds back to 1973. Gough Whitlam was Australian Prime Minister, Joh Bjelke Petersen was Premier here in Queensland, the Queen opened the Sydney Opera House and AC/DC performed in Sydney for the first time. It was also the year I entered the University of Queensland as a first-year agricultural science student. The most notable agronomic event from 1973 was that Colin M Donald retired as Waite Professor of Agriculture and Head of the Dept of Agronomy at Uni of Adelaide and we will return to Donald's part in this story later.

So a few months short of 50 years later, I stand here honoured to be receiving the CM Donald Medal for Agronomy. There are 18 others who have been honoured in the same way. Many were my agronomy heroes from days past and it is a daunting challenge to present an Oration equal those that have gone before.

This narrative is an unashamedly personal recollection of the state of agronomy in the early 1970's and it seeks to track the evolution of agronomic research approaches until the present day. The focus is largely Australian but at times international influences or comparisons are called upon. The narrative begins with a snapshot of agronomy in the 1970's and moves on to look at the key developments that have transformed agronomy to what we know today. No claim is made that this is a comprehensive treatment of all the people and teams that have shaped that journey – but it is instead my perspective of key contributions. I need to warn you that modelling is going to feature strongly in this talk, particularly the contributions from Australia. However, I will look to sprinkle the story with some favourite examples of my own personal research outputs. These will be provided in boxes so as not to overly disrupt the flow. While digging back through personal reflections of history runs the risk of accusations of self-indulgence, the motivation here is to draw out some lessons for today's agronomists and I will finish on that note.

Like other Donald Orations before, I have chosen to be as selective as possible in my citations to assist in the flow of the narrative – focusing on recognition of key papers that will allow interested readers to dig more deeply into the extensive literature.

The state of play for agronomy in the 1970's

My contention is that agronomy was not seen as the cutting edge of agricultural science in the 1970's. A number of terms were often used 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 origins of the term "white peg agronomy" are obscure but the earliest published use of the term I could find comes from Nix (1980). This term related to an agronomic method based on empirical observations of plots bounded by white pegs.

At the University of Queensland where I was enrolled, there were no Professors of Agronomy in 1973. Percy Skerman was there as someone who "knew" agriculture at home and abroad and his lectures were wonderful travelogues of crops, livestock and fences around the world. We had professors of plant nutrition, plant breeding, soil science, crop physiology, pasture science and animal nutrition but agronomy was a lower order calling. Other Universities were a little better positioned. CM Donald was of course the Waite Professor of Agriculture and Head of Agronomy at University of Adelaide from 1954-1973. UNE claim Australia's first specific title of Professor of Agronomy (Alex Lazenby) from 1965-70. Jim McWilliam took over this role in 1971. Mike Norman came out of the CSIRO Land Use Research Division working at Katherine in the 1950s. He ended up as a Professor of Agronomy at Sydney University at some point in the 1970s. Wally Stern (a student of CM Donald) was appointed foundation Professor of Agronomy at University of Western Australia in 1969. Like Mike Norman, he had an experience with CSIRO Land Use Research at Katherine in his formative background.

Unlike USA, whose American Society of Agronomy (ASA) dates back to 1907, Australia had no Agronomy Society, deferring to focus on more specialised professional societies such as the Australian Association of Animal Sciences (1954), Australian Society of Soil Science (1955), Australian Society Plant Physiology (1958), Tropical Grassland Society (1962). It was not until 1980 that we saw the emergence of an Australian Society of Agronomy and our first Australian Agronomy Conference was at Gatton which I attended as a post-grad student. It was also not till 1980 that an undergraduate text emerged on agronomy for Australia (Pratley, ed. 1980).

Agronomy's core method in the 1970's 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 method 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 ten years before French and Schulz (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. Long-term trials that were initiated or continuing through the 70's were valuable – at least in terms of revealing seasonal variability and some long-term changes in soil properties and/or environmental consequences (deep drainage, erosion, acidification, SOM change etc). These were expensive to establish and maintain and started to disappear as a routine agronomic method in the 80's.

In 3rd Year Agricultural Science at Uni of Qld (year was 1975), the biometrics group offered a subject called "Systems Analysis and Modelling" which sounded interesting so I enrolled. Our practical project was to write a Fortran program to optimise the operation of an elevator moving crowds of people up and down a multi-story building! I think I graduated with a four-year agricultural science degree without ever hearing about crop and soil simulation modelling. I heard nothing about CT deWit even though he led the way in crop modelling a decade earlier – I did however hear something about CM Donald's "ideotype" (Donald 1968) and about Henry Nix's agro-climatic indices for Australian cropping (Nix 1975). I will return to both gentlemen later.

My recollection now is that agronomy was not a prestige career choice when I was graduating in 1976. I was initially drawn into agricultural science by plant breeding (like many) because I was fascinated by genetic diversity and how breeders could shape that for practical purposes. But I was also interested in how plants responded to environment and how managers could influence this by the choice of variety, planting time and density, fertiliser and irrigation and so on. I was fascinated to see how environment and management could change a plant just as much or even more so than genetics. Somewhat by chance I ended up going down an agronomic pathway and only later started to realise the extent to which the analytical toolkit was limiting.

None of this means that Australia did not have a proud history of agronomic discovery and innovation. Much of the early work was based on close observation and astute deduction to resolve single-factor limitations to plant or animal production. Some of that was world leading, such as the work on plant nutrition given Australia's old nutrient-deprived soils. CM Donald himself was an early contributor to this body of work with his work at CSIRO on Cu, Zn and Mo deficiency in pastures. Nor does it suggest CM Donald was not starting to chart a path forward towards an agronomy based on deeper thought of systems performances. It was Donald in 1965 who first created what is now an iconic plot of Australian wheat yields over time (Figure 1) and his own contributions to the "super and sub-clover" driven lift in yields can be seen in this graph. This plot encouraged agronomists to look beyond their experimental "white pegs" to the bigger forces at work shaping the evolution of Australian cereal yields.

Historical Records of Australian Science, Volume 10, Number 1

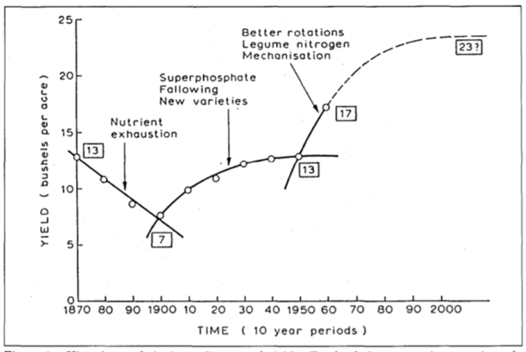


Figure 1. Historic trends in Australian cereal yields. (Ten bushels per acre is approximately equivalent to 700 kilograms per hectare.)

Figure 1. Australian wheat yields. 1870-1965. after Donald (1965). (1 bu/acre = 67.2 kg/ha)

Donald's most significant step towards charting a new course for agronomy (and his growing interest in breeding) came via his considerations of a "crop ideotype", a concept that came to define the later part of his career (Donald 1968). Donald's mid-career work was on single and multi-species competition in pastures (Donald 1963) and he built on the insights from that time to build a "model" of the plant architecture that might maximise yields in relation to environmental limitations (water, nutrients, light). So this is definitely a step towards a more wholistic "model" of the crop system. As far as I can determine from the literature, Donald never tried to translate this qualitative model into mathematical terms. It is interesting to contrast Donald's journey in the 1960s with that of the famous Dutchman of the same era, C T deWit who also became well known for his studies on plant competition (de Wit 1960). De Wit was clearly more mathematically inclined and his studies always included some quantitative analysis. By 1968, de Wit was writing code and building one of the world's first crop simulation models (Brouwer and de Wit 1968).

During the 1970's in Australia we see it was Henry Nix (not CM Donald) who started to chart a way forward using simulation models for what he called a "systems research strategy" (Nix, 1980).

The key developments and contributions along the way; 1960's-2022

On reflection, my frustrations (as I now see them) with agronomy in the early 1970s was the lack of analytical capacity to interpret experiments and lack of predictive capacity to extend the insights to other seasons, soils, climates or systems. This does not mean that advances were not made with the tools and approaches available in the 70's, 80's and 90s. Donald's (1965) plot has been regularly updated, most recently by Pratney and Kirkegaard (2020) (Figure 2). Australian average wheat yields in 2020 are almost twice those from the time of Donald in 1965.

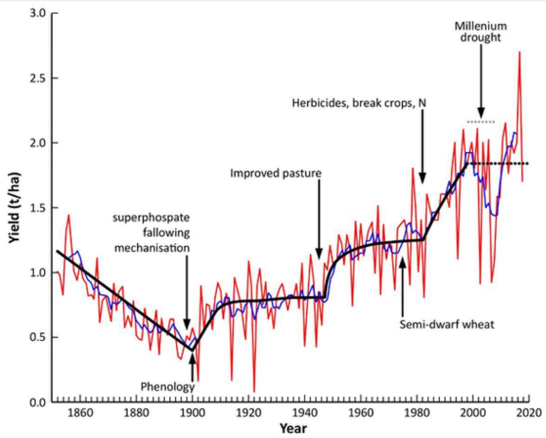


Figure 1. Growth in Australian wheat yields and technologies driving changes (updated from previous versions by Donald 1965, Angus 2001, Kirkegaard and Hunt 2010). Annual yield (red), 5-year running mean (blue), decadal trend (black)

Figure 2. From Pratley and Kirkegaard (2020) Australian Agronomy Conference Wagga

These gains reflect a multitude of efforts from farmers, advisors, agronomists and plant breeders.

There have been many insightful reviews of the drivers of these yield advances, including several earlier Donald Orations. Richards et al (2014) summarise the key agronomic changes in terms of

(i) to improve plant nutrition with the use of chemical fertilisers or legumes;
(ii) to improve the timing of cereal operations (especially sowing time) through mechanisation, herbicides, reduced tillage and stubble retention; and
(iii) the use of break crops to reduce soil pathogens and crop weeds and improve nutrition.

One can do no better than go back through the transcripts of past Donald Orations to get a sense for the advances in Australian agronomy since the 1980s. Tony Fischer's Donald Oration in 2004 explored wheat yield improvement from a global perspective although it contains a fascinating analysis of 40 years of yield and water use efficiency improvement in relation to crop rotations and management on Tony's own farm at Boree Creek. Peter Cornish's Donald Oration covers diverse topics including phosphorus nutrition, the min-till and direct drill revolution of the 70's and 80s, benchmarking water use efficiency and non-rainfall limits to yield and the emergence of farming systems research, all of this with Peter's finely honed observation and analytical skills. The Donald Oration from Tim Reeves in 2017 explores the reduced tillage transformation while John Angus's Donald Oration in 2019 is essential reading for those wanting to understand the advances in break crops and soil-borne pathogens that hitherto major barriers to yield advance.

Many others have been and will continue to be in future, better placed than I to tell these stories of the productive synergy between farmer innovators and astute practical agronomists. What I can do is tell the story of how the agronomic toolkit has been transformed over the last 50 years.

So how did this transformation of our agronomic toolkit happen? The forces at work and the key contributions go beyond any one model, research unit or country. Having said that, I know the APSIM (Agricultural Production Systems Simulator), APSRU and Australian story most intimately and hence I will focus on that. This story has a bias towards abiotic (soil water and nitrogen, climate) constraints to productivity. That does not mean biotic constraints are unimportant – just the analytics required to diagnose and treat biotic constraints have not been as dependent on a simulation approach as is the case for abiotic factors.

1950's and 60's - The science foundations (at home and abroad)

Classical growth analysis in the first half of the 1900s sought to describe plant growth in terms of an assimilation term and a leaf area term (e.g., RGR – NAR x LAR). This approach had some utility for spaced plants but was of limited value for analysis of the function of crop canopies. Watson (1947) introduced the concept of Leaf Area Index and Monsi and Saeki (1953) used Beer's Law to account for the attenuation of light with depth down a plant canopy. These were important advances and by the 1960's, quantitative treatment of light capture and photosynthesis in crop canopies was emerging from CT deWit in the Netherlands, JL Monteith (1965) in England and WG Duncan in Kentucky USA. By 1965, de Wit was publishing Fortran code to calculate light distribution and daily totals of photosynthesis to run on an "IBM 1620 computer". By 1967, WG (Bill) Duncan and colleagues (including Bob Loomis) had built a dynamic simulation model of components of a maize crop canopy photosynthesis (Duncan et al 1967). A short time later, Brouwer and de Wit (1968) released the ELCROS model of vegetative growth in maize. These early models generally had mechanistic approaches to simulation of canopy illumination over small time steps and calculated leaf level photosynthesis and respiration.

Early models of soil water balance also had a Dutch connection. C. H. M. van Bavel was a contemporary of CT de Wit and shared the same doctorial supervisor (van Wijk, a chemical engineer from the oil industry). van Baval (1953) developed a mathematical model of the soil water balance as part of a program calculating the supplementary irrigation needs of tobacco production in eastern USA.

Australian scientists were taking a lead in soil water balance modelling. Early reports from CSIRO's Land Assessment Unit were using simple water balance models. (Fitzpatrick and Arnold 1964). Computer based models began to feature in this reporting following Keig and McAlpine (1969)'s publication of the FORTRAN based "WATBAL" in 1969, which ran on the CSIRO Cyber76. However, in the introduction to this report the authors explain the history. "*The water balance model on which the system is based was originally formulated by Slatyer (1960)" … "In 1962, a program was written for an IBM1620 system and later modified to run on CDC 3600 system*". Fitzpatrick (1969) elaborated the model to express results in terms of "drought" and "growth period" periodicities and probabilities. This model's utility was demonstrated by McAlpine (1970) in the assessment of pasture growth and drought incidence. These efforts in the late 60's in Australia were some of the earliest practical applications of computer-based plant-soil models.

1970's and 80's – Crop and soil models emerge and a vision for utility is first expounded

Interest in model development and application was growing rapidly in the 70's. WG Duncan again 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" …. WG Duncan (1975).*

Much of the early crop model development activity in the 1970s can be traced back to central Texas (an agro-environment not dissimilar to southern Queensland). Joe Ritchie was an 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. FL Millthorpe and J Moorby were both at Macquarie University in Sydney and were working towards a simulation model for potato (Moorby and Milthorpe 1976). A team at UNE, under the overall direction of Jim McWilliam (former CM Donald Medal winner in 1993) set out to test some of Henry Nix's ideas on new crop evaluation with models. Extensive experimental studies were used to develop a sunflower growth simulation model (Smith et al., 1978) based on weekly weather data and used to identify areas suited to sunflower cultivation (Lovett et al., 1979). Sunflowers were also a focus of early modelling efforts in Queensland (Hammer et al., 1982) alongside similar work with an early wheat model (Hammer and McKeon (1984). At the same time further south, the SIMTAG wheat model was under development (Stapper 1984).

Cotton modelling in Australia has following a less conventional pathway. Brian Hearn was the Donald Medalist in 1996 and he explains some of that history. Upon arriving in Australia in 1970 he entered the "*agronomic culture in the CSIRO Division of Land Research that was buzzing with crop simulation, led by people like Henry Nix and Calvin Rose*". Brian was convinced he needed a model to address the pest and irrigation issues he faced in cotton. He concluded the cotton models emerging in the US at the time were too complex for practical application. He instead, developed a simple (yet elegant) model of cotton flowering and fruiting based on source-sink principles which became the core of a networked DSS system called SIRATAC. By the early 90's, this fruit model had been incorporated into a more comprehensive crop-soil model (OzCot) by inclusion of soil water, soil nitrogen and canopy development and assimilation approaches form other modelling teams.

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". The US Government funded this work initially as they wanted a means of estimating Russian wheat yields during the Cold War (Jones et al 2017). CERES-Maize and CERES-Wheat (Jones et al 1986; Godwin et al 1983) emerged from these efforts in the early to mid 80's. 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). Prof Henry Nix was active in IBSNAT and in the late 70's he proposed (Nix 1985) a "systems research strategy" (Figure 3) that placed "crop system models" and resource databanks as key tools in framing research activity and interpretation.

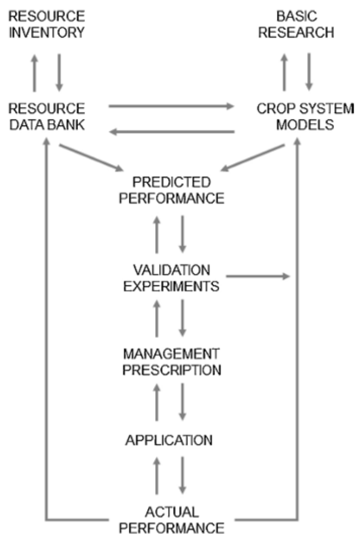


Fig. 3. Components of a systems research strategy as devised by Nix (1983, 1985).

Figure 3. Components of a systems research strategy as devised by Nix (1985).

Box 1: A PhD program on cassava agronomy 1977-1981

Cassava was being considered as a new energy crop in Australia following the oil crisis of the early 70's. We knew little about its potential adaptation and productivity and even less about appropriate agronomic management. I dived into what became a PhD program with my first planting of cassava at the University of Queensland Redland Bay farm in December 1976. John Evenson was my primary supervisor – John was a grass-roots agronomist who had a diverse background in tropical outposts of the British Empire such as Namulonge in Uganda and the Ord River in Australia. Prof. Graham L Wilson (a CM Donald Medalist from 1992) was added to my supervisory team to give it some extra "academic horsepower". Graham did more than that – he was a rigorous reviewer and editor of my draft thesis notes (I have never forgotten his contempt for my tendency to use adjectival nouns) and he gave me a solid grounding in crop physiological principles. One thing neither Graham nor John gave me was any nudges towards simulation modelling. Upon reading the 1992 Donald Oration in preparing this talk – I finally understand why when I read Graham's brutally honest statement "*I am profoundly ignorant on the subject of simulation modelling which has come to occupy a dominant position in crop physiology".*

This was unfortunate because I doubt there was ever an experimental study more primed for a simulation analysis than was the case for my PhD Thesis. A typical set of data on cassava growth and development is shown below – where planting date was used to generate a full suite of crop stages experiencing the full suite of environments (temperature, radiation and photoperiod) in this sub-tropical location.

Reading further into GL Wilson's 1992 Donald Oration, I now see he became an avid supporter of simulation models as powerful tool in taking crop physiology through to agronomic applications. He goes on to write [with reference to Hammer and Muchow's modelling studies of the riskiness of sorghum production in nth Australia] *"It is difficult to see how important questions such as those implicit in these examples could have been answered in any other way".* It seems I was just 5-10 years too early!

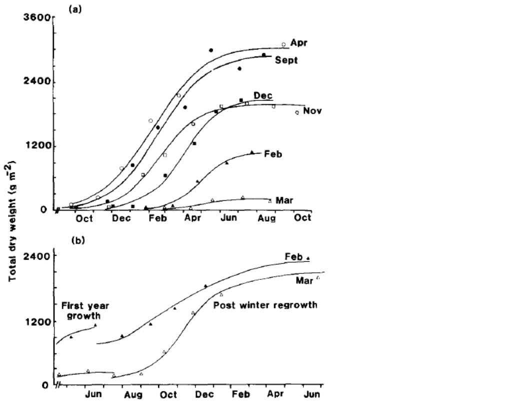


Fig. 1. Experimental points and fitted logistic curves describing changes with time in toal dry matter for cassava cultivat M Aus 10 planted at different times of a year at Redland Bay, S.E. Queensland. (a) First season's growth. (b) Second season's growth.

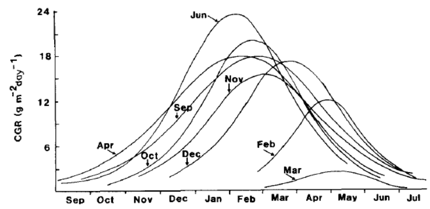


Fig. 3. Changes with time in CGR for cassava cultivar M Aus 10 planted at different times of a year at Redland Bay, S.E. Queensland. Curves were derived from the logistic equations fitted to the changes in total standing dry matter as shown in Fig. 1.

In 1981, (the year I joined CSIRO), the potential for widespread use of crop-soil models was seen by many but it would be another decade or two before widespread availability and use of crop-soil models was the norm in agricultural research. It became accepted best practice to monitor radiation interception during crop development enabling growth data to be interpreted in terms of radiation interception and radiation use efficiency (RUE). This form of "growth analysis" was strongly promoted by agronomists/physiologists such as David Charles-Edwards, Russ Muchow, Tom Sinclair of USDA Florida who were active as staff or collaborators with CSIRO Tropical Crops and Pastures in the early 1980s.

1980s – Simulation modelling meets Farming Systems Research

Farming Systems Research (FSR) emerged in the late 70's and early 80's with strong Australian links (e.g. Dillion 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 8" 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".*

McCown adapted the Collinson's FSR methodology to include crop-soil modelling (Figure 4) and this approach (broadly aligned to 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.

Figure 4. The systems research framework that builds crop-soil modelling into a Farming Sytems 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".

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 is food security interventions (see Box 2).

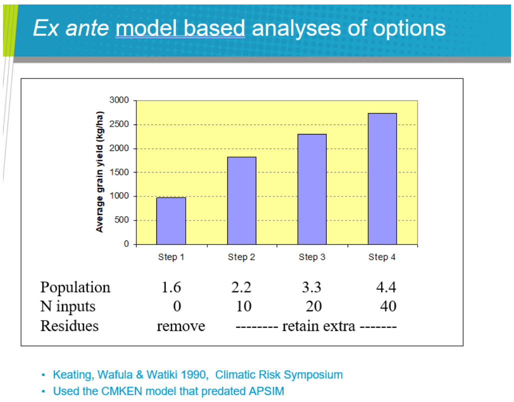
An international symposium in Brisbane Australia in 1990 showcased these emerging applications of crop-soil models, stimulated in large part by the modelling work in Kenya and companion programs in northern Australia (Carberry and Abrecht 1991). Titled "Climatic Risk in Crop Production – Models and Management 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.

Box 2. Five years in semi-arid Kenya – the real foundation to my career

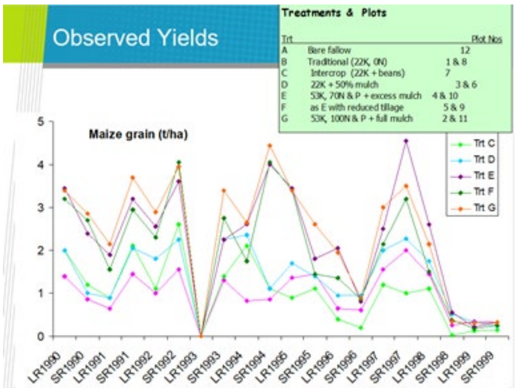
PhD programs are meant to create the foundations for a research career and my cassava experience taught me many important things, but it paled into insignificance compared to my "PhD in practice", as a young agronomist embedded in the Kenya Agricultural Research Institute (KARI). I was located at the National Dryland Farming Research Station, Katumani in semi-arid eastern Kenya. The brief was to come to grips with the factors constraining productivity in these maize-based farming systems and identify pathways forward to sustainably lift productivity and improve livelihoods of farm households. Bob McCown (based back in Townsville) and Roger Jones (based in Nairobi) were my mentors but I had to "sink or swim" in a rural village context and build the collaborations with a big team of Kenyan researchers. It was the biggest challenge of my career and also the most transformational experience.

It was immediately obvious that the constraints were both bio-physical (soils, climate, management practices), socio-economic and institutional. The region was one of the most climatically risky place on earth for maize cultivation with two separate seasons per year averaging 250-350 mm seasonal rainfall across the District and seasonal rainfall less than 250 mm in at least 40% of seasons. The elevation (1000 to 2000 m) was the only reason cropping was remotely possible. It was Bob McCown who "nudged me" into the modelling and it was an inspired decision on Bob's part to make some progress in five years in the face of such climate variability. Those years in Kenya could fill a Donald Oration on their own but let me summarise by saying I and the team of Kenyan colleagues were able to produce some truly unique data sets (yes from white "stick" trials – pegs could not be afforded), we adapted a good model (CERES Maize) and made it a high performing model for small-holder African circumstances, and we used that model to chart a pathway forward for sustainable intensification of farming systems before that term came into vogue. The insights developed around judicious inputs of nutrients as a first step in lifting productivity have stood the test of time and influenced farming systems research more broadly in sub-Saharan Africa. I will include three favourite graphs which linked together tell this story.

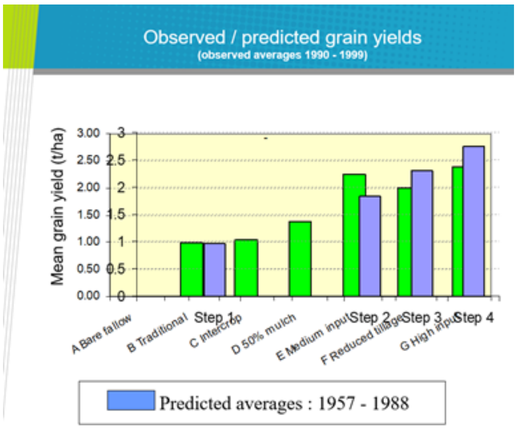
The first comes from Keating et al (1991) presented at the landmark Climate Risk Symposium in Brisbane (see further reference below). It shows our hypothesis developed with the CM-Ken model after five years of on-farm, on-station trials and model-based investigations. This analysis suggested an intensification pathway involving increasing (but still relatively low) N fertiliser inputs, adjustments in plant population in response to this additional nutrient supply and retention of any additional plant residues over and above that in the current practice scenario (Step 1). Long term average yields are predicted to rise from just under 1 tonne/ha (typically observed) to just over 2.5 tonnes/ha. There are important risk dimensions to each of these steps that the model allowed us to explore further.



My Kenyan colleagues, under the leadership of George E Okwach in partnership with John Williams of CSIRO Soils set up a large field trial to test this hypothetical intensification pathway. The trial was fully instrumented for runoff and soil loss and is a truly unique dataset that has never been fully exploited.



The field trial ran for 10 years and hence 20 seasons in this bimodal rainfall region. The trial started just after I left Kenya and the data above was shared with me over 10 years later on a visit. The last of the 3 graphs in this Box shows the observed long-term average yields overlayed with the most closely matched step from the initial 1990 model generated hypothesis (over the 1957-1988 climate record). Now that was a very satisfying moment!



Beyond Kenya, these participative action research (PAR) approaches involving on-farm research aided by crop-soil simulation modelling gained wider application in India (Dimes and Revanuru 2004), southern Africa (Whitbread et al 2010) during the 1990s and 2000s. 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).

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 modelling and DSS development, i.e., John Leslie of QDPI (Queensland State Govt) 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 was certainly plenty of fireworks as APSRU went through a decade or more of "forming, storming and ultimately performing" (not sure APSRU ever "normed").

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. I had produced adaptations we referred to as CM-Ken based on experience with low-input farming systems in Kenya. Peter Carberry published CM-SAT based on his work in the Northern Territory. One key innovation of that program was the development of a capability to simulate intercropping. These "systems capabilities" had been super-imposed on the CERES-Maize model structure but by 1990 it had become increasingly obvious to all involved that the "spaghetti FORTRAN" code was 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.

Instead of trying to link up different crop-soil models such as was done in the early DSSAT, 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 et al 1982) 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.

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 mode 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 initial blueprint was AUSIM, a modular agricultural systems simulator with the soil modules as central for crop and pasture modules that could "come and go" (Figure 5).

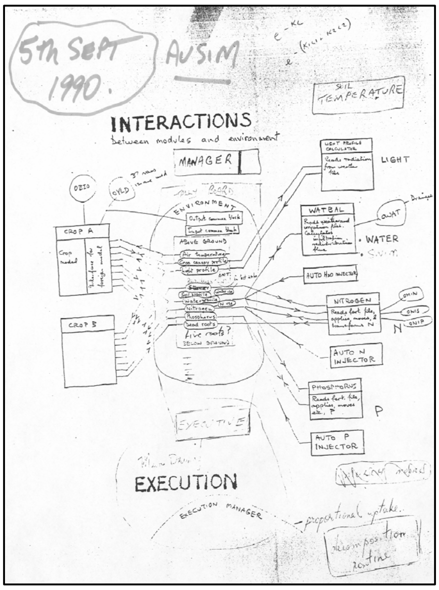


Figure 5. The oldest surviving record of APSIM's origin. This was an image from a whiteboard used at a meeting at CSIRO Davies Laboratory Townsville on 5th September 1990. Present were; Bob McCown, Brian Keating, Peter Carberry, John Hargreaves, Brian Wall, Peter Ross, John Dimes and Doug Albrecht.

The original structure of the APSIM model as published in 1996 is reproduced in Figure 6. The influence of the hand drawn diagram that first conceptualised AUSIM (Figure 5) is clear.

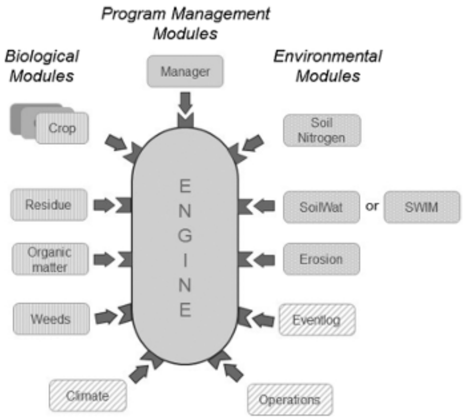


Figure 6. Structure of APSIM as published by McCown et al 1996.

Key (and still largely unique) features of APSIM include abilities in simulation of intercrops, weeds, biotic constraints, crop-livestock interactions, manure and phosphorous in low input farming systems, multi-paddock 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"*.

While I was personally involved with many others in a range of the early APSIM modules, most notably SoilWat, SoilN, Maize, Wheat and Sugar, I am most satisfied by my role in shaping the early vision for the Manager capability in APSIM. I wrote the design specification for that with considerable ambition whilst at the time having no idea how it would be achieved from a software implementation point of view. Put simply, I 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. I figured there was no way we could predict at that time what future users might want to explore in their simulations so we had to avoid any strait-jackets in how we specified the management parameters. The new specification for the Manager basically boiled down to a capability to <u>initiate any action</u> at <u>any time</u> based on the <u>status of any variable</u> in the simulation. Over time, the software team came up with a powerful means of achieving that specification via a Manager Module that could be driven by a script language and this has continued to evolve over the last 30 years.

<u>Software engineering</u> – From the outset in 1990, there was a strong 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 the strongest initial advocates of attention to good software design and testing. In 1995, an independent review of APSIM software practice was commissioned of Ray Offen, Macquarie University. The finding was essentially that while 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 was never one to hold back and his notes 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 1996/97 for a "Multi-Divisional 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.

Box 3. New challenges upon my return to Australia

The institutional developments with APSRU and APSIM described above did occupy a lot of my attention during the 90's and early 00's but there were plenty of other science projects to progress at the same time. I had growing leadership responsibilities for initially small, but fairly quickly large, teams engaged in Nitrogen, Sugarcane and Dryland Farming research. International links continued as our form of model-augmented farming systems research got better recognised and expanded around Africa and beyond (often with ACIAR support). There was still plenty of model development and testing going on (wheat, sugarcane, water, nitrogen) and colleagues helped in keeping that going as my leadership responsibilities grew. In particular, working closely with Merv Probert, Mike Robertson, Neil Huth, Don Gaydon and later Peter Thorburn made that a very productive decade. I have chosen a couple of "favourite" graphs to illustrate some key advances.

The first related to nitrogen fertiliser management in sugarcane (Keating et al 1997). We traversed the full gamut of issues, from basic data collection on growth and nutrition, to model development to on-farm fertiliser management strategy and onto to looking at the fate of nitrogen in groundwaters. It is pleasing to be told now this body of work is still in use today for GBR Reef Water Quality protection purposes, albeit with some new enhancements.

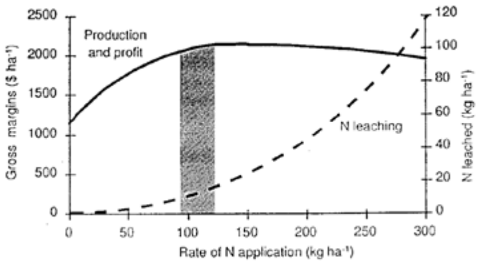


Fig. 13.8. Average gross margins and N leaching simulated in a plant and 4 ratoon cycle at Ingham, Qld over 100y of climate data. [Hatched area indicates a range of N rates that achieve both optimal economic returns and acceptable N leaching losses]

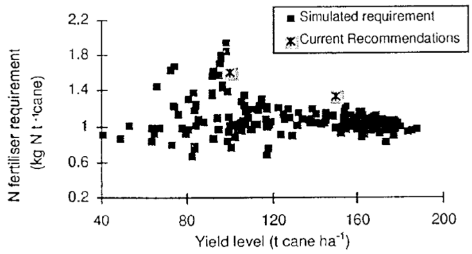
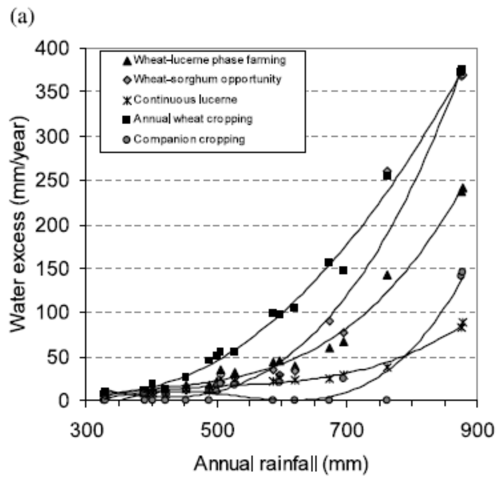


Fig. 13.9. 'Rule of thumb' measure of N fertiliser required to produce one tonne of cane. [Estimated from simulated N_{opt} and cane yield over 100 years at Ingham, Qld. Points denoted as current recommendations relate to industry recommendations (Calcino, 1994) for 100 and 150t ha^{-1} crops]

The second relates to the issue of "water excess" in dryland farming systems (Keating et al 2003a), as this is a driver for land degradation through dryland salinisation. The graphs I have chosen here synthesise a body of work on how farming systems design influences "water excess" (graph on left). What was satisfying about this analysis based on thousands of simulations across the Murray Darling Basin (MDB) was in finding that these paddock-scale models were generating water excess assessments broadly in tune with empirical catchment-scale river monitoring (Zhang curves from graph on right).



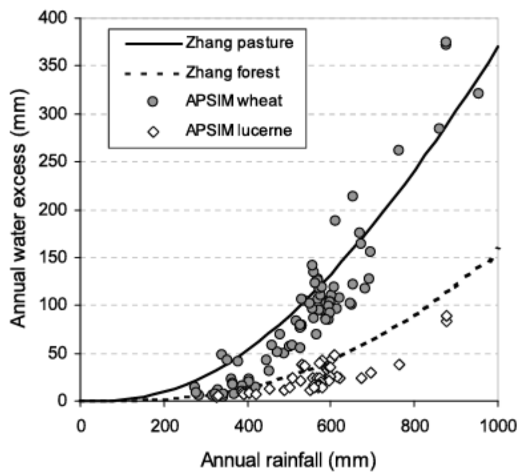


Fig. 9. APSIM estimates of average water excess for annual wheat and continuous lucerne systems in the MDB (symbols) compared with water excess for pasture and forest catchments calculated from the function of Zhang et al. (2001) (Eq. (6), with $E_o = 1100$ and $w = 0.5$ for pasture; $E_o = 1410$ and $w = 2.0$ for forest).

2000's - Model capability, availability and use grows nationally and internationally

By 2000, ten 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 ACIAR support, extending from eastern Africa to southern Africa and over to south Asia. Partnerships with CGIAR Centres (in particular ICRISAT and CIMMYT) were established. At home however, we had a situation that the nation's most powerful "systems agronomy" capability was contained into a region that produced less than 10% of the nation's cereal crops. Institutional support for QDPI staff to engage nationally was muted and the CSIRO staff were constrained to some degree by Divisional boundaries coming as they did from "Tropical Crops and

Pastures" and post 1998 "Tropical Agriculture". I was a senior leader by this time and I feared for the longer term sustainability of this capability without a broadening of its footprint nationally. We hence set out on a multi-faceted "partnerships" strategy to both underpin the capability of what was emerging in Qld and broaden its impact. Interestingly, this proved most difficult within CSIRO where there was an allergic reaction in some parts of the organisation to the idea that science leadership did not reside in Canberra. But 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 commitment of CSIRO Soils researchers to the vision of a "soil-centric" farming systems simulator remained strong. John Williams shared this initial AUSIM vision with Bob MCown in 1989 and many Soils (and later Land and Water) staff made major contributions including Merv Probert, Kirsten Verburg, Val Snow, Warren Bond, Chris Smith, Keith Bristow. Access to major national research consortia such as NLWRA, LWRRDC programs and CSIRO's Catchment Care MDP helped the Toowoomba based team with entry to the national stage.
- In the year 2000, when CSIRO's ill-fated Tropical Agriculture Division was in melt-down, there was recognition in CSIRO that the "systems research" teams were a national asset and they could be lost if split up and potentially "asset stripped" in traditional Divisions (both Plant Industry and Land & Water Divisions were making strong bids). The left-field solution was to combine these teams with the ecologists and systems researchers from CSIRO Wildlife and Ecology to create a new Division called "Sustainable Ecosystems". This put agriculturalists and ecologists, together with economists and sociologists into a unique mission-focused Division in CSIRO. It was effectively a "proto-Flagship", some few years before Flagships became a major force in CSIRO's transformation. An unexpected benefit of this change was it gave our farming systems research team a national platform and staff were relocated or recruited to places like Perth, Adelaide, Canberra and Hobart and able to engage locally, often in partnership with State Dept researchers, Universities and/or farming systems groups.
- The partnership with 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 Victoria. The origins of that partnership go back to the 10th Australian Agronomy Conference in Hobart in 2000. Peter Carberry gave a talk that questioned the rigour of some on-farm research conducted by farmer groups. BCG's response was to invite Peter to visit which he did and the initial competition quickly turned to cooperation which continues to this day. BCG's national leadership was such that benefits spilled over to collaboration with other farming systems groups nationally.
- In 2006/07, CSIRO established the Sustainable Agriculture Flagship which brought together most of its agriculture facing research under one governance structure. This was 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. This approach served a purpose initially in delivering a disciplined software development process but after 15 years, it was

clear that it was no longer fit for purpose. In 2006/07, 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 underlying philosophy was essentially that of a "creative commons". The source code was transferred to an "open source" domain and a strong oversight of software version control and performance testing was maintained. This change in approach has facilitated a significant increase in APSIM collaboration and use around the world.

2010's - 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 APSIMs 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.

Reflections on APSIM Use and Impact

The APSIM Model has been a big part of my story. Hopefully some of what I have covered today signals it is not the entire story. Nevertheless, it probably will be what my career is most associated with. So it is appropriate to ask the question about what impact it had? In this section I gather the data on APSIM usage and try to assess what difference it has made.

APSIM Use – globally

For the 2020/21 year there were **4863 non-commercial licenced users** registered (up from 4002 in 2019/20). This resulted in some **5861 downloads** of APSIM (all versions as some users download older versions or use multiple versions). In 2019/20, 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 2003b). If all three APSIM source papers were considered in aggregate (Figure 7), they would be Australia's most cited agronomy paper of all time.

Globally there have been ¾ million agronomy or agriculture multi-disciplinary papers listed in the Web of Science (WoS) database and the Keating et al (2003b) APSIM paper is ranked number 31 and still climbing (ranked number 7 if we consider the three APSIM reference papers in aggregate). So clearly these statistics suggest something has been happening in agronomic model building and application in Australia of global significance.

Box 4. Beyond 2000 - Science outputs when becoming partially useless as a Manager

By the time the 2000s had rolled past, I had significant leadership (or was it just management?) responsibilities, initially for a CSIRO Program (50 people), later a CSIRO Division (200 people), and ultimately a CSIRO Flagship (300 people). I was still active in publishing, but the focus shifted more to invited review articles or other attempts to gain broader perspectives on frontiers of agricultural systems research. My favourite graph from that time comes from a joint publication with Peter Carberry – in fact Peter really led this thinking but it had its roots back to our time in Kenya looking into ways to graphically represent risks and returns of interventions in farm practice and technology. We worked in up initially for a review CIAT asked us to do on the concept of “eco-efficiency” (Keating et al 2013) and it was further developed in the figures below which was produced for the UK’s “Foresight Program on Global Food and Farming”. (Carberry et al 2011). The origins however go way back to Jim Ryan from ACIAR and earlier ICRISAT who first introduced us to the economist’s use of the concept of E-V space (E=Expected Mean and V = Variance) when we produced the first assessments of riskiness of N fertiliser use in Kenya in the late 1980s.

The figures below show these axes as Outputs (could be yield or profit) and Risk (oftentimes Risk and Inputs are closely correlated). The curves are really “efficiency frontiers” (highest return for lowest risk) and a particular situation can be mapped as being on or below the frontier. Interventions can take us up to the frontier, move us along the frontier or potentially transform the system and generate an entirely new frontier. This framework proved particularly helpful when as research leaders and investors, we were faced with thinking about choices for our research focus. GRDC have found it useful as well as they look at their research investments portfolio.

Innovation and productivity in dryland agriculture 81

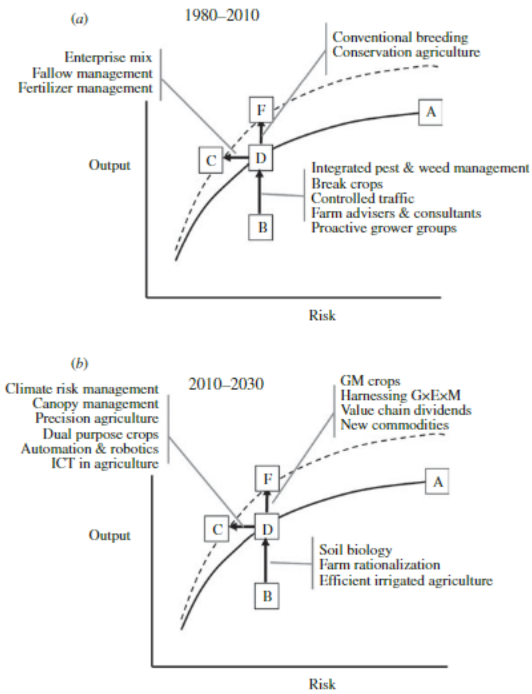


Fig. 2. Return-risk framework and technologies which either (*a*) affected Australian dryland agriculture from 1980 to 2010 or (*b*) are identified as having potential to affect it between 2010 and 2030. In both figures, A and D are representative points on the efficiency frontier for the best technologies at a point in time (—) and C and F are specific points on new efficiency frontiers for hypothesized new technologies (- -). Point B represents a position below the current efficiency frontier (Keating *et al.* 2010). Note: GM = genetically modified; G × E × M = genotype by environment by management interactions; ICT = information and communications technologies.

From: Carberry et al 2011

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 (Figure 8).

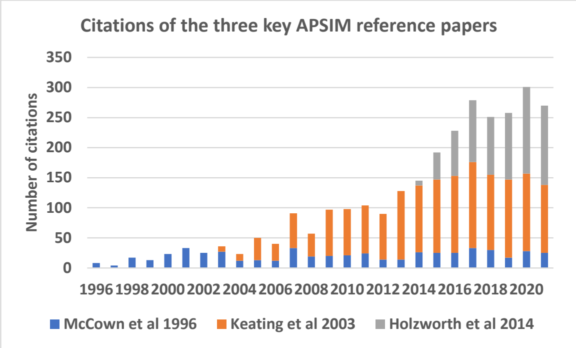


Figure 7. Citations per year since 1996 for the three standard APSIM reference papers as captured in the WoS database.

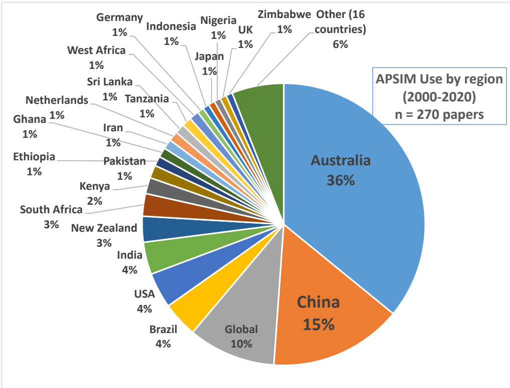


Figure 8. Country of use distribution based on WoS papers that identify APSIM as a Topic (based on 2000, 2005, 2010, 2015 and 2020 publication dates).

Figure 9 shows 22 different domains of application identified in the five "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. Beyond those topics, almost every conceivable topic has been subject to some APSIM related investigation at some point.

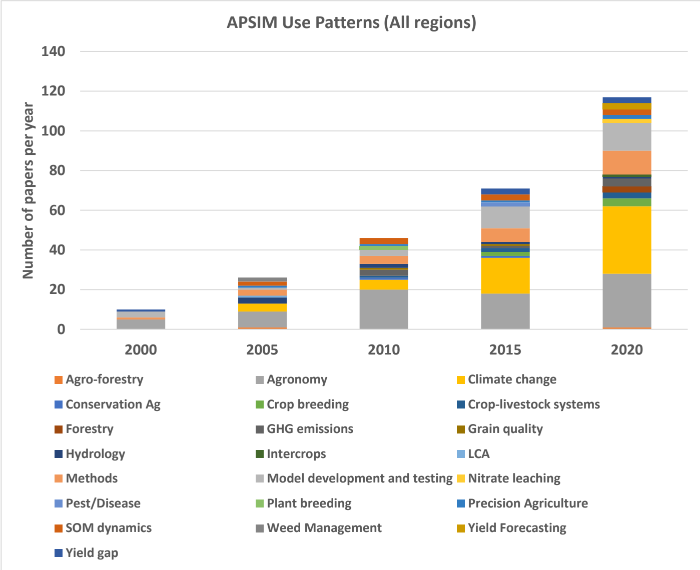


Figure 9. Estimates of the purpose of APSIM Use based on papers with APSIM as a Topic in the WoS database in 2000, 2005, 2010, 2015 and 2020.

The two most widely used farm systems simulators globally are APSIM and DSSAT (Jones et al 2003). Both were put before the global community in the European Society of Agronomy meeting in Florence, Italy in 2003. Both have some common ancestry dating back to the early 1990s in the CERES maize and wheat models but the big difference was that APSIM completely re-engineered the farming systems simulation platform with full modularity, language independence, multi-paddock and multi-point capabilities and a powerful MANAGER script language. While these tools have evolved separately now for 30 years, these platform differences in my view account for the record of APSIM use continuing to outstrip DSSAT use (Figure 10).

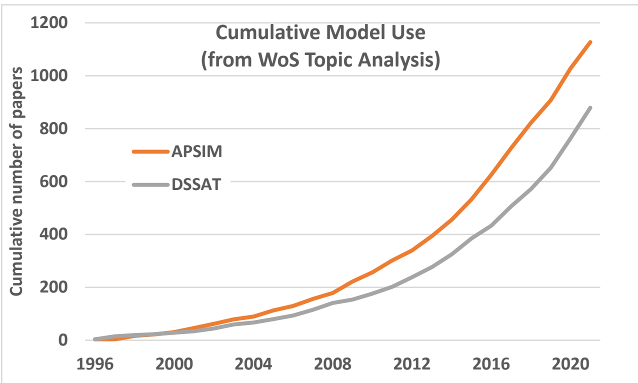


Figure 10. Cumulative number of papers since 1996 from the WoS database (all years) that identify the model as a topic.

APSIM Impact - has APSIM changed Australian agronomy?

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

Model use by research agronomists

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 simulation model use 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 2000's made use of simulation models. This compares with around 3% in the early 90's when the APSIM effort began.

At the last ASA, Hochman and Lilley (2020) 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;

- 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 Lilly (2020), impressive as it is, misses much of what was achieved before 2008. Keating et al (2003b) provide a report of APSIM application over the 1996 to 2001 period which identified some additional foci for APSIM application including;

- 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 looking 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.

I argue the case is well and truly made that simulation modelling has empowered Australian research agronomists via;

- 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.
- Exploring the potential value of crop traits *in silico* as an input to crop improvement programs (a direct extension of Donald's ideotype)

APSIM use in government and industry policy making

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 not been pretty (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 Paddock to Reef Integrated Monitoring, Modelling and Reporting Program aimed at improving GBR Reef Water Quality. The nitrogen balance capability of APSIM-Sugarcane 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 batters over crop insurance claims and there remains potential for APSIM use in the insurance domain (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. More customised tools have been developed which use APSIM as one element of the tool. GRAINCAST is a good example (Lawes et al 2021). 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 in the crop-soil simulation engine in the Graincast system. Potential applications are varied but the tool is well suited to regional or national planning for grain harvest, transport, storage and marketing activities.

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 form 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 GRDC in preparation of this talk suggests APSIM "is extensively used to provide situation analysis and business case justification for GRDC investments that underpin grain production". For instance, use of APSIM to quantify yield gaps in Australian agriculture (Hochman and Horan 2018) have 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.

The graph below (Figure 11) results from simple searches of all available GRDC records. The first shows the growing influence of APSIM from the early 2000's … the drop off after 2018 is simply a consequence of records for current projects yet to be submitted.

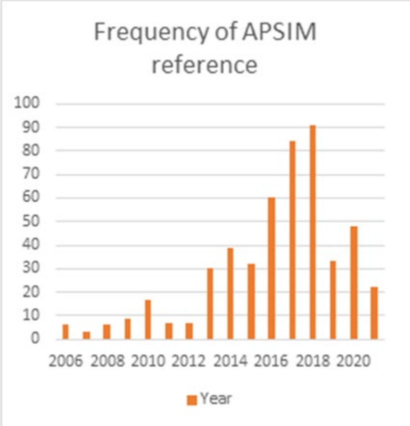


Figure 11. Reference to APSIM in GRDC outputs database (2006-2021). (Data for 2019-2021 reflect reports from current projects yet to be lodged).

Model 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 APSRUs formation in 1990 and early success with DSS tools like "Wheatman" (Woodruff 1992) and SIRATAC (Hearn et al 1981) were encouraging research managers to see value in such investments. If we look back to Nix's "systems research strategy" of the early 1980s (Figure 4), we see "Management Prescriptions" identified as a key step in 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). 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.

I have struggled to determine how to do justice to this topic within my space constraints. There is a large literature and it has been the focus of inquiry for many of my colleagues over 30 years. Two colleagues, Harm van Rees and Peter Carberry, recently shared with me their perspectives on the topic. I never took a lead on taking models directly to farmers and advisors so I will draw heavily on their insights.

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 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. A search of the literature today shows only one paper ever published that makes reference to Whopper Cropper and the product is no longer supported. One interpretation is that farmers are interested in analyses that apply to their own specific situations (soils, weather, paddock 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 seventeen-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 Profit**, a partnership between APSRU/CSIRO and the Birchip Cropping Group (BCG) which did seek 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 Profit 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)
- 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). Note Duncan (1975) first made reference to this concept of "What if" analysis.
- Whilst not the only option, generally these engagements have worked best when an experienced advisory agronomist supports a group of farmers in the model set-up 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.
- Farmers and advisors DO NOT look to these tools for a "management prescription". They see them more 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. 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 Profit, don't 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) tests this theory against the FARMSCAPE evaluation data. These were McCown's last two papers. They don't make easy reading but they are masterpieces in drawing together various bodies of theory to explain the circumstances in which science-based analytical information can add value to farm decision making. I commend them as essential reading to anyone thinking they will produce a DSS from their research.

Box 5. Beyond 2010 - Science outputs when becoming totally useless as an Executive

By the mid 2010's I had executive responsibility for all of CSIRO's Agriculture, Food and Health activities (around 1500 people). It all seems a bit of a blur now but I, with some close colleagues, did try to keep some science-based thinking and analysis going. I certainly could not have run APSIM by that stage without a lot of "re-training".

I have chosen our work that sought to frame the global food security challenge (Keating et al 2014) as my favourite for this Box. We were motivated by many voices claiming they had the solution to the food security challenge. Our supposition was there was no single solution. This mix of quantitative analysis and qualitative "Delphi style" solicitation of expert views, was used to provide a simple framing to an issue that was at the time quite opaque to many.

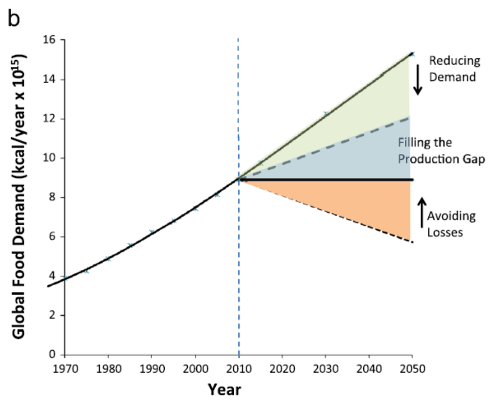
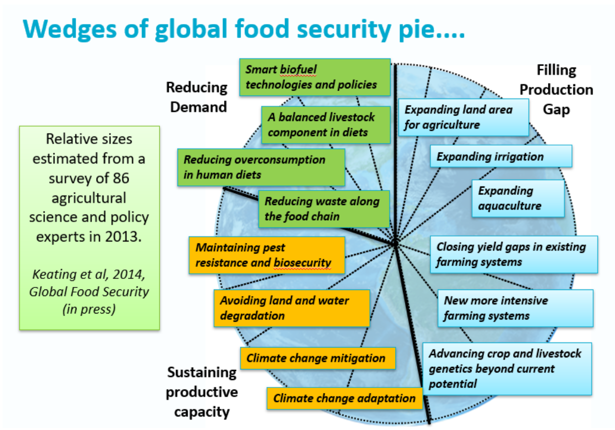


Fig. 1. Additional food demand from 2010 till 2050 represented as (a) A single "mega-wedge" of additional demand and (b) three conceptual "wedges" of equal size reflecting different strategies in the solution space.



The state of play for Australian agronomy in 2022

I judge the standing of agronomy today as a professional discipline to be much improved on its condition when I enrolled in agricultural science in 1973. This is the 20th Australian Agronomy Conference and this is the 19th CM Donald Oration and they serve as a fascinating record of Australia's agronomic journey.

The number of papers per annum classified as Agronomy or Agriculture Multi-disciplinary in Web of Science (WoS) involving Australian resident authors exceeded 1000 for the first time in 2021. This was a five-fold rise since my student days in the early 1970s (Figure 12).

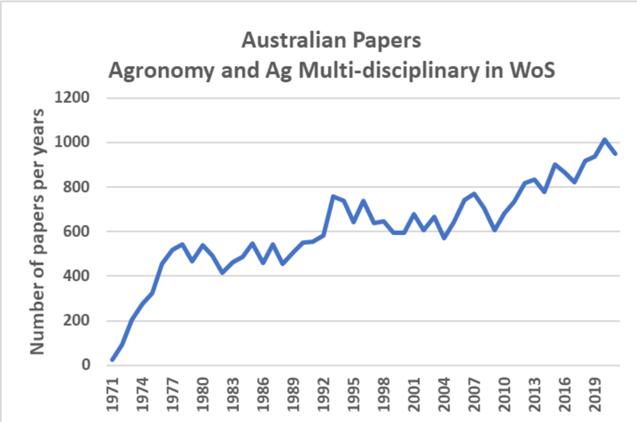


Figure 12. Number of papers per year with at least one Australian author from Agronomy and Agriculture Multi-disciplinary topics in the Web of Science (WoS) database.

Most Australian Universities with agricultural teaching and research activity have Chairs in Agronomy or Farming Systems of some sort. Despite the relentless pressures towards disciplinary specialisation, CSIRO has maintained a cohort of staff with broad agronomic skills (despite some pressures to vacate this field at different times) and these agronomists generally serve a key integration role in larger multi-disciplinary teams (my story today will go part way to explain how we managed to do that). The Australian Centre for International Agricultural Research (ACIAR) celebrates its 40th birthday this year and it has played a key role in strengthening Australian agronomy over this time. A large cohort of Australian scientists have served in senior positions or performed senior advisory roles in international agricultural research via the CGIAR.

I would argue Australia is now recognised as a global leader in agronomy informed by simulation model development and application. The citation statistics suggest Australia's agronomic models and methods are being increasingly deployed as "best practice" around the world. There is strong evidence that research agronomists and research funders in Australia are making effective use of simulation models to investigate farming systems and agronomic issues and better target their research activities. There are also instances of agronomic model application in government policy development and program delivery. Finally, there is now deep experience in the use of model-based decision tools in practical application with industry groups, farm advisors and/or farmers.

A vision is starting to emerge of what we will call for now, "**digitally enhanced systems agronomy (DESA)**". That is a digital capability to explore management interventions across climates and soils with inter-linked consideration of production, economic and environmental implications. Some are talking about **"digital twins"** of farms that form a virtual representation of a physical farm system (Verdouw et al 2021). This capability is emerging across scales including fields, farms, regions, nations and the globe. Such a vision is underpinned by advances in environmental sensing in combination with the data integration, interpretation and extrapolation capabilities of simulation models – with possibilities of further augmentation from machine learning and model-data fusion approaches starting to appear.

A number of key review papers prepared for the 19th ASA capture the state of Australian agronomy in the 2020s. I would nominate Hayman et al (2020) on climate variability and change, Hochman and Lilley (2020) on models and decision support, Hunt et al (2020) on emerging agronomic research approaches (what they call "transformational agronomy", Robertson et al (2020) on how the digital revolution is sweeping through agriculture and finally, Pratley and Kirkegaard (2020) for an overview of research and development capabilities and innovation trends. I can hardly improve on what these authors have already covered. There is a sense of excitement and forward momentum in Australian agronomy in the 2020's. While the need for "white-pegs" will hopefully never fully disappear, we have clearly entered the era of "**agronomy bounded by silicon chips"**.

Why did this effort survive and prosper for over 30 years?

Agricultural research policy and institutions in Australia have been subject to relentless change over the last 30 years – how did the APSIM effort manage to survive and prosper in the face of such change? Here I offer a few personal reflections for consideration by those with responsibility for the next 30 years of evolution of agronomic tools.

Balancing good agronomy with good software engineering.

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.

Australia is a small place and we are most effective when we work together.

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 USA, Netherlands and New Zealand.

Caution and modesty in modelling.

I will never forget the early days of application of a well-adapted model to a new problem domain. I experienced that in semi-arid Kenya in the 1980s and then again with wheat and sugar systems in eastern Australia in the 1990s. It was like one could suddenly understand the "language" those systems were "speaking". Maybe a bit like when the archaeologists discovered the "Rosetta Stone" to let them understand what the ancient Egyptians were saying. To be able to breakthrough a fragmented experimental record, plagued by site and seasonal specificity, to achieve a comprehensive view of the impacts of agronomic settings across all soils, seasons and farmer circumstances was exhilarating (sorry but we all get our kicks in different ways!). The riskiness of interventions and their interactions became the new language of agronomy from that point on.

This incredible "analytical power" of models brings with it important responsibilities. We all should know that *"all models are wrong, but some are useful"*. Injecting a strong dose of modesty into the modelling undertaking is wise. This means efforts to appropriately set up models, verify their inputs and ensure they are "getting the right answers for the right reasons" need to be relentless. There have been critiques that these models are at best "pseudo-science" or at worst the "most cumbersome for of curve fitting" possible (e.g. Passioura 1996). I accept this is a continuing danger and can best be managed by model use that is deeply informed by agronomic expertise and a relentless questioning of model inputs and outputs.

Building capable agronomists/modellers.

The jury is still out on how best to ensure the supply of agronomists who can effectively make use of the modelling tools and IT professionals who can effectively apply their skills to the agronomic domain. As a generalisation, Australian Universities have not been proactive in building capacity in this domain. There is a more prominent University role in the US (for example in the DSSAT team) and in Europe (in particular Wageningen). One of the current partners in the APSIM Initiative is a US University who uses APSIM effectively in its course design. I have no confidence there is a systemic approach to producing agronomists with the foundation skills to effectively and safely deploy the analytical tools . I am not saying we should let APSIM dominate an undergraduate curriculum, but I am saying we need to give much greater thought to how to ensure graduates emerge with the foundation skills for a "digital agriculture" future. I worry that human capability will be what ends up toppling the 32-year effort I have been discussing today.

The value of knowing what has gone before.

At the last ASA. Hunt et al (2020) put out the call for what the call a "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.

I found this paper late in my preparations for this Oration. It gave me some confidence that current and future leaders in Australian agronomy were going to make use of the systems modelling developments that I have been discussing. The "transformational agronomy" framework has much in common with the framework first proposed by McCown et al (1994) (if one wanted to be picky that would raise questions about the adjective "transformational"). Such frameworks have deep treads into 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.

Closing reflections

I feel I have been very fortunate to have been part of this agronomic journey outlined today.

- Fortunate to have chosen an agronomic pathway somewhat by chance despite by initial fascination with plant breeding.
- Fortunate to have entered the profession just at the point that visionary scientists were imagining a new form of quantitative agronomy based on simulation modelling.
- Fortunate to have worked in countries and regions where the need for and gains from model use were as large as proved to be the case.
- Fortunate to have had the mentors and colleagues I have had – I would have achieved nothing without the great teams I have been part of.

I am satisfied we have reshaped agronomy for the better. I know there have been questions about whether this is "science" or "engineering". I have no issue with agronomy being an artful mix of the two. I know the possibility of it being "snake oil" has been raised by some. I recognise that risk but am confident that it can be avoided with a rigorous approach to model development, testing and application.

I am confident the approaches developed are well entrenched in the toolkit of research agronomists and I am reasonably confident use in government and industry policy will be sustained. I am also confident the models have much to offer in the consideration of traits for crop breeding but their role in the genetic selection process *per se* is not yet clear. I would be surprised in future if we found farmers to be regular users of the models I have talked about today. Farming (especially traditional family farming) is a very personal human activity and intuition is central to many decisions farmers make. As a “small-holder” farmer myself since leaving CSIRO, I can attest to this view. Farm advisors may make more use of models in supporting groups of clients and corporate farms may also be more inclined to turn to quantitative analysis to support decision making.

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 don’t necessarily want to become just another circuit in a cybernetic world.

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There is no way I can do justice to all the people that should be acknowledged as having shaped or supported this 50-year narrative. A search of my publications in the WoS database reveals 199 co-authors so a good start would be to acknowledge those colleagues. Institutionally I would acknowledge Uni of Qld where I started and am now hosted as an adjunct and CSIRO where I worked for 39 years – never regretting for an instant having joined what I still see as a national treasure (despite the trials and tribulations that come with all big institutions!). Personally, my wife Marianne supported me in this great adventure – even going to live in a rural village in Africa with two young children in tow to make it possible. I am lost for words as to how to adequately acknowledge that.

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