Chapter 21

Impact of simulation and decision support systems on sustainable agriculture

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A brief history of the development of simulation capability in Australia

In 1987 when *Tillage* was published, few Australian agricultural researchers were working on simulation. They focused on developing and testing simulation models rather than to advise on sustainable agriculture. The models under development in Australia, such as AUSIM (McCown and Williams 1989) and PERFECT (Littleboy *et al*. 1989) were inspired by US crop models such as the CERES models (Jones and Kiniry 1986) and the EPIC soil and land management model (Williams *et al*. 1989) as well as by the Wheat model (van Keulen and Seligman 1987) and the crop nitrogen response model PAPRAN (Seligman 1981) of the 'Wageningen School' in The Netherlands. Crop modellers saw the potential to generate data that were difficult to obtain by other means, to extend the results of short-term field experiments, long enough to capture the variable climate of a region. Crop simulation analysed the effects of different management in environments where both water and N availability were major determinants of yield (Seligman 1981). Soil and land management modellers (*e.g.* EPIC, PERFECT) studied effects of crop management and climate on soil loss and land degradation processes.

Some embryonic applications of models to agricultural issues were underway in Australia but these were limited by the capability of the available models. A prescient example was the use of a crop model and long-term rainfall records to identify the likelihood of expansion of wheat cropping and the impacts of climatic change and climate forcing factors on future yields. Hammer *et al*. (1987) concluded that a better understanding of the action of the climate forcing factors was required before the likely impacts of climatic change on the reliability of cropping could be determined.

The modelling and simulation *status quo* was disrupted in 1990 when the CSIRO Division of Tropical Crops and Pastures and the Queensland Department of Primary Industries established the Agricultural Production Systems Research Unit (APSRU). APSRU brought together the groups which had developed PERFECT, to simulate the effects of soil management on erosion and the productivity of soils, and AUSIM, developed for research on the impact of management with respect to rotations and intercropping of coarse grains and legumes. The result of this collaboration was APSIM, (Agricultural Production System sIMulator), a farming systems model developed to:

- assist the search for better farming strategies;
- aid better production decision making under uncertain rainfall; and
- improve environmental stewardship where fertility depletion and/or soil erosion threatened the economic future of crop production (McCown *et al.* 1995).

Since the formation of APSRU (now rebranded as the APSIM Initiative) there has been ongoing investment in an integrated farming systems simulation platform for use as a research tool in Australia and worldwide. Progressive developments of APSIM were best described in three key papers (McCown *et al.* 1996, Keating *et al.* 2003, Holzworth *et al.* 2014). These described cycles of continuous improvements, testing and further developments in response to the APSIM , user community's research needs and to opportunities driven by new technologies.

Before a model can be used to conduct virtual (*in silico*) experiments it must first be validated against relevant data for the conditions and variables of interest. Much of the overall modelling effort focused on this validation process. Thus, papers about model development and model validation dominate the literature rather than papers on their applications (Keating and Thorburn 2018). Many of the papers cited here describe a validation process or reference previous validation efforts. We do not dwell on this important aspect of the work. Instead, we focus on the applications of simulation using APSIM, and on simulation-based decision support systems to advance sustainable agricultural productivity of rainfed cropping systems in Australia.

Impact of decision support systems on sustainable agriculture

Decision support systems (DSS) may be regarded as any method by which information can be transmitted, shared or structured to help people make a decision. Decision trees, heuristics, rules of thumb, old wives' tales and proverbs are all forms of decision support. Here we are concerned with computer-based tools that seek to inform users of the likely consequences of crop management actions that are stipulated by the user (Stone and Hochman 2004). The late 1980s were a time of great optimism for computerised DSS for agriculture in Australia, and a proliferation in the development of local DSS. Proponents believed that "Farmers need all the help they can get. They need the best information available, and they need to have it delivered quickly, reliably and efficiently. Computer-based systems offer the ability to deliver the goods" (Hamilton *et al*. 1991). At the time, a lack of farm computers was seen to be the major constraint to the greater adoption of DSS. However, by 2002 despite over 75% of grain growers owning and using computers and the ready availability of hundreds of DSS, their use in farm management had not grown (Hayman and Easdown 2002, McCown *et al.* 2002).

An important response to this realisation was the FARMSCAPE project which aimed to ascertain under what circumstances, if any, farmers could find value in the simulations for decision making. The FARMSCAPE team employed a Participatory Action Research approach (Zuber-Skenitt 1993) to work directly with small groups of farmers and their advisers on individual farmers' properties in the northern-cropping region. APSIM was used to aid discussions between researchers, farmers and their advisers or planning tactical and strategic management of their farms. Researchers found the ability to demonstrate the credibility of the simulator and their commitment to solving problems perceived by farmers made them keen to explore a wide range of management issues. An extensive evaluation program showed that farmers often attributed significant insights into their production system and changes to their management (and in some cases significant financial reward) to involvement in these sessions. (Carberry *et al.* 2002).

Researchers then turned their attention to the challenge of delivering FARMSCAPE tools and techniques in a cost effective and commercially sustainable manner and to explore the market for DSS in other Australian cropping regions. The FARMSCAPE team developed a close collaboration with the Birchip Cropping Group (BCG); a farmer driven organisation with a membership of 450 family farms in the Victorian Wimmera and Mallee. The collaboration started in 2001 with sensibility and field testing of APSIM and by conducting a series of simulation aided 'what-if' sessions. In 2002, with a degree of credibility achieved, "The Yield Prophet", a monthly fax service to all BCG members, provided updated forecasts of yield probabilities for 5 'locally representative' field sites. From the first issue on May 15 there were clear and increasingly more definite signals that 2002 would be a very low yielding season. As it happened 2002 was the worst cropping season in the collective memory of BCG farmers. But few farmers had enough faith in the simulator to influence their practice. That season, 2002, created a great deal of interest and qualified credibility for APSIM and Yield Prophet®. By 2004, the Yield Prophet® Fax service had evolved into a web-based service to reduce farmer uncertainty about yield prospects and to explore the potential effects of alternative management practices on crop production and income. Key components of Yield Prophet® included access to soil characterisation, pre-season measurement of initial soil water and soil N, access to daily and historical weather data, ability to specify critical management options and real time internet enabled access to APSIM , (Figure 1). Compared with conventional DSS, Yield Prophet offered flexibility in problem definition and allowed farmers to realistically specify the problems in their fields. Uniquely, Yield Prophet® also provided a means for virtual monitoring of the progress of a crop throughout the season. This is particularly important for in-season decision support and for frequent reviewing in real time of the consequences of past decisions and past events on likely future outcomes (Hochman *et al.* 2009).

The implementation of Yield Prophet® through participation of researchers, grower groups, agronomic advisers and farmers was a social process, involving co-learning and thinking (Jakku and Thorburn

2010). This was clearly illustrated by the proliferation of the concepts of PAW at sowing and PAWC of soils in these communities of practice and in the continuing widespread use of hydraulic soil coring equipment to facilitate their measurement. After a period of joint research and development, BCG assumed the management of Yield Prophet® as an income generating subscription-based service which was still active in 2019. By 2018, 1,686 growers supported by 377 advisers had subscribed 4,949 unique paddocks distributed throughout the grain zone (Figure 2). While the number of growers directly involved was a relatively small proportion of Australian grain producers, they tended to be the leading growers who communicated learnings well beyond their farms.

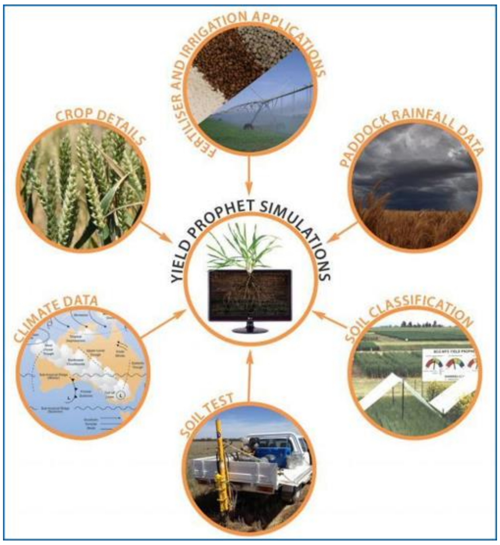

Figure 1. Schematic representation of inputs into Yield Prophet

Figure 2. Location of weather stations used for Yield Prophet paddocks in 2014

Ten years after the completion of the FARMSCAPE project, these largely-intuitive farmers were still highly enthusiastic about the analytic approach that integrated soil water data with simulation of management options. Yield forecasting and tactical decision making, had served farmers as ‘management gaming’ simulations to aid formulating action rules for such conditions, thus reducing the need for an on-going decision-aid service (McCown *et al.* 2012). This preference for intuitive rather than analytic decision-making helps explain why, while some growers continue to use Yield Prophet® as a decision tool for many years, most growers use it for one or two years only.

The experiences of the developers of Yield Prophet® and of other Australian agricultural DSS were harnessed to assess the lessons learned from developing and implementing DSS tools (Hochman and Carberry 2011). The key propositions relating to best practice, listed according to the strength of the participants’ support, were:

- It is essential to have a plan for delivery of the DSS beyond the initial funding period;
- DSS need to be embedded in a support network of farmers, consultants and researchers;
- DSS development requires the commitment of a critical mass of appropriately skilled people;
- A DSS should educate farmers’ intuition rather than replace it;
- A DSS should enable users to experiment with options that satisfy their needs rather than attempt to present ‘optimised’ solutions;
- DSS tools stand on the quality and authority of their underlying science and require ongoing improvement, testing and validation; and
- DSS development should not commence unless it is backed by marketing information.

DSS stakeholders supported the proposition to have a delivery plan beyond the funding period, but resisted the notion of DSS development being market-driven or commercially delivered. Hochman and Carberry (2002) argued that since public funding to deliver DSS for farmers’ management of climate risk is highly unlikely, DSS stakeholders need to change their perception of the commercial delivery model or find alternative funds to deliver DSS beyond the R&D phase. Yield Prophet® remains one of the few examples of an impactful DSS (Robertson *et al.* 2015, Keating and Thorburn 2018). This is an important observation given the current flurry of activity around digital agriculture and the commensurate development of 'Apps' (see Chapter 24) driven by the seductive lure of new technology-enabled possibilities.

Table 1 summarises several studies where the combination of simulation studies and experimental research has led to significant impact in Australian cropping systems. In the following sections we describe the insights gained from these studies.

Managing crops in a variable and changing climate

Australia's farmers face an extremely variable climate that diminishes their capacity to plan for any given season. Simulation provides insights into both fixed strategies and tactical adaptations to help growers adjust their crop management to this variable climate. Analysis of simulation results using long-term weather at a wide range of locations showed that some adaptations are successful regardless of climate forecasts. These include location or soil-specific choices regarding genotype maturities, sowing time and nitrogen application rate. Examples of such adaptations include wheat variety choice (Zheng *et al*. 2018) and a 'rule of thumb' about the minimum starting plant available soil water (PAW) for chickpeas in the northern grain zone (Whish *et al*. 2007). However, long-term simulation analyses do not always yield simple solutions. A simulation study to determine the value of different skip row sorghum configurations (leaving every second or third row unsown) showed that the decision required consideration of the starting soil water, the soil's plant-available water capacity (PAWC), and the farmer's risk preference (Whish *et al.* 2005). The realisation of the importance of PAW led to the measurement of field-determined drained upper limit and crop lower limit, as well as other chemical properties and soil organic matter which culminated in APSoil (www.apsim.info/Products/APSoil), a national database containing the simulation ready characterisation of over 1000 soils distributed throughout the Australian grain zone (Dalgliesh *et al*. 2009).

While fixed strategies offer 'no regrets' management options for the majority of seasons, seasonal climate forecasts offer the possibility of additional tactical responses to tailor better crop management decisions to the current season. Such adaptations require reliable seasonal forecasts and the ability to carry out *in silico* experiments to determine the impact of management options on crop yields and other outcomes of interest such as soil erosion risk. APSIM's simulation capability and its facility to flexibly specify management options were one part of this equation. Another was the availability of the Southern Oscillation Index (SOI phase system, Stone *et al*. 1996) as a readily applied forecasting system using analogue years from the past100 seasons. Since the 'millennium drought', and possibly due to the impacts of climate change on the El Nino Southern Oscillation (ENSO), the validity of the statistically based SOI phase system predictions have been called into question (Rodriguez *et al.* 2018) and the future of seasonal forecasting appears to be linked to global circulation models (GCMs). The downscaled daily outputs from POAMA (the Australian GCM) were input into the APSIM wheat model to translate forecast seasonal conditions, from hindcast data, into yield outcomes. Comparison of these outcomes to those from actual climate records for the same seasons showed that POAMA-derived forecasts exhibited more skill than may be gained by a probabilistic analysis of the previous 30 years of climate data but this advantage only applied from June or later in the season (Brown *et al.* 2018). Significant improvements in the skill of seasonal forecasts is prescribed representative concentration pathways (RCPs where RCP 2.6 represents an ambitious mitigation pathway while RCP 8.5 represents continued high emissions throughout the 21st century) as published in the IPCC fifth assessment report (IPCC 2014).

Outputs from GCMs under various RCPs are downscaled to modify local historical climate observations of key determinants of yield potential such as rain, temperature and atmospheric CO_2 concentration. The impact of these variables on crop growth and development processes are captured in cropping systems simulation models such as APSIM. By considering genetic, environment and management interactions, crop models provide a framework to capture impacts of future climates and offer an avenue to identify possible adaptations to offset the impact of climatic change on yields.

Simulation studies of impact assessment have resulted in contradictory results: some show large negative impacts while others show small or positive impacts. Examples of large negative impacts include a study of 80 CC scenarios in South Australia for 2080 with the most likely projected wheat yield changes being decreases across all locations of 13.5 to 32 % (Luo *et al.* 2005). Related studies in South Australia showed a range of negative and positive impacts on grain N contents and the influence of soil type on these impacts (Luo *et al.* 2005b) with yield declines of 10-15 % under non-limiting N supply conditions (Luo *et al.* 2009). In a study of sites in NSW, Victoria and WA, the negative consequences for crop yields were not uniform across crops and locations. Of the crops studied (wheat, barley, lupin, canola and field pea), field pea was the most sensitive to the projected future CCs, and the ensemble median decreases in field pea yields ranged from 12 to 45 % depending on location (Anwar *et al.* 2015). Contrasting results were observed in several other CC impact studies. A study of the impacts of CO_2 concentrations, temperature increases and changes in rainfall amount and intensity for Wagga Wagga in New South Wales showed small differences (+1 and -6 %) for scenarios to 2050 and 2070 (Wang *et al.* 2009). A 40-year simulation study of production of a range of forage crops and lucerne grown at three locations in southeast Australia found increases in dry matter yield of up to 93% depending on species, location and climate change scenario (Pembleton *et al.* 2016).

There has been no formal attempt to reconcile the differences in the predictions arising from these studies. Their small number and lack of uniformity of location, species and methodology rule out resolving the issue with meta-analysis. One important difference in methodologies is that rather than using downscaled GCM projections, some studies used factorial combinations of incremental change in temperature, atmospheric CO_2 concentrations and rainfall. Such combinations may miss the linkages between these non-independent parameters which drive the larger impacts shown by simulation of future climates derived from downscaled GCMs. Also, using different crop growth models produces different results and Martre *et al.* (2015) to recommend using GCM and crop model ensembles. Impacts also depend on the nature of the projected CC and the current climate conditions. A study of sorghum and wheat systems in northeast Australia with simulations spanning representative locations, soil types, management systems, and 33 climate projections found small to positive impacts of projected CC, even after the impacts of extreme heat were added to the simulations. This was attributed to a reduced frequency of drought periods for most climate projections for both sorghum and wheat in the region of study (Lobell *et al.* 2015). Less appreciated is the impact of using different downscaling methods to generate daily climate data. A study of wheat cropping systems showed that different downscaling methods generated different CC impact assessments (Liu *et al.* 2017).

Improved functions to describe the effects of severe weather events such as frosts and extreme heat are required to better represent the impacts of, and adaptations to, future CC (Chenu *et al.* 2017). Functions to estimate the effects of frost stress and heat stress on yield were developed for APSIM-Wheat (Bell *et al.* 2015) and APSIM-Canola (Lilley *et al*. 2015). These functions improved the accuracy of simulations of canola (Kirkegaard *et al.* 2016) and were applied in more recent studies to investigate a wide range of sites and sowing dates (Flohr *et al.* 2017, Hunt *et al.* 2019, Lilley *et al.* 2019).

The impact of CC on regions suited to future wheat production was investigated by combining a species distribution model together with APSIM simulations under future climate scenarios and cropping adaptation measures. This study showed an overall tendency for a decrease in the area suitable for growing wheat and a decline in the yield of the northeast Australian wheat belt while future CC may benefit South Australia and Victoria (Wang *et al.* 2018).

Examples of adaptation studies include those considering various combinations of sowing date, and cultivars with genetic differences in early vigour and flowering time; these have been conducted in a range of Australian cropping regions (Luo *et al.* 2018, Ludwig and Asseng 2010, Lobell *et al.* 2015). Different locations will require different strategies to manage the negative impacts or take advantage of future CC. Breeding of cultivars that are less sensitive to phenophase reduction in response to a warming climate or more heat and drought tolerant has also been proposed (Hunt *et al*. 2018).

Table 1. Selected examples of simulation studies which combined with field agronomy have resulted in significant impact on Australian dryland cropping systems

Description of simulation study	Impact	References
Managing crops in a variable and changing climate		
Importance of stored soil water	Industry acceptance of importance of stored soil water and 'rules of thumb' about the minimum starting plant available soil water (PAW) for different crops in the northern grain zone. Creation of APSoil - a national database containing characterisation of > 1000 soils.	Carberry *et al.* 2002; Whish *et al.* 2007; Lilley and Kirkegaard 2007; Dalgliesh *et al*. 2009
Management of summer fallow	Explained the observed limited benefits from fallow residue management and focussed attention on fallow weed management. Role of cover crops and of legumes in cover crop mixtures. Awareness of N limitation after cover crops.	Hunt *et al.* 2013; Verburg *et al*. 2004, 2012; Wunsch *et al*. 2017
Timely sowing & identification of optimum flowering periods	Simulation studies highlighted that grower sowing times with current cultivars of wheat and canola were later than optimal. Field experiments and extension effort followed (GRDC Water-Use Efficiency, GRDC Early Sowing, GRDC Canola Agronomy projects). Flohr *et al.* 2018a reported a 10-day shift in median sowing date of wheat from 20 May in 2008 to 10 May in 2015. Estimated to have added an additional 2.3 Mt per year to the Australian wheat crop worth $540 million annually.	Hochman *et al.* 2009a; Zheng 2015; Hunt 2016; Flohr *et al.* 2017, 2018a; Hochman *et al*. 2019; Lilley *et al*. 2019
Dry sowing	Demonstrated whole-farm benefits of dry sowing across the WA wheat belt. Showed that benefits in timeliness of seeding outweighed any risks. In 2018 up to 80% of WA crops were sown dry.	Fletcher *et al*. 2015; Fletcher *et al*. 2016; https://ab.co/2WP5IY4
Strategic application of N fertiliser in response to soil characteristics and seasonal conditions	Split application of N allows season specific N management decisions to be delayed until seasonal conditions and forecasts provide more knowledge about crop yield prospects. Soil-specific management of nitrogen is more widely adopted in environments with varying soil N supply and demand. Better N management decisions lead to increased profit and reduced risk.	Asseng *et al*. 1998; Carberry *et al*. 2013; Hochman *et al*. 2009, 2013; Huth *et al*. 2010; Nash *et al*. 2013; Monjardino *et al*. 2013; 2015
FARMSCAPE	Farmers gained significant insights into their production system and changed their management.	Carberry *et al*. 2002
Yield Prophet®	From 2008 to 2018 the total number of subscribed paddock-years was 8,931 (= 4,949 unique paddocks). Used by 1,686 growers supported by 377 advisers throughout the grain zone.	Hochman *et al.* 2009a
Insights from developing agricultural DSS	Lessons learned by DSS developers is internationally recognised as best practice for successful DSS development and for deciding when not to develop DSS.	Hochman and Carberry 2011; McCown *et al.* 2002, 2012; Stone and Hochman 2004
Crop genotype improvement and trait value propositions		
Value of deep roots	Stimulated further agronomic and genetic research on capturing deep water and projects seeking genotypic variation in wheat roots. Led to early sowing systems and subsoil amelioration work	Manschadi *et al*. 2006; Lilley and Kirkegaard 2007, 2011, 2016
Identifying optimum flowering periods	Flowering in the optimal window maximises yield by reducing frost and heat damage and water stress. Growers now maximise yields by matching sowing date and cultivar to achieve optimum flowering time. This work has inspired new research to develop gene-based phenology models.	Chen *et al*. 2016, 2017; Flohr *et al.* 2017; Lilley *et al.* 2019; Zheng *et al.* 2012, 2013, 2016, 2018
Value of early sowing with slow developing cultivars	Pre-experimental simulation revealed the potential to increase yield by using slow developing cultivars sown earlier than currently practiced. Field experiments and simulation studies demonstrated national value. This research convinced breeding companies to develop winter wheat germplasm for early sowing. At the time of writing these cultivars were in early stages of adoption by growers.	Flohr *et al*. 2018a,b; Hochman and Horan 2018; Hunt *et al.* 2012, 2019; Lilley *et al*. 2019; Moore 2009; Peake *et al.* 2018; Van Rees *et al*. 2014

Table 1 cont.

Industry-scale predictions - quantifying and diagnosing wheat yield gaps		
Quantifying and diagnosing Yield Gaps	Further research seeking to identify causes, and methods of closing yield gaps. Funding agencies identified closing the yield gap as a key objective and performance indicator.	Gobbett *et al.* 2017; Hochman *et al*. 2012, 2016; van Rees *et al. 2014*
Scaling up to crop sequences		
Crop sequence and rotations	Advisors are matching crop intensity and break crop frequency to balance risk and return in different production environments.	Hochman *et al*. 2014; Whish *et al.* 2019
Value of dual-purpose crops	Dual-purpose canola and wheat adopted in all southern states.	Bell *et al*. 2015; Lilley *et al*. 2015
Management of summer fallows	Simulation informed experimental design, extended evaluation of experimental results and understanding of mechanisms of yield response. Whole mixed farm simulation showed no trade-offs between crop and animal production. Complete summer weed control has become best-management practice across the cropping zone.	Hunt and Kirkegaard 2011; Hunt *et al.* 2013; Kirkegaard *et al.* 2014; Moore and Hunt 2012; Verburg *et al*. 2012
Balancing production and environmental imperatives		
Soil erosion and tillage research	Simulation and mapping of soil erosion and its effects on crop yields in Queensland inspired no-till farming and retaining stubble cover. Arrested soil erosion and improved yields.	Littleboy *et al.* 1992
Lucerne phase farming	Influenced national dryland salinity policy development and stimulated new thinking around duration of lucerne phases.	Verburg *et al.* 2007a,b
Effect of grazing on soil compaction and crop yields	Simulation demonstrated that compaction due to animals grazing stubbles during the summer fallow or dual-purpose crops in autumn were unlikely to impact soil compaction or yields. This was verified experimentally and helped reduce growers' concerns about livestock grazing cropping lands.	Allan *et al*. 2016; Bell *et al.* 2011; Hunt *et al*. 2016

Climate change is not only about the future. Historical climate records in Australia show clear trends in CO_2, temperature and rainfall patterns since the 1970s. An alternative approach to impact assessment is to quantify the impacts of these recent climate trends on potential yields by using historic daily weather records. This approach avoids the uncertainty associated with both the factorial modification and the synthetic downscaled GCM climate data. In such a study, based on simulation of 50 representative sites throughout the Australian grain zone, water-limited yield potential declined by 27% over a 26-year period from 1990 to 2015. This decline was attributed primarily to reduced rainfall (83%) but also to rising temperatures (17%) while the positive effect of elevated atmospheric CO_2 concentrations prevented a further 4% loss relative to 1990 yields (Hochman *et al*. 2017). This impact assessment is consistent with the upper range of impacts predicted by using downscaled GCM climate data for a comparable future forecast period.

Insights into adaptation to CC can be gained by examining adaptation that have already occurred over the past 30 years or so. The concept of an optimal flowering window (the flowering period which was associated with a mean yield of ≥ 95% of maximum yield) was proposed to identify suitable genotype x sowing date combinations to maximise yield in different locations for recent and predicted regional climate shifts including the decline in autumn rainfall (Flohr *et al.* 2017). A similar concept of the optimal start of the flowering period was developed for canola (Lilley *et al.* 2019). An early sowing system combined with slower-developing wheat genotypes was proposed in response to observed reduced rainfall and increasing temperatures attributed to CC. Crop simulations revealed that such a system could exploit a longer growing season. Near-isogenic lines were developed and used to test this hypothesis in experiments across the grain belt of Australia, and the results were extended using whole-farm simulations (Hunt *et al.* 2019). The authors of this study calculated that the proposed early sowing system can increase national yields by 0.54 t/ha representing an additional 7.1 Mt annually under reduced rainfall and increasing temperature regimes. This adaptation could facilitate increasing yields across Australia under CC.

Adaptation to climate change is an important stop gap measure until amelioration can contain greenhouse gas emissions to prevent the occurrence of more catastrophic global warming. Sequestering soil organic carbon (SOC) is one measure in which crop production can contribute to reducing net emissions. Another is to reduce nitrous oxide (N_2O) emissions. In a simulation study of Australian dryland cropping soils under common farmer management practices and future climate conditions, SOC was predicted to increase by 0.66 Mg C/ha (ranging from −5.79 to 8.38 Mg C/ha) during the 62-year period from 2009 to 2070. Across the regions, ΔSOC, simulated at the resolution of 1 km, exhibited great spatial variability ranging from −108.8 to 9.89 Mg C/ha showing significant negative correlation with baseline SOC level, temperature and rainfall, and positive correlation with pasture frequency and nitrogen application rate (Luo *et al*. 2019). However, the influence of nutrient availability other than N (*i.e.* P and S, see Chapter 14) on the accuracy of such estimates is unknown.

In a simulation study of the net on-farm GHG abatement and gross margins for a range of management scenarios on two grain farms from the western (Dalwallinu) and southern (Wimmera) grain growing regions of Australia (Meier *et al.* 2017), increased cropping intensity consistently provided emissions reductions across site-soil combinations. The practice of replacing uncropped or unmanaged pasture fallows with a winter legume crop was the only one of nine management scenarios to decrease GHG emissions and increase gross margins relative to baseline practice at both locations over a 100-year simulation period. Annual N_2O emissions were an order of magnitude lower from sandy-well-drained soils at the Western Australian location than at the Wimmera site with a clay soil, highlighting the importance of interactions between climate and soil properties in determining appropriate GHG abatement practices.

Crop genotype improvement and trait value propositions

Crop models have the potential to predict plant phenotype based on its genotype, especially for complex adaptive traits. This requires existing crop models to be enhanced with sufficient physiological rigour for complex phenotypic responses to the environment to be predicted by the model dynamics. The approach quantifies capture and use of radiation, water, and nitrogen within a framework that predicts the realised growth of major organs based on their potential and whether the supply of carbohydrate and nitrogen can satisfy that potential (Hammer *et al.* 2010). Current and prospective enhancements to crop models are designed to enable them to better:

- characterise the environment that crops experience;
- assess the value of physiological and genetic traits in targeted environments;
- de-convolute G × E interactions in statistical models; and
- utilise high-throughput phenotyping to identify 'hidden' traits of interest (Chenu *et al.*2017).

Examples of this approach include the use of an enhanced APSIM sorghum model to investigate the value of genetic effects associated with crop height. Genotypes differing in height differed in biomass partitioning among organs; a tall hybrid had significantly increased radiation use efficiency - a novel finding in sorghum. The enhanced model also predicted differences in green leaf area retention during grain filling via effects associated with nitrogen dynamics (Hammer *et al.* 2010).

Simulation can be used to characterise drought-related environmental stresses, thereby enabling breeders to analyse their experimental trials with regard to the broad population of environments that they target. Simulations based on more than 100 years of historical climate data were conducted for representative locations, soils, and management systems for a check cultivar (Chenu *et al.* 2011). Three main environment types with different patterns of simulated water stress around flowering and during grain-filling were identified and opportunities to improve breeding and germplasm-testing strategies of 18 representative genotypes were investigated. Other studies similarly have used simulation to characterise the environments and estimate genotype by environment variance in sorghum (Chapman *et al*. 2002) and genotype by environment by management (GxExM) in barley (Ibrahim *et al.* 2019) and to demonstrate the need to match crop design to specific sites and seasons (Clarke *et al.* 2019). Simulations also demonstrated the value of a proposed crop ideotype compared to commercial genotypes in a wide range of environments throughout the Australian grain zone (Kaloki *et al.* 2019).

A case study for improved wheat root systems

This case study explores use of simulation to assess the impact of a hypothetical change in wheat roots systems. The experimental study of Kirkegaard *et al.* (2007) showed that in terminal drought, water extracted from deep in the soil (below 1.2 m) was extremely valuable because it was not lost to evaporation, and became available later in the crop growth during flowering and grain-filling, a period when yield development is particularly sensitive to water stress (Fischer 1979). The experiment reported a marginal water use efficiency of 59 kg grain/ha/mm for the subsoil water, around 3 times more efficient than overall crop water use efficiency of 20-24 kg grain/ha/mm for crops in southern Australia (French and Schultz 1984, Sadras and Angus 2006, Sadras and Lawson 2013). Subsequent simulation studies were used to place these results in the context of the climate record and different soil types, and investigated;

- How valuable would subsoil water be in other seasons in that region, and for other regions or on soils with different water holding capacities (Lilley and Kirkegaard 2007)?
- Would a wheat variety bred to be better at extracting water from deep in the soil be valuable? Where, and under what circumstances would this occur (Lilley and Kirkegaard 2011)?
- What would the legacy of crops with improved water uptake be on subsequent crops in the sequence and how would soil type and crop management interact with these new varieties (Lilley and Kirkegaard 2016)?

Seasonal variation in the value of subsoil water The first simulation study (Lilley and Kirkegaard 2007) was conducted at three locations in the Riverina region of NSW (Cootamundra, Junee and Ardlethan), which varied in average annual rainfall by 140 mm. Soil parameters were initialised on 15 December (representing harvest date of a previous crop) as either (1) at the wilting point in all layers to a depth of 1.8 m, or (2) at the wilting point from the surface to 1.2 m and at field capacity from 1.2 to 1.8 m depth. The soil profile then filled according to seasonal conditions before a crop was sown in the typical sowing window (between 15 May and 15 June of the following year) according to a rainfall rule. On average, the value of the stored deep water was 35 kg/ha/mm, less than the 59 kg/ha/mm in the experiment, but could vary from 0 to 100 kg/ha/mm. Counterintuitively, the study revealed that the value of stored subsoil water was much greater in higher rainfall environments and seasons, due to its more frequent occurrence (the profile was sufficiently wet to allow roots to penetrate to deeper layers). Farm management strategies that increased the likelihood of full-profile wetting such as summer weed control, stubble retention and no-till increased the benefit to subsequent crops in drier environments and seasons.

Benefits of modified root traits for crop water uptake The second simulation study (Lilley and Kirkegaard 2011) investigated the benefits of modifying roots to increase soil exploration and water extraction. The study included the locations of the previous study where rainfall distribution was equi-seasonal, and two additional environments; Wongan Hills, WA, with a deep sandy soil and winter-dominant rainfall, and Dalby, Qld with a deep clay soil and a summer dominant rainfall. In that study, similar initial soil profiles to the above study were set on 15 December and appropriate cultivars and sowing windows were set for each region. Model parameters were modified to create hypothetical cultivars with more rapid downward root growth, and/or more rapid water uptake from all soil layers below 0.5 or 0.8 m (location-dependant). The study predicted that maximum root depth varied with location and season. In wetter seasons and where initial soil profiles were wetter, rooting depth increased, while the inability of roots to penetrate dry soil restricted rooting depth in dry seasons. Later sowing also restricted rooting depth due to inadequate time to reach deep soil layers before the start of grain filling when downward root growth ceased. Depending on the location, faster roots increased maximum water extraction by 3-11 mm, more efficient roots by 12-28 mm, and for the combination of faster and more efficient roots by 14-40 mm. The simulation suggested that wheat varieties with faster and more efficient roots would provide significant long-term average yield benefits of 0.3-0.4 t/ha at all locations tested, and that such traits would rarely result in a yield reduction. A subsequent study showed that greater benefits were achieved by early sowing of long-season cultivars, than by more rapid root growth of spring wheat (Lilley and Kirkegaard 2016).

Farming system context drives the value of deep wheat roots The third simulation study in this series (Lilley and Kirkegaard 2016) accounted for the legacy of greater water extraction by a crop on productivity of subsequent crops. In this study, simulations were set to run continuously without soil resetting, so that soil water extraction of a crop had a direct impact on the availability of soil water to the following crop. In essence, the study investigated the long-term benefit of sowing cultivars with more effective root systems in every year. The study was expanded to include 3 additional locations (Esperance WA, Paskeville, SA and Birchip, Vic) with shallow soils (0.7-1.0 m). Increased water extraction was simulated in two ways, firstly by emulating roots with a faster rate of descent and more efficient extraction rate, and secondly using a cultivar with a greater duration of soil exploration and water extraction by sowing a longer-season cultivar around 3 weeks earlier (similar flowering and maturity dates, Figure 3). The study demonstrated that at sites with shallower soils (depth 1 m or less), which make up a significant area of the Australian cropping zone, the benefits of more extensive root systems were negligible. On deeper soils, more extensive root systems were clearly valuable to acquire resources to increase crop yield, but created a legacy of a drier soil for subsequent crops which reduced the average benefit at some locations and created a negative response in some years. In Dalby, Qld, where crops are grown on stored water (due to the summer dominant rainfall), increasing soil water extraction left the soil in a drier state for subsequent crops and long-term average yield decreased (Figure 3). On all soil types in Australia's southern cropping zone, earlier sowing of slower-maturing crops increased water uptake and average yield.

This series of simulations shows that interactions between root traits and the seasonal rainfall distribution, soil type and crop management at specific sites influence their impact on yield. In a cropping sequence, increasing the proportion of crops which dry the subsoil extensively has implications for the longer-term productivity of the farming system. The crop sequence can be managed tactically by considering stored soil water at sowing, seasonal rainfall and use of fallows, legumes or other crops which extract less water to optimise overall system benefits across the full range of seasons.

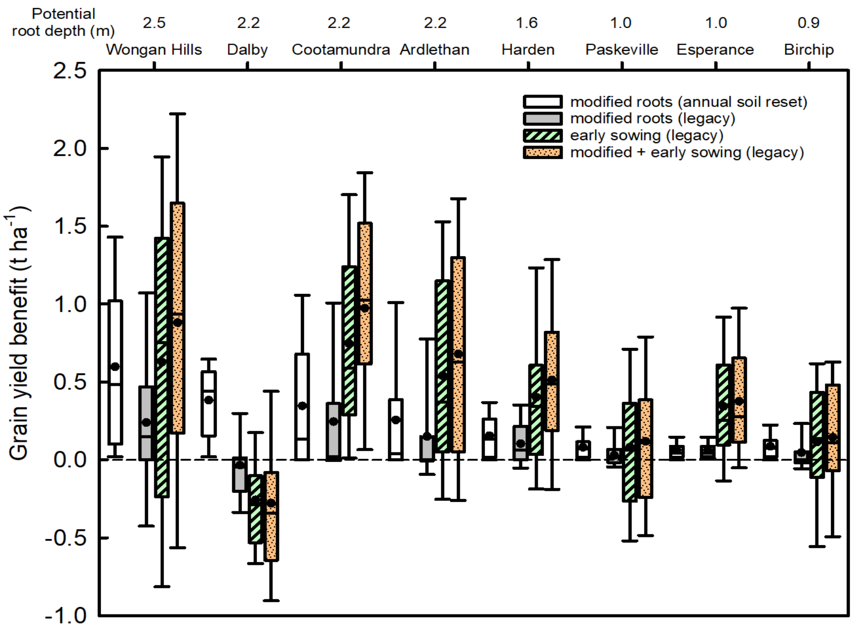

Figure 3. Box plots of simulated yield benefit of cultivars with either modified root systems and/or were sown early relative to the standard cultivar sown in the conventional window at eight sites varying in climate and soil type. Simulations were either reset annually (white) or run continuously (shaded) so that the legacy of crop history affected soil water content. Median (black line), mean (circle), 25th and 75th percentile (box), 10th and 90th percentile (whisker) are presented for 100 years of simulation (redrawn from Lilley and Kirkegaard 2016).

Industry-scale predictions – quantifying and diagnosing wheat yield gaps

Crop yields must increase substantially over the coming decades to keep pace with global food demand driven by population and income growth. This is also an imperative for Australian grain producers who are pressed to increase yields to combat a sustained cost-price squeeze. Quantifying food production capacity on every hectare of current farmland is needed to inform decisions on policy, research, development and investment into future crop yield and land use, and to inform on-ground action by local farmers and their knowledge networks. For rainfed crops, production capacity can be evaluated by estimating water-limited yield (Yw). Yield gaps (Yg) are defined as the differences between this theoretical yield level and actual farmer yields (Ya) such that

$$Yg = Yw - Ya$$

It is also meaningful to express the yield gap in terms of relative yield (Y % = 100 x Ya/Yw) where a low relative yield denotes a relatively high yield gap. To determine yield gaps it is necessary to have good estimates of both Ya and Yw. While census-based empirical methods have been used to estimate both Ya and Yw, the use of locally validated simulation models, coded to reflect best agronomic practice, results in more robust estimates of Yw and hence of yield gaps (Van Ittersum *et al.* 2013).

In Australia Ya values are best determined from ABARES and ABS surveys of individual farmers for which data are aggregated at statistical units that are roughly equivalent to shire boundaries (SA2). The availability of a thoroughly validated crop model, detailed soil maps, and over 3,900 weather stations in the Australian cropping zone, enabled the calculation a highly detailed map of Yw. Surprisingly these analyses revealed that the average wheat yield gap in Australia is about 50% of Yw (Figure 4; (Hochman *et al.* 2012, 2016). Yields and yield gaps vary considerably from shire to shire and at regional and subregional levels. They also vary between neighbouring wheat producers. To enable growers, consultants and policy makers to determine how these yield gaps impact them, an interactive series of maps was produced and are publicly available via www.yieldgapaustralia.com.au. Yield gaps for wheat, barley, canola, sorghum and the major pulse crops can be interrogated at multiple scales including a 'compare my farm' feature. The website was launched in 2015 and by April 2019 there were 16,517 sessions from 10,163 users, of which 69% were from Australia.

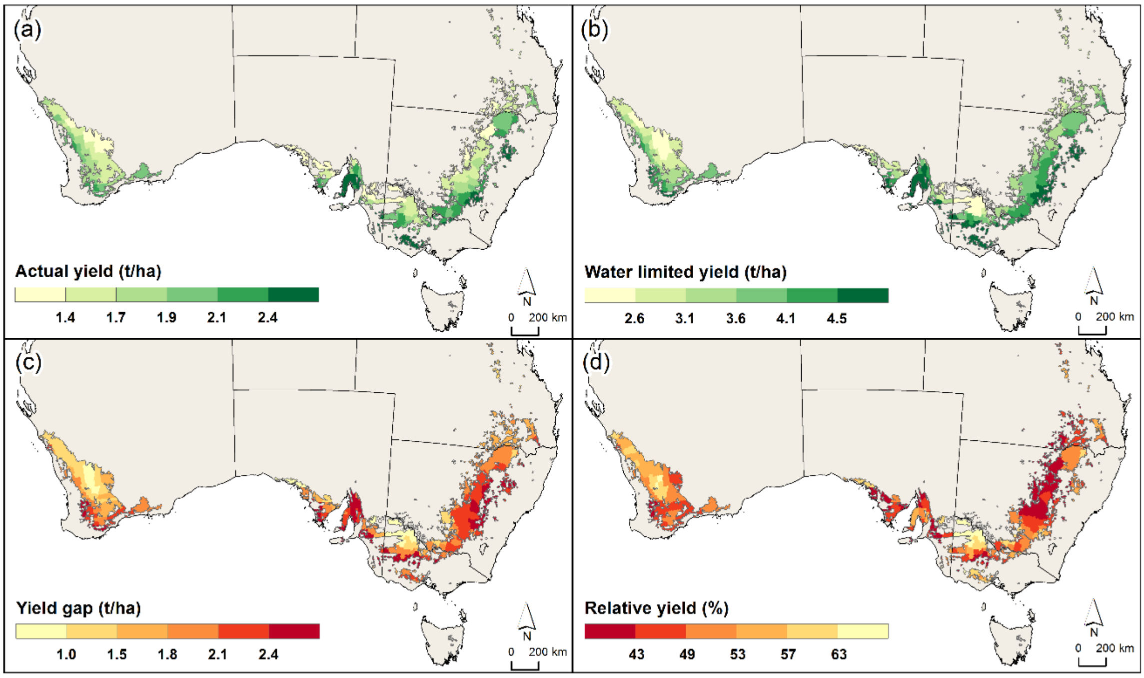

Figure 4. Long-term (1996-2010) average yield maps of (a) actual yields, (b) simulated water limited yields, (c) yield gaps and (d) relative yields (Y% = 100 * Ya/Yw) mapped at SLA resolution and masked to a boundary indicating the winter cereals area of 2005 (source: Hochman *et al.* 2016)

Why then do Australian grain growers achieve only half the yield potential of their crops? The answer to this question has multiple dimensions: biophysical, economic and social. These dimensions were explored in a series of investigations.

Biophysical causes of wheat yield gaps

To ascertain the impact of a range of suboptimal practices on grain yield compared to 'best management practice' rules that achieved benchmark water-limited yields simulations were conducted over 15 years at 50 weather stations. Average national losses per suboptimal practice (Treatments 2-8) relative to Yw (Treatment 1) are presented in Table 2. The combined impact of frost and heat stress accounted for yield losses of 16 to 26% depending on the stress function used (Treatments 9, 10). The key message from this analysis was that current levels of N fertiliser application (45 kg N/ha/year) are by far the most limiting biophysical factor and this holds back the national yield by 40%. Treatments 2-8 were not only lower yielding than the Yw treatment - they also had higher CV values indicating greater yield instability. Other research suggests that additional biophysical factors contribute to the yield gap. These include biotic stresses such as plant diseases, insects and other pests, in-crop weeds and extreme weather events (*e.g*. floods, strong winds and hail) other than frost and heat stress (Hochman and Horan 2018).

The large impact of average N fertiliser rates on the yield gap in the above study is in contrast with results of several earlier studies ((Hochman *et al.* 2009, Carberry *et al.* 2013, Hochman *et al.* 2014). The explanation for the difference is that the earlier studies involved farmers, such as Yield Prophet® subscribers, who were well connected to knowledge networks, whereas the more recent study is based on average N usage including all growers.

Table 2. Impacts of sub-optimal management factors, as well as of frost and heat stress, on water-limited yield (Yw) at a national scale

Treatment Number	Treatment	Mean (t/ha)	St Dev (t/ha)	CV (%)	Y% (%)
1	Yw (water-limited yield)	4.28	0.91	21	100
2	Seedling density (50 plants/m^2)	3.78	1.10	29	88
3	Late sowing (2 week delay)	3.97	1.04	26	93
4	Summer weeds	3.18	1.17	37	74
5	Tillage	2.86	1.08	38	67
6	N fertiliser (45 kgN/ha)	2.57	0.78	30	60
7	N fertiliser (90 kgN/ha)	3.30	0.96	29	77
8	Combined N fertiliser (45 kgN/ha) & Summer weeds	2.55	0.92	36	60
9	Frost and heat	3.15	1.00	32	74
10	Frost and heat 2 (moderate impact)	3.60	0.95	26	84

Profit-risk-utility dimension of wheat yield gaps

Large yield gaps may be attributable to (rational) sub profit-maximising input levels in response to risk and risk aversion. To investigate the proposition that risk aversion drives yield gaps, a novel Profit-Risk-Utility Framework that incorporates crop simulation, probability theory, finance techniques, and risk aversion analysis was implemented at fourteen case-study sites in 7 different sub regions across the Australian grain zone. The study demonstrated how farmers might select practices that manage the trade-off between maximising economic net return and exposure to risk across sites ranging from low to high yield potential. Risk-adjusted profit (the difference between the expected mean net return and a risk premium) varied with risk preference and yield potential. Risk aversion had a strong influence on the choice of practice in low yield potential sites, which helps explain yield gaps in those agro-climatic zones. However, in medium to high yielding areas, applying the management inputs required to achieve water-limited yield is the most economical choice even for highly risk averse growers (Monjardino *et al*. 2019).

Socio-psychological dimension of wheat yield gaps

To gain some insight into the socio-psychological drivers of farm level yield gaps, computer assisted telephone interviews were conducted with 232 wheat producers from the same 14 contrasting local areas as the economic risk analysis study described above. The interview data, together with the simulation-based estimates of each farm's wheat yield potential (Yw), were used to develop a comprehensive framework to understand the causes of wheat yield gaps in 2016. Results revealed significant differences in farming management as well as in farm and grower characteristics between farms with smaller versus larger yield gaps. Farms with smaller holdings, growing less wheat on more favourable soil types were more likely to have smaller yield gaps. Growers with smaller yield gaps were more likely to apply more N fertiliser, to have a greater crop diversity and to be less likely to grow a wheat crop directly after either another cereal crop or a pasture. In addition, they were more likely to soil-test a greater proportion of their fields and to adopt new technologies but were less likely to have problems with herbicide resistant weeds. They were also more likely to use and trust a fee-for-service agronomist and to have a university education (Zhang *et al*. 2019).

Scaling up to crop sequences

The production-environment trade-offs are best evaluated in a whole farm context rather than for individual crops. The APSIM architecture was uniquely designed to enable simulation of crop rotations and cropping sequences. The centrality of soils in multi-seasonal simulations distinguished APSIM as a farming systems simulator rather than as a series of crop models: "*Crops come and go, each finding the soil in a particular state and leaving it in an altered state*" (McCown *et al.* 1995). A simulated chickpea-wheat rotation was an early example that demonstrated how a model may be useful for addressing aspects of cropping system performance (yield as well as loss of organic matter and soil N) in terms of both productivity and sustainability issues (Probert *et al.* 1998).

Analysis of whole systems over multiple seasons is particularly important in cropping regions such as Australia's northern grain zone, where farmers have the option of growing a variety of winter and summer crops and where fallowing is required to store water to safeguard yields of following crops. The agronomic efficiency of cropping sequences compared to individual crops was investigated in a simulation study and longitudinal survey of 94 cropping sequences over 3.5 years. While the income from 36% of the individual crops in the study was found to be more than 80% of their attainable yield (based on N inputs), only 29% of whole cropping sequences achieved this benchmark. Similar results were achieved when crops and crop sequences were evaluated in terms of their metabolisable energy and crude protein yields. In order to increase the agronomic efficiency of crop production in Australia's northern grain zone, attention should be focussed on the intensity and configuration of cropping sequences and on the management of fallows in addition to the management of individual crops (Hochman *et al*. 2014).

Balancing production and environmental imperatives

World population growth, changing diets and limited opportunities to expand agricultural lands will drive agricultural intensification in the decades ahead. Concerns about the reliance of past agricultural intensification on non-renewable resources, about its negative impacts on natural resources, both on and off farm, and on greenhouse gas emissions, provide an imperative for future agricultural intensification to become ecologically efficient. The challenge is to produce more food per unit resource use while minimising the impact of food production on the environment. Ecological efficiencies can be achieved by improved matching of the supply of nutrients to crop requirements both temporally and spatially, and thus minimise the opportunities for excessive nutrients to impact on soil health and water quality (Hochman *et al.* 2013).

Management of soil erosion

From 1950 to 1990 soil erosion in Australia was found to be nearly five times greater under cropping than under uncultivated pasture and forest lands (Koch *et al.* 2015). This difference was attributed to a greater susceptibility to water and wind erosion due to soil disturbance by tillage and to lack of groundcover. Soil loss can have implications for soil fertility, soil organic matter, soil surface structure and soil acidification. It is generally accepted that soil erosion results in a loss of productivity, but information was sparse on the degree to which erosion reduces yields and was difficult to obtain experimentally because erosion was slow and sporadic, and its effects were often masked by climatic variability and advances in technology.

The PERFECT model was used to estimate the impact of soil erosion on yield through loss of soil depth, plant available water capacity (PAWC) and nitrogen. For a shallow soil on the eastern Darling Downs, erosion caused yield declines that increased rapidly after 25-35 years due to loss of both PAWC and nitrogen. For deeper soils, yield decline was less than 10% for up to 100 years. Yield reduction was variable from year to year, depending on seasonal conditions. In favourable seasons, yield reduction was related to reduced PAWC and less nitrogen, while in drier years yield was determined by growing season water supply rather than soil properties (Freebairn *et al*. 1996).

To examine the spatial distribution of erosion and its effect on production, multiple simulations using the PERFECT model combined information on soil type, slope and rainfall. Fallow management strategy did not affect the area experiencing soil erosion in the highest category (>100 t/ha/y), however, large differences due to fallow management were evident for the lower erosion categories. For NT, only 0.3% of the total area was included in the 50-100 t/ha/y category and approximately 85 % of the study area had less than 10 t/ha/yr of erosion. For stubble burnt management 7.7% of the land area was in the 50-100 t/ha/y category and only 42% had less than 10 t/ha/yr of erosion (Littleboy *et al.* 1992).

The rapid adoption of NT cropping practices in Australia since the 1980s (Llewellyn *et al.* 2012) has had a marked effect on soil erosion in the cropping zone. This is illustrated by a reversal of the soil erosion trend across regions in south eastern Australia where net soil redistribution switched from a loss of 9.7 t/ha/year in 1954-1990 to a gain of 3.9 t/ha/year in 1990-2010 (Chappell *et al.* 2012). Simulation of a mixed farming enterprise in the Murrumbidgee region of NSW showed that seasonal conditions were the dominant effect on the mean farm cover, rather than crop and stock management practices and that retention of wheat stubble increased long-term mean cover by 1-4% (Lilley and Moore 2009). A simulation-based assessment of NT practices showed that the effect of stubble cover on conservation of soil water during the fallow and the earlier sowing opportunities that arise, has increased the national average water-limited yield by 1.4 t/ha (Hunt and Kirkegaard 2011, Hunt *et al*. 2013, Hochman and Horan 2018). Reducing soil erosion by adoption of NT cropping and retaining stubble to improve groundcover appears to be a win-win for the environment and productivity. However, the growing problem of herbicide-resistant weeds will need to be managed carefully to avoid the need to revert to conventional tillage practices.

Management of deep drainage

The replacement of perennial natural vegetation with annual crops in Australia's grain zone has accelerated the rate of leaching of salts beyond the rooting zone. The consequent concentration of these salts elsewhere in the landscape results in dryland salinity (Dunin *et al.* 1999) which is, in turn, a major soil constraint to crop yields (Orton *et al.* 2018). Simulations including a perennial lucerne phase in rotation with crops (phase-farming) showed a reduction in long-term drainage and initially local retreat of water tables by 0.3 m/y (Dunin *et al.* 1999). The temporal variability in transpiration, soil evaporation, runoff and drainage was explored for selected locations in the Murry-Darling Basin over the 1957-1998 climate record. Water excess (*i.e*. runoff plus drainage) was shown to be strongly episodic (60% simulated to occur in 25% of years) and was highest for the annual wheat farming system and lowest for perennial lucerne pasture (Keating *et al.* 2002). While phase farming including 2 or 3 years of lucerne reduced average annual deep drainage significantly, it was achieved at the cost of lower average annual gross margins (Verburg *et al.* 2007).

Nitrogen management for production and environmental protection

Nitrogen fertiliser is a significant source of N for crops on mixed farms in Australia. It is produced from natural gas, a non-renewable resource and is subject to energy-market related fluctuations in supply and price. Efficient use of N by crops results in higher yields, increased protein in grain and increased return of stubble cover and maintenance of soil organic matter. Conversely, inefficient use of N by crops and pastures can result in increased emissions of potent greenhouse gases including nitrous oxide (N_2O) and in loss of N from the root zone. These losses lead to subsequent acidification of soils and to nitrate contamination of water resources. Inefficient use of N fertiliser is clearly inconsistent with concepts of agricultural sustainability and ecological efficiency.

Scenarios embracing a range of cropping rotations, N fertilisers and leguminous crops were evaluated using APSIM with long term data from the Brigalow Catchment in Queensland. Analyses of alternative management systems demonstrated that the use of legumes within cereal rotations was not always as effective in reducing N_2O emissions as improved fertiliser practice. For example, replacing wheat with chickpea did not reduce N_2O emissions relative to fertilised systems and did not assist in increasing soil C due to impacts on stubble cover over the summer months (Huth *et al.* 2010).

Two studies counter-intuitively identified N fertiliser application strategies in which increased N application led to increased yield, water and N uptake, thereby reducing long-term leaching of NO_3. At a deep sand site in the 500 mm rainfall zone west of Moora, Western Australia there was a 50% probability that 141 mm of winter rainfall and 53 kg N/ha could be leached below 150 cm under wheat following a lupin crop. Application of N fertiliser at sowing increased both grain yield and NO_3 leaching. Splitting the N application between the time of sowing and 40 days after sowing decreased NO_3 leaching, increased N uptake by wheat and increased grain yield (Asseng *et al.* 1998). In the high rainfall zone of south eastern Australia, flexible topdressing of N after minimum N application at sowing, maximised crop potential and also economic and environmental performance (Nash *et al.* 2013).

This study of 849 commercial wheat crops in southern and western Australia (2004-2011, Yield Prophet database, Hochman *et al.* 2009) found that only 22% of these crops could expect >20% higher yields from an increased investment in N fertiliser, while 50% of the farmers would realise no benefit from additional fertiliser application. Across all of the crops, regions, and conditions studied, 13% of cases simulations predicted no released of N_2O, and 95% of crop emissions had a global warming potential intensity <200 kg CO_2e/Mg grain, an environmental threshold deemed reasonable for crop production (Grassini and Cassman 2012). Nitrate leaching was predicted in only 17% of cases, with average and maximum leaching losses estimated at 0.7 and 75 kg N/Mg grain. These farmers operate close to eco-efficient frontiers with regard to N (Carberry *et al.* 2013). In the northern grains region, simulation and a survey of 68 fields indicated 50% received more N than required to achieve their yield potential while 71% received more N than required to achieve 80% of their yield potential, with low N use efficiency causing susceptibility to NO_3 leaching (Hochman *et al*. 2014).

Conclusions

The ongoing development and improvement of the cropping systems simulation model APSIM has had considerable impact on Australian cropping systems. We have described three pathways in which this impact has been achieved. The first pathway explored was the direct engagement of researchers with farmers and their advisers in the development and use of decision support systems. The impacts that can be achieved with this approach were illustrated through the FARMSCAPE and Yield Prophet® experiences. Recapping the lessons learned from these experiences is recommended as a guide to current and future efforts inspired by new advances in digital agriculture and App technologies. The case studies on use of models for genotype improvement and on quantifying and diagnosing wheat yield gaps provide a deeper dive into recent coordinated simulation-enabled efforts to improve the productivity of cropping systems. Both efforts are having an impact on farmer practice and an influence on the direction of agronomy research.

The second was through simulation extrapolating experimental results in space and time. This has enabled results, typically obtained from three years of research at two or three sites, to be extrapolated temporally to cover the full range of climate variability and extrapolated geographically to cover the region/s of interest including the whole cropping zone. This pathway is exemplified here by the sections on managing crops in a variable climate, on balancing production and environmental imperatives and in investigation of crop rotations and sequences.

The third pathway explored was applying a model into situations that have not yet been experienced or cannot be readily measured. This was illustrated by investigations into the impacts of, and adaptations to, possible future climate pathways, and by simulations to quantify, over a wide range of environments, the yield improvements that might be gained by potentially desired, but thus far only imagined, crop genotype manipulations.

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