Chapter 25

Australian Agronomy in the Anthropocene: the challenges of climate

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Introduction

Climate has always been challenging to Australian agriculture; the low and erratic rainfall across much of the country combined with frost, heat events and untimely rainfall makes Australian farming risky and frames the work of agronomists conducting research and providing advice. Australia is the driest inhabited continent with one of the highest year-to-year variability in rainfall (CSIRO and BoM 2015). Australian farmers face a higher degree of production volatility than farmers in any other OECD country and most of this is due to climate (Kimura and Anton 2011). Compared with other OECD countries they have equal highest price volatility and relatively low levels of direct and indirect income support from government (Kimura and Anton 2011). Within Australia, agriculture is more than 2.5 times more volatile than the average of all industries and significantly more volatile than the next ranking industries of insurance and construction, which were 1.5 times the average of all industries (Keogh *et al*. 2011). As pointed out by Malcolm (1994) and Mudge (2009), this variability in climate presents both opportunity and risk. Much of the success of Australian agronomy has been to manage the variability through finding ways to capture more out of seasonal rainfall and use all available water more efficiently (Kirkegaard and Hunt 2010).

Given the importance of climate to Australian agriculture, Connor (1992) expressed surprise that there was no Australian university department or CSIRO division of agrometeorology or agroclimatology. The widespread drought of 1982 coincided with an El Nino event yet there was very little recognition of this link in the agricultural research community. Much of the early applications of modern climate science to farming systems was undertaken by Queensland agricultural researchers in the mid to late 1980s. This work was presented and summarised at a symposium on Climatic Risk in Crop Production held in Brisbane in 1990 (Muchow and Bellamy 1991). CSIRO and the then Queensland Department of Primary Industries formed the Agricultural Production Systems Research Unit in 1991, which had a specific mandate to develop approaches and tools for better climate risk management. Other state departments of agriculture also formed small climate applications groups through the 1990s. Ongoing links between climate science and agricultural science were strengthened and coordinated by the 'Managing Climate Variability Program' which started in 1992 and continues. Hammer *et al*. (2000) provide a good summary of the work during the 1990s. An important legacy of this work has been the strong demand pull for information from agronomy, which contrasts with a supply push from climate science in some other parts of the world.

The invitation to contribute this chapter is an example of the increasing emphasis on climate over the last 30 years. The term climate is not listed in the index or any chapter titles in Cornish and Pratley (1987). This was not so much because climate was overlooked or ignored; rather it played a role that was implicit not explicit. Climate-driven processes of erosion and water productivity underpin many of the developments in tillage in Australia, including concepts adapted from other dryland regions, especially the USA (Pratley and Rowell 1987, Fischer 1987). Problems such as excessive tillage during fallows or dust mulching were attempts to deal with erratic and low rainfall. The benefits of stubble retention were largely due to the more efficient storage and use of water and hence ways to manage climate variability (Felton *et al*. 1987, Fisher 1987). Another implicit use of climate was the distinction in tillage practices for crop production between regions with winter and summer rainfall.

In this chapter we argue that over the last three decades, the notion of climate for Australian agronomy has dealt with three broad concepts:

- climate as a static description of a farming region (*e.g.* Mediterranean, subtropical);
- climate variability associated with climate drivers at different time scales such as El Nino Southern Oscillation (ENSO, interannual) and the Madden Julian Oscillation (MJO; intraseasonal); and finally,
- human induced climate change.

These concepts or phases are overlapping and build on each other. The last phase of human induced climate change leads to a range of new challenges for agronomists such as gaining appropriate confidence in climate trends and projections, researching the impacts of changes to temperature, rainfall and carbon dioxide on agricultural systems and identifying the challenges and opportunities to reduce greenhouse gas emissions and sequester carbon. Beyond these practical challenges there is the sobering realisation of the scale and pace that human activity (including agriculture) has had on the planet. In short, agronomists, along with society at large, must come to terms with operating in the Anthropocene.

Agronomists in the Anthropocene

The notion of the Anthropocene is not without controversy. Some geologists see it as a buzzword and remain unconvinced that there has been sufficient evidence of a change in rock strata. Other commentators argue the term is too broad because it covers humanity across time and space when much of the impact and benefit relates to a restricted group of OECD countries since 1950 (Hamilton 2015, Finney and Edwards 2016). A common transition from the Holocene to Anthropocene coincides with the invention of the steam engine in 1784 (Crutzen and Stefan 2003) and the consequent burning of fossil fuels. Others point to the emergence of agriculture 10,000 years ago, which enabled the growth in populations and civilisations (see Lewis and Maslin 2015 for review). A further link between agriculture and the Anthropocene is the hypothesis that carbon dioxide released from clearing forests 8000 years ago and methane from rice irrigation 5000 years ago prevented the next ice age (Ruddiman 2003). A recent example of the Anthropocene is the deposition in New Zealand glaciers of dust from Australian farming (Marx *et al*. 2014).

Fundamental to the concept of the Anthropocene is the ‘Great Acceleration’ since 1950 associated with an exponential increase in population, global prosperity, resource use and changes in natural processes (Stephan *et al*. 2015). Hamilton (2015) argues that using starting points other than 1950 tends to distract from the time and scale of human impact. He cites Stephan *et al*. 2015 *“…Only beyond the mid-20th century is there clear evidence for fundamental shifts in the state and functioning of the Earth System that are beyond the range of the Holocene and driven by human activities*”. This recent time frame is relevant to modern Australian agronomy. The three decades considered by this book (1990 to present) have seen accelerating change which has coincided with causes for both optimism and pessimism about human progress (Pinker 2018 as example of optimism, and Goldin 2018 for review). Modern agronomy is part of the ‘Great Acceleration’ and benefited through advances in germplasm, herbicides, fertilisers, crop protection, satellites, computers and machinery. The productivity gains from agriculture have been a fundamental, if under-recognised, driving force for the Great Acceleration by freeing up resources for other fields of technology and wealth generation (Harari 2011, Meinke *et al*. 2017).

Demand for food and fibre from a growing and more prosperous population requires enormous improvements in production with headwinds of a more hostile climate and other stresses on the earth system (*e.g.* disturbed hydrology, pollution, loss of biodiversity: Rockstrom and Karlberg 2010, Fischer and Connor 2018). Accepting that we are in the Anthropocene is important to this chapter because it distinguishes between the comfortable and accepted notion of climate variability and the less comfortable notion of human induced climate change. While this gives agency to agricultural practitioners, it also assigns responsibility for their actions to the sector. This fundamentally changes the way we view the cause and effect relationships between climate and agricultural production. Clarity on the cause of climate change not only provides confidence in the underlying trends but also points to the challenge for agriculture to reduce emissions and seek opportunities to sequester carbon.

Agronomists may have an advantage in coming to terms with the Anthropocene and human agency when compared with related disciplines such as plant biology, genetics, ecology, geology and meteorology. These natural science disciplines tend to emphasise a distinction between the natural and human world which has been blurred by the Anthropocene (Cook and Rickards 2017). This human-nature divide has always been blurred by agronomy. Agronomists start with the treatment of agriculture as a human activity and approach landscapes as managed ecosystems. In recent decades agronomists have been encouraged to think more about agriculture as a human activity with increased emphasis on the social and psychological aspects of technology and decision making. The three overlapping concepts of climate addressed below can be seen as increasing levels of human agency. If climate is treated as static, the primary role of humans is to adjust and learn to live with it. Climate variability came with an emphasis on management that identified ways that some Australian farmers worked with the variability to their advantage. The third phase of climate change comes with human agency in adapting to local impacts and mitigating global climate change. Incorporating historical climate information, seasonal climate forecasts and climate change projections into risk assessment and risk management all serve to further, and appropriately, blur the divide between humans and nature.

Climate as a static characteristic of a region

The notion of climate as a static characteristic of a region is captured in Connor's (1992) keynote address to the 1st Australian National Conference on Agro-meteorology where he argued that climate might be of interest to agriculture (averages that characterised a location) but not very relevant to farmers who were mostly interested in weather (deviations from the average that persisted for days or weeks). This argument is valid and backed by farmer interest in weather apps and forecasts. However, this distinction attributes temporal variability and change to weather and restricts climate to spatial variability between regions ignoring year to year and decade to decade temporal variability.

Characterising and comparing average climates is a sensible first step. An early example was Nix (1975) who divided arable land in Australia into five major agroecosystems:

- humid tropics and subtropics (along the Queensland coast);
- semi-arid tropics and subtropics with summer rainfall (far northern Australia), arid (interior);
- subtropical with summer and winter rainfall (Queensland and northern NSW grains belt); and
- temperate with winter dominant rainfall (grains belt of southern NSW, Victoria, Tasmania, South Australia and Western Australia).

More recent classifications include agro-climatic zones (Williams *et al.* 2002, Hutchinson *et al*. 2005) or agro-ecoregions (Padbury *et al*. 2002).

These agro-climatic zones are useful to distinguish farming systems, identify appropriate agronomy and guide the boundaries of cropping activity. Summer rainfall in Queensland and northern NSW allow for both winter and summer cropping whereas the temperate zone is mainly restricted to winter cropping. At most points in the Australian grains belt there is also a transect running from a high rainfall zone bound by topography through medium to low rainfall. The inner edge of the Australian grains belt is a transition zone between cropping and extensive grazing. This margin has attracted a high level of interest, especially in South Australia where, during a severe drought in 1863-1866, the then Surveyor-General George Goyder established a line marking areas of reliable and unreliable annual rainfall. This line became to be understood as the line beyond which cropping was too risky (Meinig 1961, Sheldrake 2005, Nidumolu *et al.* 2011).

Australia is fortunate to have excellent spatial and temporal coverage of climate records, especially rainfall. Yet, in 1863 Goyder had limited rainfall records (the SA colony was only formed 27 years earlier, in 1836). As pointed out by McCown *et al*. (2002), it is a gross underutilisation of the rich data set to take just the average and describe a region as a 400 mm or 600 mm annual rainfall. Maunder (1989) maintained that, although the emphasis on 'average' climate and treating climate as constant was at odds with experience, it was convenient for planning. He argued it was the Sahel drought of the 1970s that prompted the use of the climate archive for planning and risk assessment. The failure of zonation schemes to account for inter-annual variability was noted by Parry and Carter (1988). Similarly, Hutchinson *et al*. (1992) acknowledged that their classification system using pattern analysis based on long-term mean monthly data could be misleading as locations with similar plant growth response patterns based on long-term mean data can have very different probabilities of cropping success.

This static view of climate was not only held by agriculture. Until relatively recently, meteorological services around the world viewed climate as average weather or 'meteorological book-keeping'. McGregor (2006) maintained that a system's view of the earth's climate, backed up by more ready access to computing power, enabled climate to develop as a scientific study of the dynamics of water and energy fluxes and, in doing so, shift away from classification and regional descriptions of weather. Viewing the climate as a system acts to reverse the idea of climate as 'average weather' and sees weather as a sampling process of the envelope provided by climate (McGregor 2006).

Parry and Carter's (1988) critique of agro-climate zonation systems was deeper than the fact that they ignored variability. They were also critical of the many climate impact studies that dominated the literature until the mid-1970s that treated agriculture as a passive exposure unit. They called for a systems approach, which emphasised the ability of agriculture to interact with, and adapt to, a variable climate. In Australia the early discussion on variability and its management was focussed on drought. Perhaps as an overstatement, Anderson (1979) despaired that *"...the majority of Australian farmers seem to subscribe to the view that rainfall variability, in particular rainfall deficiency, is merely an unfortunate occasional abnormality of the environment; and that, when drought does occur, government assistance will aid survival".* There are some that still hold that view.

The 1990s National Drought Policy entailed a major re-evaluation of how Australians perceive climate variability and the respective roles of farmers, governments and providers of RD&E in dealing with climate variability. In essence, government shed the responsibility for managing climate variability and handed it to farmers who were expected to be more self-reliant. Government funded providers of RD&E assisted the exchange of responsibility by improving farmers' risk management through better access to historical climate data, climate forecasting, and the development of decision tools (Kerrin and Botterill 2006). The transfer of risk from government to farmers has been patchy and generated ongoing arguments (Hughes *et al*. 2017). Meinke *et al*. (2019) provide a succinct review of the Australian experience of managing drought, including some of the key risk management tools such as seasonal climate forecasts and agricultural simulation models. They also provide an historical context on how policies have evolved and were developed that shaped the self-reliance of Australian rural businesses.

Managing climate variability

Notwithstanding the complex history of drought policy, Australian agriculture prides itself on an ability to deal with the variable climate. European farming in Australia had to cope with what must have seemed extreme variability. (London and Sydney have approximately the same annual average rainfall; the difference is the variability). As pointed out by Nicholls (1994), the settlement was greeted by an El Nino drought three years after settlement. Captain Arthur Phillip reported in 1791 that *"...so little rain has fallen that most of the runs of water in the different parts of the harbour have been dried up for several months and the run which supplies this settlement is greatly reduced. I do not think it is probable that so dry a season often occurs".* Nicholls has traced drought as a recurring theme through history. He points out that the late 1800s, in both America and Australia, was a time of rural optimism based partly on the belief that rain followed the plough. In 1881, the official yearbook attributed the run of good seasons to the settlement of the interior stating with confidence that *"...droughts are no longer the terror they used to be".*

This optimism was ill-founded. In 1888, as the centennial celebrations commenced, the worst drought yet seen in the Colonies began. Henry Lawson wrote in the Bulletin of December 1888*"...Beaten back in sad dejection/After years of weary toil/On the burning hot selection/where the drought has gorged his spoil".* In December 1888, H.C. Russell, the New South Wales Astronomer, predicted that drought would break in January 1889. This prediction was based on his observation that previous droughts broke in late summer. He was right. There were widespread floods in the early part of 1889. In his "History of Australia", Manning Clark commented on the breaking of the 1888 drought that *"...another dry year* *was over; there was to be another green year in Australia. Men were to again believe they would find profit from all their labour under the sun".* Again the optimism was short-lived. A few years later a drought commenced that did not reach the intensity of the 1888 drought – but it lasted a decade. Despite the steady reduction in the relative importance of agriculture during the 20th century, droughts continue to receive extensive media coverage. Two centuries later, in 1994, an El Niño event again led to grain imports. In 2003, following the 2002 El Niño, grain was shipped from Britain to Brisbane and in 2018 it was only biosecurity considerations that stopped grain imports (Heard 2018).

High variability makes farming difficult, but what is the impact for agronomy? Apart from the obvious point that the wellbeing of farmers and those servicing farmers are linked, climate variability presents a particular suite of challenges for agronomists. Core activities of interpreting field experiments and providing advice for farmers are tasks that would be easier, or at least significantly different, if the climate was less erratic. Making sense from field trials in a variable climate is made even more difficult by the shift over recent decades away from longer term experiments at research stations toward various forms of short term, on-farm research. Although there are many advantages in developing relevant science with end users, one of the trade-offs that has not received as much discussion has been between a higher degree of spatial representation and a lower degree of temporal representation. The difficulty of separating out signal from noise in a variable climate is well documented in agricultural science in Australia. Some examples are as follows:

- Wockner and Freebairn (1991) measured runoff and erosion for 14 years (1976-1990) on the eastern Darling Downs. They found that 70% of the 556 t/ha of soil loss from a bare fallow wheat-system occurred in only six storms.
- Clewett *et al*. (1995) used the simulation model GRASSMAN to show decadal shifts in optimum stocking rates in central Queensland ranging from 10 to 30 head of cattle per 100 ha, concluding that such variation made learning from graziers' own, or even their parents' experience, problematic.
- McCaskill and Blair (1988) noted the bias of the 1950s, 60s and 70s in experimental work, extension programs and data for models on superphosphate and stocking rates in the northern tablelands of NSW. Across most of eastern Australia this was a wetter period. They recommended the climatic conditions prevalent between 1900 and 1949 should be taken into account when assessing management options.
- Chapman (2007) used crop simulation modelling combined with long-term rainfall records to index the climatic environment at a particular location. This allowed the construction of datasets that adequately quantify gene by trait by environment interaction in terms of their key statistical attributes (*e.g.* means, variances and correlations). This approach reduced the 'biological and experimental noise' and allowed for cultivar selection based on an assessment of the upcoming season. It also adds value to traditional plant breeding trials by reducing the environmental noise previously regarded as an inevitable consequence of location-based trials.
- Hochman *et al*. (2017) analysed trends between 1990 and 2015 at 50 sites across the Australian grains belt in: rainfall decline, maximum temperature (0.04 degrees/year) and water limited simulated yield. As noted by other authors (Hunt and Kirkegaard 2010, Fischer *et al*. 2014) this decline can be explained by the Millennium Drought (2002-2009). This last study raises important questions about disentangling drought from drying or drought from an increase in aridity.

Forecasting the climate

Cornish and Pratley (1987, p420) referred to wind erosion from the 1982-3 drought followed by water erosion in 1984. Like almost all agricultural scientists at the time, they made no reference to the fact that 1982 was a strong El Nino and 1984 a La Nina. The three decades being considered by this chapter have seen a growing understanding within the agricultural community that droughts and floods are not just random but influenced by climate drivers such as El Nino and Southern Oscillation (Meinke and Stone 2005, Risbey *et al.* 2006). Subsequent studies have shown that most of the major land degradation events in eastern Australia can be attributed to ENSO cycles (McKeon *et al.* 2004).

Official seasonal climate forecasts, based largely on the ENSO cycle were first available to Australian farmers in the late 1980s. This was a long wait; Charles Todd, a contemporary of Goyder in the colony of South Australia observed in 1893 *"...the importance to the farmer, the horticulturalist, and pastoralist of knowing beforehand the probabilities of dry or wet seasons, and whether the rains will be early or late, or both, has naturally led to a desire for seasonal forecasts, they have them it is said in India, why not Australia."* About a century later the eminent agronomist Reg French (1987) urged the study of the variability of weather patterns *"...One of the biggest deficiencies in agricultural research is the inability to both predict the probability of rainfall during the growing season and to estimate the yield and economic returns of different crops".*

Climate varies on all timescales and at each timescale the variability can be partitioned into:

- a predictable portion;
- a portion that is likely to be predictable in the near future; and
- a residual, irreducible uncertainty.

Up until 2013, seasonal outlooks in Australia were based on statistical relationships between sea surface temperatures or the southern oscillation index. Since 2013 the Bureau of Meteorology has used dynamic models which are similar to numeric weather models but run at a coarser spatial scale with a daily rather than hourly time step. Another important distinction from statistical models is that dynamic models include adjustments to the radiative properties of the atmosphere from the enhanced greenhouse effect (Baume *et al*. 2015).

Climate change

In 1987, the same year that *Tillage* was published, the Greenhouse 87 conference was held. The first set of climate change projections for Australia were released (high confidence in warming, lower confidence in rainfall, but concerns about winter rainfall in southern part of the continent). Since that time projections have been released by CSIRO in 1990, 1991, 1992, 1996 and 2001, 2007 and 2015 (Whetton *et al*. 2016). Attention to climate change was limited until the Millennium drought 2002-2009 ending with extensive bushfires in February 2009. This coincided with international and national debate on human induced climate change (Hansen 2010).

Current projections for Australia are available at the Climate Change in Australia website (www.climatechangeinaustralia.gov.au/en/). The Australian Climate Futures web tool sorts the projections for a region from all available climate models by two variables; annual mean temperature and rainfall. This provides a matrix of climate futures such as 'warmer and wetter' or 'hotter and much drier' and the number of models in different futures. The user can change the representative emission pathway and time period to see how this changes. It is envisaged that future emission runs will be able to repopulate the matrix. This allows adaptation planning to proceed with different climate futures rather than always waiting for the publication of the next set of climate model runs (CSIRO and BoM 2015).

There is a higher level of confidence from climate science in the trends and projections in temperature than rainfall. Table 1 lists six aspects of climate change and summarises the confidence from climate science in the projections and the confidence in agricultural science on the impacts. For example the confidence in the rainfall projections is low but the impacts on agricultural systems of any changes to rainfall are well understood. The interaction between these 6 aspects of climate change is important but uncertain. For example elevated carbon dioxide is likely to partially offset some of the impacts of a decline in rainfall, but it is less clear how a drier but carbon dioxide enriched future will respond to a heat wave.

Table 1. Six aspects of climate change showing; confidence in trends and projections from climate science, confidence from agricultural science on impacts and a summary of management options.

1. Elevated levels of carbon dioxide	
Confidence from climate science	**Very High** for next 10 years; future emissions depend on policy and technology.
Confidence on impacts from agric science	**High** for growth and yield of crops but **lower** for longer term cropping systems (soil C and N) and grain quality components *e.g.* protein and its various end use requirements. The growth rate of weeds, pests and disease will also change with elevated CO_2.
Management options	In the future there is likely to be deliberate selection of species (C3 vs C4) and varieties that respond more positively to elevated CO_2. Monitoring of changes to pests, weeds and disease and revising nutrition will be essential.
2. Increased mean temperature	
Confidence from climate science	**Very high** Inland regions are expected to warm faster than coastal regions due to less water and hence an increase in sensible heat. The greatest trends in warming across most of the grains belt have been in spring, this may be due to the decrease in spring rainfall associated with the Millennium drought (2002-2009).
Confidence on Impacts from agricultural science	**High** confidence that rate of crop development will increase. Growth rates will increase in cooler months and regions (*e.g.* winter in Tasmania). Increased evaporation and more challenging conditions for emergence.
Management options	Understanding of crop phenology can be used to grow slower maturing varieties. Opportunities for expansion of irrigated summer crops *e.g.* cotton. Stubble retention to reduce evaporation. Long coleoptile wheat varieties.
3. Increased extreme hot temperatures	
Confidence from climate science	**High** confidence that in a warmer world the weather patterns that bring heat to the grains belt will result in more intense heat waves. Lower confidence in how the weather patterns that set up the hot spells will change.
Confidence on Impacts from agricultural science	**Moderate** understanding of the impact of heat on different phenological stages and thresholds for different field. Impacts are modified by soil moisture and or irrigation. Relatively poorly represented in simulation models despite recent advances.
Management options	Optimising flowering time for winter crops. Selecting crops and varieties that can tolerate high heat loads through genetic selection.
4. Changes to frost frequency and intensity	
Confidence from climate science	**Low –** a perceived paradox that, despite warming, the frequency and intensity of frost has increased in some regions. This may be simply due to dry springs or other drivers related to synoptic patterns.
Confidence on impact from agric science	**Moderate to low –** although impact of extreme frost at critical times can be obvious, the exact link between minimum temperature recorded in the Stevenson screen and damage to crops is noisy. Frost damage is poorly represented in simulation models.
Management options	Using the variation between winter crops minor variation in wheat varieties. The use of hay production and switching to livestock in
5. Changes in seasonal rainfall	
Confidence from climate science	**Moderate** confidence in drying in southern winter growing season. **Lower** confidence for other seasons and the rest of the Australian grains belt.
Confidence on impacts from agricultural science	**Very high** – there are extensive studies that provide a good basis for understanding water productivity of major crops and pasture.
Management options	More effective storage of water prior to the growing season, then using the water efficiently by matching sowing time and cultivar to the environment. The impact of dry autumns can be partially offset by sowing part of the cropping program into dry soil.
6. ***Changes in the intensity of rainfall***	
Confidence from climate science	**High** – a warmer atmosphere contains more energy and will hold more water. This leads to intensification of the hydrological cycle, increasing variability further. Lower confidence in changes to weather systems that bring high or low intensity of rainfall.
Confidence on impacts	**High** for changes to daily intensity. In regions of numerous low intensity falls, an increase in intensity will improve efficiency of soil water gains. Most contemporary simulation models are not set up to handle sub-daily changes in intensity
Management options	Stubble retention and other erosion management especially on sloping sites.

Perhaps the clearest indication that agronomists are working in the Anthropocene is the need to consider the change in carbon dioxide concentration. The effects of elevated CO_2 depend on the interactions between all other climate variables (*e.g.* temperature, humidity, rainfall, solar radiation). New experimental work at Horsham since 2007 ('Free-Air Carbon dioxide Enrichment', FACE) has shown positive and negative effects of elevated atmospheric CO_2 concentrations on field crops (wheat, field pea, lentil, canola and barley). In these experiments the ambient CO_2 concentrations was elevated from approximately present-day levels of 400 µmol/mol to 550 µmol/mol, the level expected by 2050 (Figure 1, Mollah *et al*. 2009).

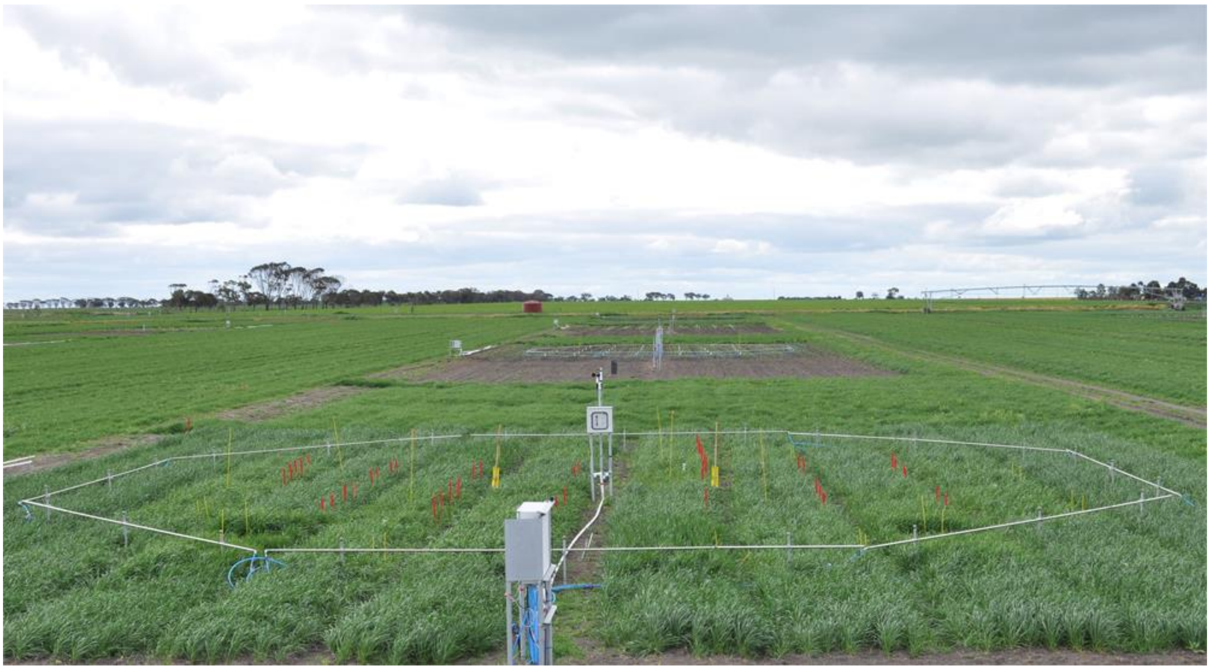

Figure 1. Ambient CO_2 concentrations was elevated in the field from approximately present-day levels of 400 µmol/mol to 550 µmol/mol by 'Free-Air Carbon dioxide Enrichment' (FACE) technology in octagonal rings where CO_2 gas was emitted upwind and computer controlled by atmospheric and wind sensors (Mollah *et al*. 2009, photo courtesy of Rob Norton)

On the positive side, crop biomass, leaf area and yield of many winter crops (wheat, canola, field pea and lentil) all increased about 10-25% from elevated CO_2. Seasonal water use was not greatly affected – crops are nearly always short of water at Horsham resulting in greater water use efficiency. Surprisingly, the quality (protein and baking parameters) of wheat grain was uncontrollably reduced (~6%) by elevated CO_2. More fertiliser does not help and we need more research to find adapted germplasm and management to maintain and increase quality parameters (Fernando *et al*. 2014, Panozzo *et al*. 2014, Walker *et al*. 2017).

The Horsham FACE experiment, however, does not reflect the nominal climate in 2050 because it did not raise the temperature or apply drought in line with 2050 climate projections. It did however, sow some crops late in the first 3 years of the experiments to emulate a hotter environment during maturity. This provided some explanatory account of the interacting effects of elevated CO_2 but not entirely with some large unexplained responses under unstressed conditions (O'Leary *et al*. 2015, Fitzgerald *et al*. 2016). Models that account for known effects of CO_2, temperature and water supplies show more subdued response to elevated CO_2 nationally, but there is optimism that adaptation towards more thermally tolerant crops that do not greatly accelerate development with heating will reduce the potential negative impacts that threaten yields, particularly in southern Australia (Figure 2, Wang *et al*. 2018).

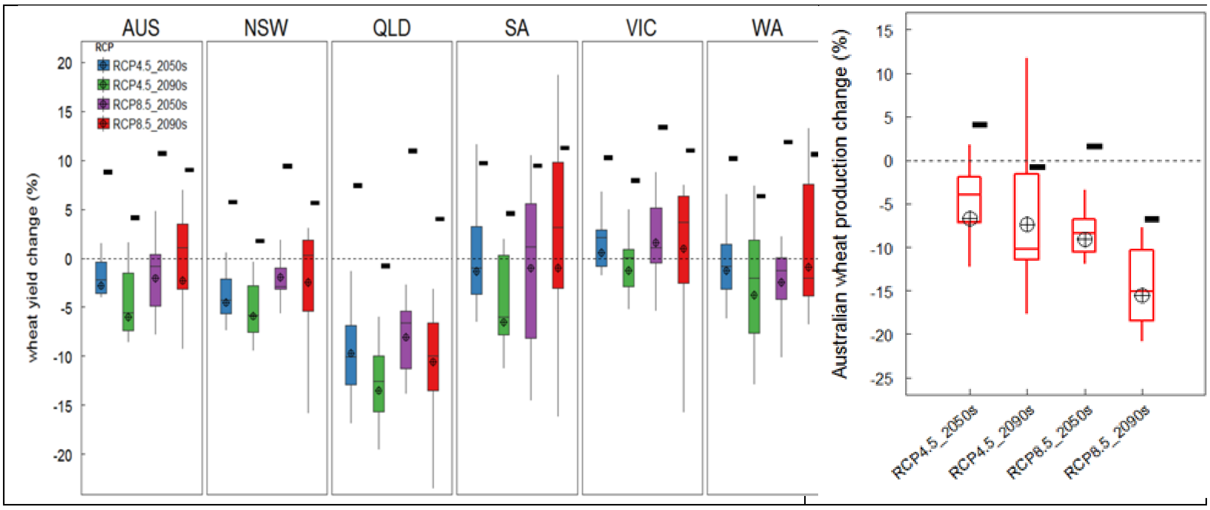

Figure 2. Simulated expected change in wheat yield under various RCP climate change scenarios for each Australian State from Wang *et al*. (2018). An adaptive strategy of increasing heat tolerance without accelerating phenological development raises optimism for increased mean yields for most production regions (black rectangle, -)

As the climate changes, pests and disease can be expected to change in our agroecosystems. In the Horsham FACE experiment barley yellow dwarf virus was increased (over 10%) by elevated temperature (Nancarrow *et al*. 2014) and elevated CO_2 (Trębicki *et al*. 2015). This was brought about by changes in the aphid vector, the bird-cherry oat aphid (*Rhopalosiphum padi*).

The dominating control of climate and weather of our agricultural systems requires more than the classic systems approach – it can be done with a collaborative multi-disciplinary approach "*…provided everybody and every organization support a stronger scientific approach by collaboration beyond our traditional partners and borders*" (O'Leary *et al*. 2018). This is a challenge for the future generations to adapt to a new environment. We know more than earlier generations, so we should put that know-how to good work for everyone's benefit. Agronomists have the advantage of systems knowledge and will play a key role in such integrated approaches to solve the almost intractable problem.

The role of the agronomist to assess and manage climate risk

Managing risk is an essential part of modern agronomy. In both agronomy research and advisory work there is an increasing request to be more than just cognisant of risk, or acknowledging that things do not always go as planned. An emphasis on business management involves explicitly addressing the trade-offs between risk and reward. Climate is a major source of production risk and agronomists are in a strong position to provide context for the advances in climate science.

The concepts of assessing and managing risk are closely linked to human agency. Bernstein (1996) notes that risk comes from the Italian 'riscare', to dare, and emphasises choice, opportunity and gain as much as fate and loss. He maintained risk was one of the key revolutionary ideas that defined the boundary between modernity and the past. The future is more than a whim of the gods, and rewards and risk for different ventures can be weighed, compared and factored into decision making.

Historical climate records underpin the management of climate risk and ready access to patched data sets of daily climate data has underpinned simulation modelling (Jeffries *et al.* 2001). Recent work has increased confidence with interpolation between data points (Bracho-Mujica *et al*. 2018). Tools providing easy access to rainfall records on personal computers such as Rainman (Clewett *et al*.1995) and on mobile devices CliMate (Freebairn and McClymont 2013) have been used by agronomists in planning and to place the current season in historical context.

Initiating stakeholder engagement between agriculture and climate science is relatively easy because farmers like talking about the weather. It has proven more difficult to develop the conversation and foster links between local farmer knowledge, which is tacit, informal and context specific, and climate science, which is quantitative, formalised and often expressed as probabilities (Hayman *et al*. 2007, Bruno Soares *et al*. 2018).

Risk assessment can be defined as a quantification of uncertainty. This distinction made by Knight (1921) defines a toss of a fair coin as risk, whereas a biased coin involves uncertainty. After experimenting with the biased coin, the uncertainty could be quantified as risk. As assumptions emerge of stationarity in climate, farmers and agronomists have to reassess whether simple assumptions of the past are the best guide for the future (Quiggen 2001, Howden *et al*. 2014). Similar arguments have been mounted for water managers who based their risk modelling on stationary time series (Milly *et al*. 2008). Cook *et al*. (2015), referring to geographers, indicated *"…the Anthropocene presents a disconcerting possibility that, with humans ascending to the scale/scope of geologic forces, their knowledge base and methodologies will become obsolete or less applicable for prediction into some human shaped epoch"*.

Concluding remarks

The Anthropocene not only has implications for the human-nature divide. It also accelerates changes in the science-society divide. As agronomists working on the interface between science (agricultural and climate) and farmers, there are new challenges and opportunities. Incomplete knowledge about the future represents opportunities for wider engagement; understanding the interactions of carbon dioxide is an example (O'Leary *et al*. 2018). This fits an increasing emphasis in climate risk on participatory and more equitable approaches (Bruno Soares 2018). Meinke (2019) differentiates between forecasting the *outcome* of management interventions and *foreseeing the likelihood and severity of opportunities and consequences* that might arise from a combination of climate, soil, plant, animal and human interactions. Predicting an outcome transfers all power to the person making the prediction (usually a scientist), while foreseeing likelihoods and consequences empowers actors to choose and actively create the desirable future they envision, while avoiding undesirable outcomes. Foresighting requires all stakeholders working together, using a common tool-kit. This gives agency to the managers, enabling them to draw in tacit as well as scientific knowledge as the basis for their deliberate decisions. This builds trust and a common understanding of what the future holds.

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