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The changing roles of science in managing Australian droughts: An agricultural perspective

Mark Howden [b,*], Serena Schroeter [b], Steven Crimp [a,b], Ivan Hanigan [b,c]

[a] Commonwealth Scientific and Industrial Research Organisation (CSIRO), Ecosystem Sciences, Canberra ACT 2601, Australia
[b] Commonwealth Scientific and Industrial Research Organisation (CSIRO), Climate Adaptation Flagship, 6 Clunies Ross Street, Acton ACT 2601, GPO Box 1700, Canberra ACT 2601, Australia
[c] National Centre for Epidemiology and Population Health, Research School of Population Health, Australian National University, Canberra ACT 0200, Australia

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ABSTRACT

As the driest inhabited continent with a highly variable climate, Australia has had a long and evolving history of drought management in agriculture. This paper analyses the changing roles of science in the management of climate risk and uncertainty and how this may continue into the future. Initially science had a role in documenting the underlying nature of Australia's climate, and later broadening the understanding around the drivers of variability so as to provide useful climate forecasts and developing metrics to measure and compare the severity of extreme climatic events. Over time this has shifted to providing effective integrating approaches to enhance social cohesion, rural economies, environmental protection, health, and food security under drought conditions. Institutional responses initially framed drought as a natural disaster, for which State and Federal funding for farmers was distributed; however, the need for farmers to proactively manage climate risk and build adaptive capacity has resulted in climate variability being seen as a risk to be managed as part of normal practise. The formulation of a national drought policy in 1992 placed responsibility for adaptation and education in the hands of the farmers, where science played various roles, including the provision of training for strategic business planning and decision-making, methods of managing uncertainty as well as via delivery of climate data and methods to integrate this into meaningful information that is embedded into the social and institutional processes through which decisions are made. This policy continues to evolve and science inputs will evolve with this. In particular, we anticipate that ongoing and projected climate changes will impact on drought frequency and severity and will require science integrated with stakeholder input into developing climate adaptation practices and technologies and effective adoption paths particularly to deal with climate extremes. A key need will be science that enhances processes of engagement between science, institutions and the agricultural community and is increasingly self-reflective and self-critical.

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1. A brief history

From the first years of Australia's European colonisation, drought has been an ongoing critical issue (Tench, 1793). This was not uniquely a European experience but one shown to be a part of Aboriginal community life well before this time (Flood, 2004; Berndt, 1964; McGowan et al., 2012). The early European settlers had a little experience with climate as variable as that in Australia (Tench, 1793; Henzel, 2007; Gergis et al., 2009) and so did not possess the plant varieties, farm management, infrastructure or institutional arrangements to deal with it. Nor did they have the climate records or climatological understanding to allow assessment of the frequency and severity of droughts or to forecast them. In one extract, Tench indicated: "*My other remarks on the climate will be short; it is changeable beyond any other I ever heard of; but no phenomena, sufficiently accurate to reckon upon, are found to indicate the approach of alteration*" (Tench, 1793).

Because of the initial dependence of Australia's economy and community on rural industries, and the continued dominance of this land use to now, the impact of climatic variability on Australian agriculture as well as on the broader culture and society has been well documented across time (MacKellar, 1908; Bean, 1910; Heathcote, 1965, 1973). Drought has been a particular focus due to its effects on economic and social values and the negative and long-lasting impacts on the natural resource base (McKeon et al., 2004). Significant droughts include the long-term intense

* Corresponding author. Tel.: +61 2 6246 4118; fax: +61 429 026 050.
E-mail addresses: mark.howden@csiro.au, smhowden@gmail.com (M. Howden).

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droughts: the 1895–1902 Federation Drought, the 1937–1945 World War II Drought, and the 2001–2009 Millenium Drought (Verdon-Kidd and Kiem, 2009) as well as shorter and/or less intense droughts, including the intense 1982–1983 drought over most of central and eastern Australia and the 1991–1995 drought in north-eastern and central Australia (BoM, 2013; DAFF, 2011).

The development of effective climate records and analysis over the century following colonisation by early climatologists such as Jevons (1858) and Russell and Krefft (1877) started to provide the basis for climate risk management which has progressed to the current time (Gergis, 2008, 2009; Gergis et al., 2009, 2010a, 2010b). Insightful analysis by climate applications pioneers such as George Goyder started to integrate this emerging climate information with soil and vegetation characteristics to assess agricultural production risk and landuse capability in response to the severe drought of 1864–1865 in South Australia (Meinig, 1962). Understanding of the drivers of Australian climate variability started with Charles Todd in the 1880s who related the co-occurrence of high atmospheric pressures over India and Australia to droughts in both countries. Sir Gilbert Walker in the early part of the twentieth century described the oscillation of atmospheric pressure between the Pacific and Indian Oceans and the linkage of this to rainfall in many regions; crucial to our modern understanding of the ENSO system which is the key driver of inter-annual climate variability across Australia (Gibbs and Maher, 1967). The state of the ENSO system (i.e. in El Niño years) considerably alters the probabilities of droughts, particularly over eastern Australia but it is important to note that not all El Niño years are droughts nor do all droughts occur in El Niño years (McKeon et al., 2009).

This understanding has expanded to climate drivers in other regions including the Indian and Southern Oceans (Ummenhofer et al., 2009) and across different timescales (e.g. the Pacific Decadal Oscillation: Mantua et al. (1997); Mantua and Hare (2002)). Inclusion of these various drivers allows (within the limits of the various historical records and spatially sparse palaeo-climate records) characterisations of climate risk. In some cases seasonal forecasts are possible depending on the states of these drivers. These analyses demonstrate that Australian rainfall variability is the product of a complex web of global regional and local teleconnections with interactions between these teleconnections shifting the dominance of any individual driver on Australian variability (Folland et al., 1998, 2002; Crimp and Day, 2003; Robertson et al., 2006).

In turn this information can be used to vary agricultural management to try to reduce risk or realise opportunities (Clewett et al., 1991; Nicholls, 1991; Meinke and Stone, 2005; Stone et al., 2003). For example, seasonal climate forecasts are reported to be used by up to 50% of agricultural producers across Australia (Keogh et al., 2004, 2005). Somewhat ironically, just at the point where this climate understanding has become adequate to inform agricultural drought-management decisions, anthropogenic climate change now may alter the probability distributions of droughts, the drivers of these and the interactions between the various drivers (Solomon et al., 2011, IPCC, 2014) and in this way undermining both statistical and dynamic climate forecast accuracies. Crucially, climate change appears likely to not only increase the frequency of exceptional droughts and floods (Hennessy et al., 2008; Cai et al., 2014), but also the intensity of these events as temperatures continue to rise (Nicholls, 2004) thereby challenging the capacity of both policy and management to cope. These potential changes will require Australian primary industries to respond both strategically and opportunistically in order to maintain current levels of production (Stokes and Howden, 2010). This will in turn require ongoing development of the underpinning climate science in a way that integrates seasonal, decadal and multi-decadal climate information with improved biophysical, social and economic systems analyses (Howden et al., 2013) as well as improved approaches for communicating this information across a broad section of the community.

In this paper we aim to learn from past experience to address some of the ways in which changing science contributions can enhance outcomes for the Australian agricultural sector in the face of this changing situation following a brief summary of evidence as to why drought is so significant in Australia.

2. The impact of drought on Australian agriculture

Drought is a socially-constructed concept and due to the large range of perspectives across society, definitions of drought abound; they range from simple rainfall deficiency-based approaches to the more recent sophisticated integrations of climatological, biological, hydrological, economic and social factors such as used in the past declarations of Drought Exceptional Circumstances under the National Drought Policy. The start and end of droughts and their spatial extent are particularly problematic to define (Stafford Smith and McKeon, 1998, Botterill and Hayes, 2012). For the purposes of this chapter we take an integrative perspective on drought that includes all the factors highlighted above.

Drought impacts on Australian agriculture in many ways. It reduces production in various agricultural sectors to well below levels experienced in non-drought years; as an example, Fig. 1 depicts production impacts of low rainfall during the winter cereal-growing season. Since 1973, in all but one of the eight years where growing season rainfall was at or below the 20th percentile, wheat production has been at or significantly below median levels. The outlier year of 2012 serves to demonstrate the importance of sub-soil moisture, accumulated from two prior years of 92nd and 60th percentile rainfall amounts (see also Fig. 2). The effects of extended drought are particularly significant where irrigation is practised as decreased water allocations reduces the production of irrigated crops such as rice and cereals which in turn increases prices, creates tension between different water users, and results in major and costly infrastructure such as desalination plants or new water distribution systems.

Agricultural production impacts from drought can encompass both a reduction in the farm's cash income and an increase in debt from investment for future climate variability. For example, during the major drought of 1997–2009, the particularly dry period from 2002 to 2003 caused both the grain industry and the beef industry

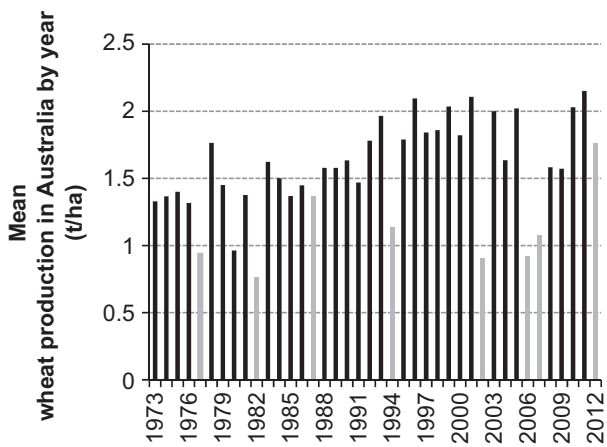

Fig. 1. Wheat production in Australia by year (grey years depicting years at or below the 20th percentile rainfall; black years depicting above the 20th percentile rainfall). Data sourced from Bureau of Meteorology and ABARE.

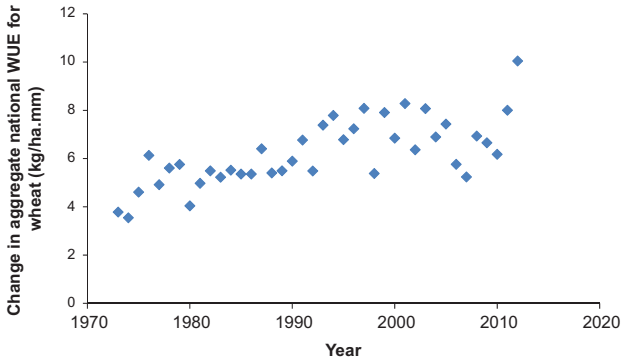

Fig. 2. Change in aggregate national WUE for wheat (kg/ha mm) over time for the Australian wheat industry, using data from Fig. 1 (note that the area over which rainfall is averaged is not the same as that of the cropped area – the figure is thus intended to be indicative only).

incomes to drop by up to 40% compared to the previous financial year and contributed to a reduction in GDP of about 1% (ABARE, 2004). The dairy industry recorded the greatest loss of income in the 27 years that the statistics have been recorded, falling from $11,2800 in 2001–2002 to approximately $3,1080 in 2002–2003. As this necessitated increased borrowing for working capital, and increased investment in additional land, farm business debt also increased – a trend that continued to the next financial year (ABARE, 2005). Previous major droughts have seen income reductions of even greater proportions. Long-term investment losses of drought include removal of permanent plantations, orchards and vineyards (Ejaz Qureshi et al., 2013).

Rural economies and communities are also impacted by drought. Statistical analysis in rural communities has shown that up to one-third of the economies of small towns is directly fuelled by farm expenditure (DAFF, 2008). Drought impacts on these small towns in many ways; for example, loss of employment causing worker relocation and reduced income potential for local businesses, reducing populations (especially young people) with subsequent reduced social networks, community activities, volunteering and community engagement. This builds isolation of remaining rural families, leading to increased stress and the breakdown of familial relationships. Social and psychological impacts often follow; for example, drought stress is associated with increasing suicide rates of middle-aged males in farming communities (Hanigan et al., 2012) and in other cases can increase costs of counselling, health treatment and other social costs (Logar and van den Bergh, 2013).

Drought has significant impacts on soil and vegetation, with some of these impacts being effectively irreversible over the time-horizons usually used in agricultural management decisions (McKeon et al., 2004). Amongst many other issues, drought reduces vegetation and litter cover of the soil, exposing it to subsequent wind and water erosion which impact both on-site and off-site including through dust storms (Webb et al., 2009). One of the increasingly important aspects of this is the potential loss of soil carbon and biomass carbon via droughts which may impact on the ability of landowners to claim either voluntary or market-based carbon credits. One of the key causes of loss of above ground carbon is fire; and fire hazard is increased through drought periods, with drying of fuel and increased incidence of high temperatures and low humidity. Fires can also impact on agriculture through loss of stock and crops, infrastructure, feed and occasionally human life.

The environmental costs of drought encompass damage to wildlife and fish habitat, animal disease, loss of biodiversity, loss of wetlands, deteriorated water and air quality, reduced quality or loss of recreational sites, and aesthetic impacts (Hammer et al., 2000). Health costs primarily arise from an increased risk of diseases, stress-related conditions and malnutrition related to loss of income.

These widespread and pervasive impacts of drought and climate variability could be argued to have been imprinted on our national psyche and give rise to how we see ourselves as a nation: *a sunburnt country, a land … of droughts and flooding rains* (Dorothea Mackellar: 1885–1967).

3. Farmer and institutional responses

Unsurprisingly, given the scale of the above impacts, the Australian agricultural community has become increasingly adept at managing climate variability and at using effectively climate-limited resources such as water. For example, water use efficiency of irrigated cotton cropping has improved by 40% over the last 10 years through water-management systems and as a result the yield increases (Hunt and Kirkegaard, 2011). In addition, studies by Hochman et al. (2009a) as well as Hunt and Kirkegaard (2011), for many sites across Australia, have shown similar proportional improvements by elite wheat farmers with on-farm yields increasing to be, on average, 77% of potential yield (which is estimated based on WUE of 21.4 kg grain/ha mm). At an aggregated level this results in much greater crop production per unit growing season rainfall, termed water use efficiency (WUE) which has risen markedly over the past decades (Fig. 2). These improvements have arisen from productive interaction between farmers and the research community developing and testing often farmer-led climate-risk management innovations such as minimum tillage, canopy management, dry sowing, drought-tolerant varieties and breeds, climate sensitive stocking rate adjustment amongst many others (Stokes and Howden, 2010). There has also recently been expansion of cropping into the previously higher rainfall zones (Nidumolu et al., 2012) and this can also partly explain the increases in WUE in Fig. 2.

A range of institutions have emerged to provide science to support effective climate risk management in agriculture, including the Bureau of Meteorology, CSIRO, State Government agencies such as the Queensland Climate Centre of Excellence, Catchment Management Authorities and their equivalents, farmer groups such as the Birchip Cropping Group and Landcare groups amongst others (Hammer and Nicholls, 1996; Hastings, 1993; Meinke and Hochman, 2000; Nicholls, 2000). Similarly, a large number of policy responses have been explored and implemented, particularly over the past four decades (Fig. 3). Prior to the 1960s national drought policies appear to have been reactive and fragmentary, due to drought predominantly being seen as a State issue (see Botterill, 2003 for a more complete history). The 1960s saw matching Commonwealth and State funding for drought in some situations. The first national approach was the Natural Disaster Relief Arrangements (NDRA) from 1971 which framed drought as a natural disaster. A watershed change in policy occurred in 1989 with the removal of drought from the NDRA due to a growing

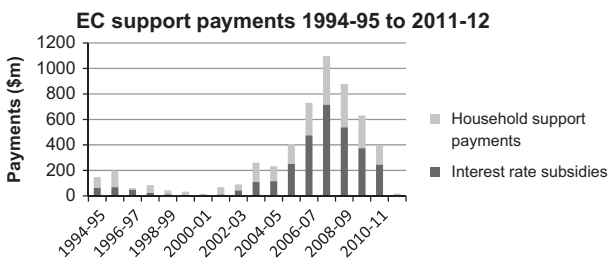

Fig. 3. Exception Circumstances (EC) payments from 1994–1995 to 2011–2012 (data from 1994–2009 [inclusive] from Productivity Commission (2009); data from 2010–2012 provided by Australian Government Department of Agriculture).

recognition that it was poorly targeted, distorted farm input prices and worked as a disincentive for farmers to prepare for drought (Keogh et al., 2011). Following an extensive national review that included broadly-based science inputs, the National Drought Policy was announced in 1992 which framed climate variability as an expected part of the environment and a risk to be managed as per normal business practice. It had objectives of:

- encouraging primary producers and other sections of rural Australia to adopt self-reliant approaches to manage for climate variability;
- facilitating the maintenance and protection of Australia's agricultural and environmental resources base during periods of climatic stress;
- facilitating the early recovery of agricultural and rural industries, consistent with long term sustainable levels.

Under each of the objectives, there is an underlying rationale for contributions by science: provision of the knowledge needed to explore and implement effective farm businesses, understanding of the interaction of climate factors and management on the condition of soil and vegetation resources and identifying boundaries of what may be considered sustainable systems. The initial programs under this policy included the Rural Adjustment Scheme (consisting of grants and interest rate subsidies) and the Drought Relief Payment (income support for farmers within drought-declared areas). In 1997, these were replaced by various programs based on 'Exceptional Circumstances' (EC). For an area to be declared subject to an EC event, the criteria included that the event be rare, severe (i.e. at least a 1-in-20 event), widespread, result in a rare and severe downturn in farm income over a prolonged period of time (that is, greater than 12 months) and not be predictable or part of a process of structural adjustment. Again, there is a clear rationale for science input into the drought declaration and revocation processes including both retrospective and prospective analyses of climate, soil moisture, feed availability, crop yield and farm economics (Stafford Smith and McKeon, 1998). A focus by the science assessment bodies on increasing precision of analysis and the inclusion of multiple factors for declaration resulted in increasing resource demands for the analysis and presentation of data on which drought assessments were made. There was also input from social science via the Rural Financial Counselling Service program. As can be seen in Fig. 3, the EC program provided some $4.5 billion of assistance during the 'Millenium Drought' that occurred from 2001 to 2009 (Fig. 4): the worst recorded drought in Australian history by some metrics (Verdon-Kidd and Kiem, 2009).

The perceived changing nature of droughts in Australia resulted in Commonwealth-State Ministers agreeing in 2008 that the EC arrangements were no longer appropriate in the context of a changing climate and that alterations to drought policy were needed to ensure farmers increasingly prepare for seasonal and climatic variability and change (Keogh et al., 2011). Crucial science inputs into this included: 1) assessment that there is a projected increased risk of severe drought over the next 20–30 years due to reduced rainfall and increase potential evaporation, 2) the current definition of 'Exceptional Circumstances' based on the historical climate record being out of date due to changes in the underlying probability distributions of drought and, 3) that farmers needed progressively updated information to be able to change their climate risk management in an ongoing way (Hennessy et al., 2008). This need for change was supported by economic analysis that indicated that some of the EC programs (interest rate and fodder and transport subsidies) were ineffective, perversely encouraged poor management practices and were inequitable. Social science input suggested re-framing the approaches from crisis-assistance to early intervention and preparation and planning for personal and family wellbeing to reduce farmer and community stress (Productivity Commission, 2009; Keogh et al., 2011).

Consequently, in 2013 a new drought policy was implemented that had the basic elements of a farm household support payment, taxation measures including enhancements to the Farm Management Deposits Scheme, a national approach to farm business training and a coordinated, collaborative approach to the provision of social support services and tools and technologies to inform farmer decision-making in a variable and changing climate. Science has potential roles in terms of input into the training, climate information provision and tools, effective social and biophysical monitoring systems and enabling risk management technologies.

This brief history of changes in drought policy demonstrates an evolution of approaches to deal with drought in Australia which

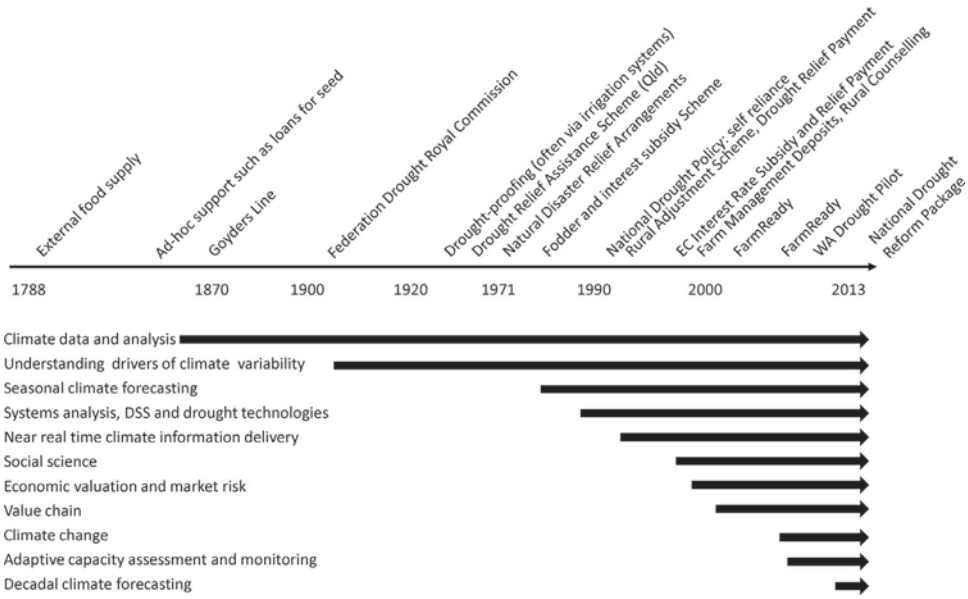

Fig. 4. The evolution of science input to dealing with drought in Australia.

progressively involve different types of science (Fig. 4). Broadly this has changed from science with a focus on climate inputs to a focus on people and outcomes, from a physical science activity to integration of biophysical science with economics and social science, from a focus on resource-demanding classification of drought that reactively triggers inappropriate support mechanisms to science-based approaches that build adaptive capacity and proactively manage risk. In the following part of this paper we outline our perspectives of the developing science needs over the next decades.

4. Climate data, analysis and delivery

High quality and continuing collection, maintenance, distribution and analysis of climate data will continue to be a core activity over the next decades. This has been crucial information for climate decision-making from the time of the establishment of Goyder's line onwards, not only to frame and quantify climate risk but also to understand drivers of climate and to provide robust climate forecasts at a range of scales, regardless of whether using statistical or dynamic models. SILO is an example of an effective, demand-driven distribution system: a seamless, national database of daily climate records (Jeffrey et al., 2001) continuous from 1890 to the present, delivered in multiple formats to researchers, policy-makers and farmers including via smartphone apps. However, for many farm-level decisions, climate change is increasingly making a less robust reliance only on the risk assessment using the approximately 100-year climate record. For example, in the cropping region around Emerald, progressive and large reductions in frost incidence over a long period mean that simulations of cropping decisions using frost risk based on the entire 100-year climate record almost halved the gross margin when compared with a cropping strategy that used frost risk based only on the previous decade of experience (Howden et al., 2003). This is because the 100-year frost risk strategy understates risk in the early part of the climate record resulting in high levels of crop damage whilst overstating the risk in the latter part of the record, resulting in underperformance in production. Hence, a flexible strategy using shorter climate data 'windows' as the climate changes resulted in a more productive, profitable and less risky system than using the whole 100 years of record. The situation in south-eastern Australia is different, with increases in frost risk over the past decades, requiring more risk averse but flexible strategies: not the 100-year frost risk (Crimp et al., 2013). Similarly, the existing and prospective uncertain increases in drought as a function of climate change (Hennessy et al., 2008) resulted in recognition that the probability-based component of EC assessment (a 1-in-20 year event) was no longer a robust operational criterion, contributing to the finalisation of the EC system. The policy that replaced it was re-framed to avoid the same climate-probability-based definitional constraints. These examples make for some interesting considerations in relation to the value of the investment in converting old paper-based climate records to more accessible computer-based data such as occurred in the CLIMARC project.

Clearly, it is not enough to just collect climate data as the value embedded in this is realised only when this data is analysed, converted into agriculturally-meaningful metrics such as probabilities of pasture or crop yield or livestock performance (White et al., 1998; McKeon et al., 2004), indicators of bio-economic performance (Kokic et al., 2007; Nelson et al., 2005) or risks of degradation (Carter et al., 2000) and then delivered to decision-makers in appropriate formats in a timely manner. These steps require the integration of biophysical, economic and social sciences: the latter particularly important in developing appropriate user-engagement strategies that link closely the users and producers of climate information so as to address the correct time and spatial scales and climate variables and embed this information into the social and institutional processes through which decisions are made (Howden et al., 2013). Most of this capability was developed during the 1980s and 1990s although the industry and policy support for this had been intermittent.

5. Understanding drivers of climate variability over different timescales

Enhancing the understanding of the various drivers of climate variability will continue to be an important element of improving climate risk management. It is important to reflect that it is only 25 years ago that reliable weather prediction was available only for 2–3 days ahead and seasonal climate forecasts were treated with scepticism due to a lack of broad understanding of the basic processes such as the El Niño Southern Oscillation (ENSO) system. Now there is a broad understanding in the agricultural industries of how Australia's highly variable climate is influenced by complex interactions with a number of climate phenomena including ENSO, the Indian Ocean Dipole (IOD), the Southern Annular Mode (SAM), the quasi-biennial oscillation (QBO) and Inter-decadal Pacific Oscillation (IPO) (White et al., 2003; Verdon-Kidd and Kiem, 2009). These climate drivers interact with natural changes in the environment such as variations in solar radiation and geological events such as volcanic eruptions, as well as anthropogenic forcing due to greenhouse gas accumulation, chemical and aerosol use, and ozone depletion (McKeon et al., 2009). The interaction of these climate variables causes a number of recurring extreme climate events such as flood, storms, and drought as well as graduated shifts in mean conditions (CSIRO and BoM, 2007). Nevertheless, the enhanced understanding of the drivers has not necessarily translated to marked improvements in forecast ability or utility with predictive skill of recent models being only slightly improved over that available in the first generation of seasonal climate forecast applications (Clewett et al., 1991). Stakeholders consistently report that they would like improved reliability and longer lead times in seasonal climate forecasts (Ash et al., 2007) and even if that occurs it is not a foregone conclusion that such forecasts will result in enhancement of sustainable agriculture, welfare or equity (Rickards et al., 2014).

In contrast, stakeholder feedback often reveals that the timeframes usually used for climate change analyses (i.e. the years 2050, 2070, 2100) are too long for their decision timeframes (Howden et al., 2013). Most strategic agricultural decisions have a maximum time-horizon of ten or occasionally twenty years. This is a challenge for GCMs because for key climate variables relating to drought such as rainfall, the climate change signal does not emerge from the noise until about 2040: which does not match well with the capacity of the models to deliver. Importantly, the rate of improvement in key variables to agriculture appears to be quite slow (Ramirez-Villegas et al., 2013). More importantly, there are already changes in key climate drivers such as the sub-tropical ridge, cyclones, ENSO, land-surface feedbacks and enhancement of the hydrological cycle which are not well-simulated in GCMs (Christiensen et al., 2007; Hegerl et al., 2007; Kent et al., 2011; Durack et al., 2012; Guilyardi et al., 2012) and thus contribute significantly to the uncertainty of future projections (Hallegatte, 2009; Wilby et al., 2009) with little likelihood of resolution in the near term (Hallegatte, 2008, 2009). In contrast, there are some large infrastructure decisions such as dam construction and irrigation system development that have expected lifetimes of several decades which can feasibly be informed by the existing GCM-based climate projections in tandem with other analyses.

In many cases these are public investments rather than private ones which characterise agriculture in Australia. For example, in Western Australia process-based understanding of existing rainfall reductions in concert with projections of further future change contributed to the confidence needed for large government investment decisions in relation to construction of dams and desalination plants, changes in groundwater use policy, water trading, wastewater recycling, improved catchment management processes, demand-side management and education and broad-scale water-resource management reform (Bates et al., 2008).

Consequently, the capacity to deliver robust and useful forecasts is either too short (current seasonal climate forecasts which are useful for tactical decisions) or too long (current climate change analyses) for most strategic operational decisions in agriculture and other sectors. This has started to initiate discussions as to the capacity of the science community to deliver multi-year or decadal scale climate forecasts, with attempts to do this via both statistical and dynamic approaches (White et al., 2003; Cane, 2010). We anticipate significant focus on this in years to come.

6. System analysis, decision support systems and drought technologies

To assist producers' decision making, climate information is often converted into factors of more direct interest such as yields, economic benefit or livelihood options through a climate-oriented decision support system (DSS) that systematically combines climate data with other information to assist with multi-factorial decisions of the sort agricultural producers need to make in relation to drought (Nelson et al., 2002). Many such systems have been developed for agriculture, often with high hopes and considerable effort (Hammer et al., 2000; Jakku and Thorburn, 2010; Cobon and Toombs, 2013). Although these aspirations for DSS have largely been unmet (Hayman, 2003; Matthews et al., 2008), DSS can serve as valuable boundary objects when embedded into the social and institutional processes through which decisions are made (Matthews et al., 2008; Maricle, 2011) for example by facilitating inter-personal interactions between producers, researchers and extension agents (Cash et al., 2006, 2003; Jakku and Thorburn, 2010; Duru et al., 2012; Leith, 2011; Dilling and Lemos, 2011; Moser and Dilling, 2011).

In contrast to the expectations of the researchers involved, the main value of DSS to producers for drought management may be primarily pedagogical rather than informative. For example McCown (2012) and McCown et al. (2012) found that producers in Northern Australia used the DSS as an exploratory tool to refine their management heuristics (rules-of-thumb), and then discontinued DSS use to focus on applying their new, personalised mental-models of decisions – a process found even for the very first decision support system (SIRATAC) in the 1980s (Hearn and Bange, 2002). Such an outcome highlights that producer decision making is strongly framed in terms of local knowledge and pragmatism, not necessarily detailed climate information (Rickards et al., 2014). The interaction between farmer heuristics and sophisticated simulation models can also be planned. For example, in south west Queensland rangelands, the specialised knowledge of both researchers and graziers was combined through intensive science-based engagement processes to develop a decision-support suite for grazing management scaleable from the farm (heuristics combined with coarse climate data) to policy levels (spatial simulation and probabilistic analysis: Carter et al., 2000) based on a unifying understanding of grazing system processes (Johnston et al., 2000). Nevertheless, there is a new generation of DSS emerging that is farmer-owned and designed and that delivers near-real time and highly contextual (i.e. specific decisions for specific fields) probabilistic information on outcomes of specific farming decisions. One example of this is the Yield Prophet system which is owned by the Birchip Cropping Group, commercialising the power of a sophisticated, well-validated farming systems model with a tailor-made internet interface (Hochman et al., 2009b). The current trends towards increasing climate variability and change suggest that farmers will increasingly have to adopt flexible approaches and DSS can be a core part of exploring new options without the risk of on-farm trial and error.

In addition to information systems for drought management, there is a long-term recognition of the need to have a range of other technologies. Past efforts include crop varieties with attributes such as low transpiration, stay-green, early vigour, short season cycle, deeper rooting and management options such as dry sowing, skip rows, canopy management, stubble retention, fallow moisture storage, weed control, efficient sub-soil irrigation (e.g. partial rootzone drying) amongst many others. In livestock systems these include breeding of heat resistant but productive lines, feed management and provision of shade and cooling amongst others (Lee et al., 2013; Stokes and Howden, 2010; Wasson et al., 2012; Chapman et al., 2012). Together, these types of technologies can provide farmers with options that allow them to better manage climate uncertainty through flexible implementation of 'robust' strategies that reduce stress (Wilby and Dessai, 2010). However, these approaches usually involve trade-offs in production and profit as they are not intended to 'optimise' these factors – something that requires lower levels of climate uncertainty than seem likely for Australian farming over the coming decades.

For DSS to be successful there is mounting evidence that they need to be embedded into the social and institutional processes through which decisions are made (Matthews et al., 2008; Maricle, 2011). This provides some clear challenges for current research on adapting to future climate changes and the associated expected increase in frequency and severity of droughts: neither the future adaptation community nor the social or institutional adaptation pathways exist as yet. In fact, none of the basic requirements for adoption of innovation (Rogers, 1962) are easily met: relative advantage, compatibility, simplicity, trialability and observability. We anticipate considerable focus on this topic over the next years.

7. Social science

Whilst the hardship that drought causes is implicitly recognised and provides a basis for past policy responses, it is not until the early 1990s that the social science perspectives of drought hardship and farmer and community stress started to be more explicitly assessed (Stehlik, 2005) resulting in public and policy interest concerning the relationship between drought and rural mental health, including suicide (Hanigan et al., 2012; Guiney, 2012). Similar concerns about rural suicide exist in other nations such as India (Sainath, 2013).

There are several mechanisms through which droughts may increase the suicide rate. First, droughts increase the financial stress on farmers, their families and farming communities (even if partially compensated by drought relief welfare payments). Such difficulty may occur in conjunction with other economic stresses, such as rising interest rates, falling commodity prices, or an unfavourable foreign exchange rate. This may affect the broader economic system, depress economic activity in rural towns or across whole regions, accelerating migration to metropolitan areas, weakening and stressing social support systems and lessening social interaction. In some cases, rural depopulation may pass a tipping point, leading to an ongoing loss of critical services, such as hospitals, schools and doctors. Second, there can be a substantial

psychological toll during and following environmental degradation (Speldewinde et al., 2009) and this may be acute during droughts, being linked with decisions and actions to sell or kill starving animals or to destroy orchards and vineyards, which in some cases were developed over generations. Such loss, and even the apprehension of loss, can place a burden on the mental health of farmers and their families and can extend to other sections of the community likely to be impoverished by long-term environmental degradation.

The number of studies that have examined the relationship between suicide and drought in Australia is limited but there appears to be a clear linkage. One analysis of annual suicide rates in New South Wales (NSW) found an association between suicide and year-to-year decline in annual rainfall between 1964 and 2001 (Nicholls et al., 2006). In that study a decrease of 300 mm of rain was associated with an increase in suicide rate of about 8% above the mean annual rate. A longer-term study in NSW (for the period 1901–1998), found that drought years were associated with an increased suicide risk of about 7% for men and 15% for women, across the whole population (Page et al., 2002). This in part contrasts with a more disaggregated study using 38 years of data (1970–2007) to explore potential drought effects, especially on farmers and farm workers (Hanigan et al., 2012). The drought exposures were calculated from climatic data for 11 subregions of NSW, and stratified by rural/urban region, age and gender. A strong association between drought and suicide was observed in rural males aged 10–49, with an estimation that around 9% of rural suicides in males aged 30–49 were due to drought over the entire study period. This estimate is an average over the course of the 38 years of the study, as the majority of years are not droughts – hence, the percentage is much greater than 9% in the actual drought years, since these are episodic and confined to a distinct minority of years. The statistical model used in the study also controls for other well-known trends in suicide data, including that times of unusually high maximum temperatures increased suicide risk (Qi et al., 2009), that there is an increased risk in spring and early summer, and that there has been a marked drop in suicide rates over the last decade. Surprisingly the study showed that suicide risk decreased in rural females aged over 30, raising interesting questions as to the possible causes including the effects of social networks in reducing isolation.

Social science also has a role in highlighting some of the deeper and more complex discourses about drought. For example, the 'Millenium Drought' proposals from the regional water corporation arose to build the large Tillegra Dam in the Hunter Valley to 'drought-proof' the region, including taking into account projected reductions in rainfall. However, local opposition to this proposal developed based around concerns about harmful effects involving environmental, economic and ethical perspectives, the existence of alternative, cheaper demand-side options and questions about the longer-term need for the dam even given expected climate changes (Sherval and Greenwood, 2012). The way in which different stakeholder arguments were framed and communicated appears to have influenced the outcome against the dam going ahead. This case highlights the increasingly important role that communities can play in altering institutional decision making. It also highlights how fixed attitudes, institutions and thresholds are probably maladaptive given changes in social attitudes and communication modes and climate risk profiles.

The importance of inclusion of social aspects has also been demonstrated by studies of adaptive capacity by Nelson et al. (2010a, 2010b) which show that lack of financial, social and human capital and limitations to substitutability between these are the main determinants of vulnerability to climate risk rather than natural or physical capital (e.g. infrastructure) which have often been the focus of past drought definitions and policy. Factors that reduce vulnerability include the willingness to adopt new technologies, good farmer networks and sense of rural community, sufficient off-farm income and enterprise diversification (Nelson et al., 2010a, 2010b) whilst managerial and planning ability are also important (Marshall et al., 2013). Factors that enhance vulnerability include poor succession planning, restrictive farm business size, poor equity to debt ratios and increasing cost of production and labour costs.

There also appears to be a propensity for drought stress to repeat itself through what is termed the hydro-illogical cycle (Wilhite, 1993). This suggests socially conditioned, repeating cycles of drought, followed progressively by awareness, concern, panic, rain and finally apathy which limits the instigation of learning or institutional change or other activities that can break the cycle. In a climate like that of Australia where there are both quasi-biennial and quasi-decadal climate oscillations related to drought (White et al., 2003) the hydro-illogical cycle can be reinforced as the inter-drought spells can be just long enough to erode personal, social and institutional 'memories' of the drought. We hypothesise that the repetition of major degradation episodes in Australia (McKeon et al., 2004) is a psycho-climatic phenomenon that arises when expectations of forthcoming conditions are not aligned with climate and agricultural system realities especially when economic or other external conditions create incentives for misjudging the risk-return of farm management options.

8. Value chain analysis

Research on climate risk in Australian agriculture and elsewhere has predominantly focussed on farm level decisions, productivity and profitability with very few studies addressing pre- or post-farmgate aspects (see Stathers et al., 2013 for developing country examples) except at aggregate levels. Arguably, there is a range of climate factors that can affect input supply chains such as those dealing with type and amounts of fertiliser, herbicide, insecticide, fungicide, seeds, machinery and other inputs. Similarly, there are arguably climate-related impacts on the availability, quantity and quality of farm-level outputs that can effect distribution and storage, manufacturing options, other agricultural industries (e.g. feed grain supplies for the feedlot industry) and through various feedbacks, the rural communities and the regional and broader economy. This could be a key area for new research into drought management because as well as the above relationships, many decisions at farm level are influenced by expectations of conditions in value chains both before and after the farm enterprise some of which can be expressed through decisions such as forward selling (Jackson et al., 2009). One example of more integrated value chain studies including climate forecasts is that of the Australian sugar cane industry. This industry consists of tightly linked grower and processor arrangements which aim to: 1) reduce variability in supply to the sugar mills having limited capacity which can be exceeded by cane supply during the peak of the growing season but at the same time need to operate at nearly full capacity for efficiency reasons and thus cannot afford to be under-supplied, 2) extend the sugar production season as much as possible, stretching it into sub-optimal shoulder periods for growers and 3) maintaining cane with high sugar content. Climate, and hence climate variability, has strong influences on all of these factors and inclusion of seasonal climate forecasts has been shown to help with cane production scheduling, providing benefits to growers, processors and distributors (Everingham et al., 2008).

By taking a whole-value chain approach when examining the role of climate variability and change on production risk we will be able to develop adaptive management strategies that are effective

across multiple nodes of the chain and reduce the implementation of risk management strategies that result in disruptions across the chain.

9. Conclusions

The science input into managing droughts in Australia has evolved markedly as both knowledge and policy perspectives have matured. To date this has resulted in changes from science with a focus on climate data to a focus on people, communities and outcomes, from a physical science activity to integration of biophysical science with economics and social science to deliver to specific policies. This shift in approach has resulted in a de-emphasis of classification of drought and triggers for action to one of developing science-supported approaches that build adaptive capacity and proactively manage risk. Science has also had a role in re-framing drought from a natural disaster requiring crisis management to a normal part of farm operation and the associated fundamental changes in policy that consequently follow. Further alignment of science with societal need can be achieved through expanding the unit of study to value chains rather than single enterprises, to stronger involvement of social science to better understand the increasingly complex discourses in which drought is embedded, and to designing improved engagement and delivery systems which are more inclusive of the knowledge of all stakeholders. Self-critical evaluation of success and failure of science in delivering enhanced outcomes will become increasingly important. A particular and growing challenge will arise from climate change and the uncertainties surrounding this. Climate changes will alter the frequency and intensity of drought, resulting in new and evolving risk profiles, requiring development of approaches that manage uncertainty rather than managing quantified risk. It will also require new and forward-looking investment in climate change adaptations to overcome the lack of immediate demand so that innovative ways of dealing with the changed drought regimes are available and understood when the demand arises. As managing drought in a changing climate will be a journey rather than a destination, there will be a need for ongoing revision of institutional arrangements as fixed thresholds and responses based on past situations will likely be increasingly inappropriate over time.

References

ABARE 2004, Agricultural commodity statistics 2004, Australian Bureau of Agricultural and Resource Economics, December, Canberra.

ABARE 2005, Agricultural commodity statistics 2005, Australian Bureau of Agricultural and Resource Economics, December, Canberra.

Ash, A., McIntosh, P., Cullen, B., Carberry, P., Stafford Smith, M., 2007. Constraints and opportunities in applying seasonal climate forecasts in agriculture. Crop Pasture Sci. 58 (10), 952–965.

Bates, B.C., Hope, P., Ryan, B., Smith, I., Charles, S., 2008. Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia. Clim. Chang. 89 (3–4), 339–354.

Bean, C.E.W., 1910. On the Wool Track: Pioneering days of the Wool Industry. Alston Rivers, London.

Berndt, C.H., 1964. The World of the First Australians: An Introduction to the Traditional Life of the Australian Aborigines. Ure Smith, Sydney.

BoM, 2013. 'Living with drought'. Bureau of Meteorology, Canberra. 〈www.bom.gov.au/climate/drought/livedrought.shtml〉 (accessed December 2013.).

Botterill, L.C., 2003. Uncertain climate: the recent history of drought policy in Australia. Aust. J. Polit. Hist. 49 (1), 61–74.

Botterill, L.C., Hayes, M.J., 2012. Drought triggers and declarations: science and policy considerations for drought risk management. Nat. Hazards 64 (1), 139–151.

Cai, W., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M.J., Wu, L., England, M.H., Wang, G., Guilyardi, E., Jin, F.F., 2014. Increasing frequency of extreme El Nino events due to greenhouse warming. Nat. Clim. Change 4, 111–116.

Cane, M.A., 2010. Climate science: decadal predictions in demand. Nat. Geosci. 3 (4), 231–232.

Carter, J.O., Hall, W.B., Brook, K.D., McKeon, G.M., Day, K.A., Paull, C. ., 2000. Aussie GRASS: Australian grassland and rangeland assessment by spatial simulation, Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems. Springer, Netherlands, pp. 329–349.

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jager, J., MitchellL, R.B., 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. USA 100, 8086–8091.

Cash, D.W., Borck, J.C., Patt, A.G., 2006. Countering the loading-dock approach to linking science and decision making – comparative analysis of El Nino/Southern Oscillation (ENSO) forecasting systems. Sci. Technol. Hum. Values 31, 465–494.

Chapman, S.C., Chakraborty, S., Dreccer, M.F., Howden, S.M., 2012. Plant adaptation to climate change – opportunities and priorities in breeding. Crop Pasture Sci. 63, 251–268.

Christiensen, J.H., Hewitson, B., Busuioc, A., et al., 2007. Regional climate projections. In: Solomon, S., Qin, D., Manning, M., et al. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Clewett, J.F., Howden, S.M., McKeon, G.M., Rose, C.W., 1991. Optimising farm dam irrigation in response to climatic risk. In: Muchow, R.C., Bellamy, J.A. (Eds.), Climatic Risk in Crop Production: Models and Management for the Semi-Arid Tropics and Subtropics. CAB International, Wallingford, UK, pp. 307–328.

Cobon, D.H., Toombs, N.R., 2013. Forecasting rainfall based on Southern Oscillation phases at longer lead-times in Australia. Rangel. J. 35, 373–383.

Crimp, S.J. and Day, K., 2003. Evaluation of multi-decadal variability in rainfall in Queensland using indices of El Niño-Southern Oscillation and interdecadal variability. In: Proceedings of National Drought Forum, 2003, 106 (1977).

Crimp, S., Bakar, K.S., Kokic, P., Jin, W., Nicholls, N., Howden, M., 2013. Bayesian space-time model to analyse frost risk for agriculture in South-East Australia: explaining the frost paradox. Int. J. Climatol., accepted for publication.

CSIRO and Bureau of Meteorology, 2007. Climate Change in Australia. Technical report. 〈www.climatechangeinaustralia.gov.au〉.

Department of Agriculture, Forestry and Fisheries (DAFF), 2008. Drought Policy Review Expert Social Panel . It's About People: Changing Perspective. A Report to Government by an Expert Social Panel on Dryness. Department of Agriculture, Forestry and Fisheries, Canberra.

Department of Agriculture, Forestry and Fisheries (DAFF), 2011. 'Exceptional Circumstances'. 〈www.daff.gov.au/agriculture-food/drought/ec〉 (accessed July 2011).

Dilling, L., Lemos, M.C., 2011. Creating usable science: opportunities and constraints for climate knowledge use and their implications for science policy. Glob. Environ. Change 21, 680–689.

Durack, P.J., Wijffels, S.E., Matear, R.J., 2012. Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. Science 336, 455–458.

Duru, M., Felten, B., Theau, J.P., Martin, G., 2012. A modelling and participatory approach for enhancing learning about adaptation of grassland-based livestock systems to climate change. Reg. Environ. Change, 1–12.

Ejaz Qureshi, M., Hanjra, M.A., Ward, J., 2013. Impact of water scarcity in Australia on global food security in an era of climate change. Food Policy 38, 136–145.

Everingham, Y.L., Clarke, A.J., Van Gorder, S., 2008. Long lead rainfall forecasts for the Australian sugar industry. Int. J. Climatol. 28 (1), 111–117.

Flood, J., 2004. Archaeology of the Dreamtime. JB Publications, Sydney, Australia.

Folland C.K., Parker, D.E., Coleman, A.W. and Washington, R. ,1998. Large scale modes of ocean surface temperature since the late nineteenth century. Climate Research Technical Note, CRTN 81.

Folland, C.K., Renwick, J.A, Salinger, M.J., Mullan, A.B., 2002. Relative influences of the inter-decadal Pacific Oscillation and ENSO on the South Pacific convergence zone. Geophys. Res. Lett. 29 (13), 211–214.

Gergis, J., 2008. Documentary accounts of the impacts of past climate variability on the early colony of New South Wales, 1788–1791: a preliminary analysis. Bull. Aust. Meteorol. Oceanogr. Soc. 21 (5), 103–107.

Gergis, J., 2009. Leaping forward through the past: how historical documents can help scientists understand climate change. Univ. Melb. Collect. 4, 42–44.

Gergis, J., Karoly, D.J., Allan, R.J., 2009. A climate reconstruction of Sydney Cove, New South Wales, using weather journal and documentary data, 1788–1791. Aust. Meteorol. Oceanogr. J. 58, 83–98.

Gergis, J., Brohan, P., Allan, R.J., 2010a. The weather of the First Fleet voyage to Botany Bay, 1787–1788. Weather 65 (12), 315–319.

Gergis, J., Garden, D., Fenby, C., 2010b. The influence of climate on the first European settlement of Australia: a comparison of weather journals, documentary data and palaeoclimate records, 1788–1793. Environ. Hist. 15 (3), 485–507.

Gibbs, W.J., Maher, J.V., 1967. Rainfall Deciles as Drought Indicators. Bureau of Meteorology, Melbourne (Bureau of Meteorology Bulletin No. 48).

Guilyardi, E., Bellenger, H., Collins, M., Ferrett, S., Cai, W., Wittenberg, A., 2012. A first look at ENSO in CMIP5. CLIVAR Exch. 58, 29–32.

Guiney, R., 2012. Farming suicides during the Victorian drought: 2001–2007. Aust. J. Rural Health 20 (1), 11–15.

Hallegatte, S. , 2008. Adaptation to climate change: do not count on climate scientists to do your work. Regulation2point0, Working paper 458.

Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. Glob. Environ. Change 19, 8.

Hammer, C.L. and Nicholls, N. , 1996. Managing for climate variability: the role of season climate forecasting in improving agricultural systems. In: Proceedings of the Second Australian Conference on Agricultural Meteorology, Brisbane, Bureau of Meteorology.

Hammer, G.L., Nicholls, N., Mitchell, C., 2000. Applications of seasonal climate forecasting in agricultural and natural ecosystems: the Australian experience. Kluwer Academic Publishers, The Netherlands p. 469.
Hanigan, I.C., Butler, C.D., Kokic, P.D., Hutchinson, M.F., 2012. Suicide and drought in New South Wales, Australia, 1970–2007. Proc. Natl. Acad. Sci. 109, 35.
Hastings P.A. , 1993. Seasonal climate forecasts: perceptions and responses of Queensland rural producers. (PhD thesis). University of Queensland, Brisbane.
Hayman, P. , 2003. Decision support systems in Australian dryland farming: a promising past, a disappointing present and uncertain future. In: Proceedings for the 4th International Crop Science Congress, Brisbane, Australia, 26 September–1 October 2004.
Hearn, A.B., Bange, M.P., 2002. SIRATAC and CottonLOGIC: persevering with DSSs in the Australian cotton industry. Agric. Syst. 74, 27–56.
Heathcote, R.L., 1965. Drought perception. In: Lovett, J.V. (Ed.), The Environment, Economic and Social Significance of Drought. Angus and Robertson, Sydney, pp. 17–40.
Heathcote, R.L., 1973. Australia. In: Glantz, M.H. (Ed.), Drought Follows the Plow: Cultivating Marginal Areas. Cambridge University Press, Cambridge, pp. 91–102.
Hegerl, G., Zwiers, F., Braconnot, P., et al., 2007. Understanding and attributing climate change. In: Solomon, S., Qin, D., Manning, M., et al. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
Hennessy, K., Fawcett, R., Kirono, D., et al., 2008. An Assessment of the Impact of Climate Change on the Nature and Frequency of Exceptional Climatic Events. CSIRO and the Australian Bureau of Meteorology, Melbourne (accessed 13.06.2013.).
Henzel, T., 2007. Australian Agriculture: Its History and Challenges. CSIRO Publishing, Collingwood, Victoria, Australia, ISBN: 9780643993426.
Hochman, Z., Holzworth, D., Hunt, J.R., 2009a. Potential to improve on-farm wheat yield and WUE in Australia. Crop Pasture Sci. 60, 708–716.
Hochman, Z., Van Rees, H., Carberry, P.S., Hunt, J.R., McCown, R.L., Gartmann, A., McClelland, T., 2009b. Re-inventing model-based decision support with Australian dryland farmers. 4. Yield Prophet® helps farmers monitor and manage crops in a variable climate. Crop Pasture Sci. 60 (11), 1057–1070.
Howden, S.M., Meinke, H., Power, B., McKeon, G.M., 2003. Risk management of wheat in a non-stationary climate: frost in Central Queensland. In: Post, D.A. (Ed.), Integrative Modelling of Biophysical, Social and Economic Systems for Resource Management Solutions. MSSANZ Inc., Canberra, Australia, pp. 17–22.
Howden, M., Nelson, R.A., Crimp, S., 2013. Food security under a changing climate: frontiers of science or adaptation frontiers?. In: Palutikof, J., Boulter, S.L., Ash, A.J., Stafford Smith, M., Parry, M., Waschka, M., Guitart, D. (Eds.), Climate Adaptation Futures. John Wiley and Sons, United Kingdom, pp. 56–68.
Hunt, J.R., Kirkegaard, J.A., 2011. Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. Crop Pasture Sci. 62, 915–929.
Intergovernmental Panel on Climate Change, 2014. Climate Change 2013: The Physical Science Basis (5th Assessment Report). (accessed 11.02.2014).
Jackson, E., Quaddus, M., Islam, N., Stanton, J., 2009. Sociological factors affecting agricultural price risk management in Australia. Rural Sociol. 74, 546–572, http://dx.doi.org/10.1111/j.1549-0831.2009.tb00704.x.
Jakku, E., Thorburn, P.J., 2010. A conceptual framework for guiding the participatory development of agricultural decision support systems. Agric. Syst. 103, 675–682.
Jeffrey, S.J., Carter, J.O., Moodie, K.B., Beswick, A.R., 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environ. Model. Softw. 16, 309–330.
Jevons, W.S., 1858. Some data concerning the climate of Australia and New Zealand. In Waugh's Australian Almanac for the Year 1859.
Johnston, P., McKeon, G., Buxton, R., Cobon, D., Day, K., Hall, W., Scanlan, J., 2000. Managing climatic variability in Queensland's grazing lands – new approaches. In: Hammer, G.L., et al. (Eds.), The Australian Experience. Kluwer Academic Publishers, The Netherlands, pp. 197–226.
Kent, D.M., Kirono, D.G.C., Timbal, B., Chiew, F.S., 2011. Representation of the Australian sub-tropical ridge in the CMIP3 models. Int. J. Climatol., 1–10.
Keogh, D.U., Bell, K.L., Park, J.N., Cobon, D.H., 2004. Formative evaluation to benchmark and improve climate-based decision support for graziers in western Queensland. Aust. J. Exp. Agric. 44, 233–246.
Keogh, D.U., Watson, I.W., Bell, K.L., Cobon, D.H., Dutta, S.C., 2005. Climate information needs of Gascoyne Murchison pastoralists: a representative study of the Western Australian grazing industry. Aust. J. Exp. Agric. 45 (12), 1613–1625.
Keogh, M., Granger, R. and Middleton, S., 2011. Drought Pilot Review Panel: a review of the pilot of drought reform measures in Western Australia, Canberra, September.
Kokic, P., Nelson, R., Meinke, H., Potgieter, A., Carter, J., 2007. From rainfall to farm incomes—transforming advice for Australian drought policy. I. Development and testing of a bioeconomic modelling system. Crop Pasture Sci. 58 (10), 993–1003.
Lee, J.M., Clark, A.J., Roche, J.R., 2013. Climate change effects and adaptation options for temperate pasture based dairy farming systems: a review. Grass Forage Sci..
Leith, P., 2011. Public engagement with climate adaptation: an imperative for (and driver of) institutional reform?. In: Whitmarsh, L., O'Neill, S., Lorenzoni, I. (Eds.), Engaging the Public with Climate Change: Behaviour Change and Communication. Earthscan, London.
Logar, I., van den Bergh, J.C., 2013. Methods to assess costs of drought damages and policies for drought mitigation and adaptation: review and recommendations. Water Resour. Manag., 1–14.
MacKellar, D., 1908. My Country (earlier titled Core of My Heart), A Sunburnt Country. Golden Press, Sydney p. 1978 (The Sydney Mail, 21st October 1908 cited by H. Bogdan).
Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Am. Meteorol. Soc. 78 (6), 1069–1079.
Mantua, N.J., Hare, S.R., 2002. The Pacific decadal oscillation. J. Oceanogr. 58 (1), 35–44.
Maricle, G., 2011. Prediction as an impediment to preparedness: lessons from the US Hurricane and Earthquake Research Enterprises. Minerva 49, 87–111.
Marshall, N.A., Park, S., Howden, S.M., Dowd, A.B., Jakku, E.S., 2013. Climate change awareness is associated with enhanced adaptive capacity. Agric. Syst.
Matthews, K., Schwarz, G., Rivington, M., Miller, D., 2008. Wither agricultural DSS? Comput. Electron. Agric. 61, 149–159.
McCown, R.L., 2012. A cognitive systems framework to inform delivery of analytic support for farmers' intuitive management under seasonal climatic variability. Agric. Syst. 105, 7–20.
McCown, R.L., Carberry, P.S., Dalgliesh, N.P., Foale, M.A., Hochman, Z., 2012. Farmers use intuition to reinvent analytic decision support for managing seasonal climatic variability. Agric. Syst. 106 (1), 33–45.
McGowan, H., Marx, S., Moss, P., Hammond, A., 2012. Evidence of ENSO mega-drought triggered collapse of prehistory Aboriginal society in northwest Australia. Geophys. Res. Lett. 39, 22.
McKeon, G., Hall, W., Henry, B., Stone, G., Watson, I., 2004. Pasture degradation and recovery in Australia's rangelands: learning from history. Queensland Department of Natural Resources, Mines and Energy, Brisbane.
McKeon, G.M., Stone, G.S., Syktus, J.I., Carter, J.O., Flood, N.R., Ahrens, D.G., Bruget, D.N., Chilcott, C.R., Cobon, D.H., Cowley, R.A., Crimp, S.J., Fraser, G.W., Howden, S.M., Johnston, P.W., Ryan, J.G., Stokes, C.J., Day, K.A., 2009. Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of issues. Rangel. J. 31 (1–29).
Meinig, D.W., 1962. On the Margins of Good Earth – The South Australian Wheat Frontier. Rand McNally and Co., Chicago, pp. 1869–1884 (Association of American Geographers).
Meinke, H., Hochman, Z., 2000. Using seasonal climate forecasts to manage dryland crops in northern Australia: experiences from the 1997–98 seasons. In: Hammer, C.L., Nicholls, N., Mitchell, C. (Eds.), Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems: The Australian Experience. Kluwer Academic Publishers, The Netherlands, pp. 149–165.
Meinke, H., Stone, R.C., 2005. Seasonal and inter-annual climate forecasting: the new tool for increasing preparedness to climate variability and change in agricultural planning and operations. Clim. Change 70 (1–2), 221–253.
Moser, S.C., Dilling, L., 2011. Communicating climate change: closing the science-action gap, The Oxford Handbook of Climate Change and Society. Oxford University Press, USA, pp. 161–174.
Nelson, R.A., Hammer, G.L., Holzworth, D.P., Hayman, P., 2002. Infusing the use of seasonal climate forecasting into crop management practice in north east Australia using discussion support software. Agric. Syst. 74, 393–414.
Nelson, R., Kokic, P., Elliston, L., King, J.A., 2005. Structural adjustment. Aust. Commod. 12 (1), 171–179.
Nelson, R., Kokic, P., Crimp, S., Martin, P., Meinke, H., Howden, S.M., Nidumolu, U., 2010a. The vulnerability of Australian rural communities to climate variability and change: Part II—Integrating impacts with adaptive capacity. Environ. Sci. Policy 13 (1), 18–27.
Nelson, R., Kokic, P., Crimp, S., Meinke, H., Howden, S.M., 2010b. The vulnerability of Australian rural communities to climate variability and change: Part I—Conceptualising and measuring vulnerability. Environ. Sci. Policy 13 (1), 8–17.
Nicholls, N., 1991. The El Nino/Southern Oscillation and Australian vegetation, Vegetation and Climate Interactions in Semi-Arid Regions. Springer, The Netherlands, pp. 23–36.
Nicholls, N., 2000. Opportunities to improve the use of seasonal climate forecasts. In: Hammer, C.L., Nicholls, N., Mitchell, C. (Eds.), Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems: The Australian Experience. Kluwer Academic Publishers, The Netherlands, pp. 309–327.
Nicholls, N., 2004. The changing nature of Australian droughts. Clim. Change 63 (3), 323–336.
Nicholls, N., Butler, C.D., Hanigan, I., 2006. Inter-annual rainfall variations and suicide in New South Wales, Australia, 1964–2001. Int. J. Biometeorol. 50 (3), 139–143.
Nidumolu, U.B., Hayman, P.T., Howden, S.M., Alexander, B.M., 2012. Re-evaluating the margin of the South Australian grain belt in a changing climate. Clim. Res. 51, 249–260.
Page, A., Morrell, S., Taylor, R., 2002. Suicide and political regime in New South Wales and Australia during the 20th century. J. Epidemiol. Community Health 56 (10), 766–772.
Productivity Commission, 2009. Government Drought Support. Productivity Commission, Melbourne (Report No. 46, Final Inquiry Report).
Qi, X., Tong, S., Hu, W., 2009. Preliminary spatiotemporal analysis of the association between socio-environmental factors and suicide. Environ. Health 8, 46–58.
Ramirez-Villegas, J., Challinor, A.J., Thornton, P.K., Jarvis, A., 2013. Implications of regional improvement in global climate models for agricultural impact research. Environ. Res. Lett. 8 (2), 024018.
Rickards, L., Howden, M., Crimp, S., 2014. Channelling the future? The use of seasonal climate forecasts in climate adaptation. In: Fuhrer, J., Gregory, P. (Eds.), Climate Change Impact and Adaptation in Agricultural Systems (In press).

Robertson, A., Kirshner, S., Smyth, P., Charles, S.P., Bates, B.C., 2006. Subseasonal-to-interdecadal variability of the Australian monsoon over North Queensland. J. Royal Meteorol. Soc. 132, 519–542.
Rogers, E., 1962. Diffusion of Innovations. Free Press of Glencoe, New York, U.S.A, p. 367.
Russell, H.C., Krefft, G., 1830–1881. Notes on the fauna of Tasmania, Chamberlain, Henry, 1836–1907. Klima von Neu-Süd-Wales, 1877. Climate of New South Wales: Descriptive, Historical, and Tabular. Charles Potter, Acting Government Printer, Sydney.
Sainath, P., 2013, May 19. India Losing 2000 Farmers Every Single Day: A Tale of a Rapidly Changing Society. IB Times. Retrieved from 〈http://www.ibtimes.com/india-losing-2000-farmers-every-single-day-tale-rapidly-changing-society-1232913〉.
Sherval, M., Greenwood, A., 2012. 'Drought-proofing' regional Australia and the rhetoric surrounding Tillegra Dam, NSW. Aust. Geogr. 43 (3), 253–271.
Solomon, A., Goddard, L., Kumar, A., Carton, J., Deser, C., Fukumori, I., Stockdale, T., 2011. Distinguishing the roles of natural and anthropogenically forced decadal climate variability: implications for prediction. Bull. Am. Meteorol. Soc. 92 (2), 141–156.
Speldewinde, P.C., Cook, A., Davies, P., Weinstein, P., 2009. A relationship between environmental degradation and mental health in rural Western Australia. Health Place 15 (3), 880–887.
Stafford Smith, D.M., McKeon, G.M., 1998. Assessing the historical frequency of drought events on grazing properties in Australian rangelands. Agric. Syst. 57 (3), 271–299.
Stathers, T., Lamboll, R., Mvumi, B.M., 2013. Postharvest agriculture in changing climates: its importance to African smallholder farmers. Food Secur., 1–32.
Stehlik, D., 2005. Managing risk? Social policy responses in time of drought, From Disaster Response to Risk Management. Springer, The Netherlands, pp. 65–83.
Stokes, C.J., Howden, S.M., 2010. Adapting Agriculture to Climate Change: Preparing Australian Agriculture, Forestry and Fisheries for the Future. CSIRO Publishing, Collingwood p. 296.
Stone, G., Crimp, S., Day, K., Hall, W., Henry, B., McKeon, G., Watson, I., 2003. Preventing the 9th degradation episode in Australia's grazing lands. In: Stone, R., Partridge, I. (Eds.), Science for Drought, Proceedings of the National Drought Forum, pp. 62–73.
Tench, W., 1793. A Complete Account of the Settlement at Port Jackson in New South Wales Including an Accurate Description of the Situation of the Colony; of the Natives; and of its Natural Productions. Nicol and Sewell, London, UK.
Ummenhofer, C.C., England, M.H., McIntosh, P.C., Meyers, G.A., Pook, M.J., Risbey, J.S., Taschetto, A.S., 2009. What causes southeast Australia's worst droughts? Geophys. Res. Lett. 36 (4), L04706.
Verdon-Kidd, D.C., Kiem, A.S., 2009. Nature and causes of protracted droughts in southeast Australia: comparison between the Federation, WWII, and Big Dry droughts. Geophys. Res. Lett. 36, 22.
Wasson, A.P., Richards, R.A., Chatrath, R., Misra, S.C., Prasad, S.S., Rebetzke, G.J., Kirkegaard, J.A., Christopher, J., Watt, M., 2012. Traits and selection strategies to improve root systems and water uptake in water-limited wheat crops. J. Exp. Bot. *63* (9), 3485–3498.
Webb, N.P., McGowan, H.A., Phin, S.R., McTainsh, G.H., 2009. AUSLEM (AUStralian Land Erodibility Model): a tool for indentifying wind erosion hazard in Australia. Geomorphology 78, 179–200.
White, D.H., Howden, S.M., Walcott, J.J., Cannon, R.M., 1998. A framework for estimating the extent and severity of drought, based on a grazing system in south-eastern Australia. Agric. Syst. 57, 259–270.
White, W.B., McKeon, G.M., Syktus, J.I., 2003. Australian drought: the interference of multi-spectral global standing modes and travelling waves. Int. J. Climatol. 23, 631–662, http://dx.doi.org/10.1002/joc.895.
Wilby, R.L., Troni, J., Biot, Y., Tedd, L., Hewitson, B.C., Smith, D.G., Sutton, R.T., 2009. A review of climate risk information for adaptation and development planning. Int. J. Climatol. 29, 1193–1215.
Wilby, R.L., Dessai, S., 2010. Robust adaptation to climate change. Weather 65, 180–185, http://dx.doi.org/10.1002/wea.543.
Wilhite, D.A., 1993. Drought Assessment, Management and Planning: Theory and Case Studies. Kluwer Academic Publishers, Norwell, USA, p. 293.