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Climate change through the farming systems lens: challenges and opportunities for farming in Australia

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Abstract. Adaptation to and mitigation of climate change in Australian agriculture has included research at the plant, animal, and soil level; the farming system level; and the community and landscape level. This paper focuses on the farming systems level at which many of the impacts of a changing climate will be felt. This is also the level where much of the activity relating to adaptation and mitigation can usefully be analysed and at which existing adaptive capacity provides a critical platform for further efforts. In this paper, we use a framework of nested hierarchies introduced by J. Passioura four decades ago to highlight the need for research, development and extension (RDE) on climate change at the farming systems level to build on more fundamental soil, plant, and animal sciences and to link into higher themes of rural sociology and landscape science. The many questions asked by those managing farming systems can be categorised under four broad headings: (*1*) climate projections at a local scale, (*2*) impacts of climate projections on existing farming systems, (*3*) adaptation options, and (*4*) risks and opportunities from policies to reduce emissions. These questions are used as a framework to identify emerging issues for RDE in Australian farming systems, including the complex balance in on-farm strategies between adapting to climate change and reducing greenhouse gas concentrations.

Climate is recognised as one of the defining features of different farming systems in Australia. It follows that if the climate changes, farming systems will have to shift, adapt, or be transformed into a different land use. Given that Australian farming systems have been adaptive in the past, we address the question of the extent to which research on adaptation to climate change in farming systems is different or additional to research on farming systems in a variable climate.

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Introduction

Farming systems research, development, and extension (RDE) involves the integration of component plant, animal, and soil science at the paddock and farm level by researchers with farm managers. The term ‘farming systems’ and the related term ‘farming systems research’ were commonly used in development work through the 1970s in recognition of the fact that improved agricultural outcomes require more than just technological inputs such as new genotypes, fertilisers, and pesticides (Scoones and Thompson 1994). Dillon (1992) indicated the following characteristics of farming systems:

- *purposeful* (they select goals and allocate resources to achieve these goals);
- *dynamic* (change over time in response to internal or external influences);
- *stochastic* (future behaviour is uncertain and difficult to predict);
- *open* (they interact with their environment);
- *abstract* (they are conceptual rather than purely physical in nature).

Central to the notion of farming systems is the key role of the farmer as decision maker (Chambers 1994). This interest in farming systems from agricultural science was part of a wider shift in the conduct and application of science, which Gibbons *et al*. (1994) describe as a move from Mode 1 traditional, mono-disciplinary science to Mode 2 trans-disciplinary research. In the first, the RDE model is one of a serial progression in which knowledge is created by research, communicated by extension, and used by farmers. In the second, RDE is based on a more participatory model where there are pools of knowledge in the research, extension and farming community, and research is inherently more applied (Rölling 1988; Vogel and O’Brien 2006). A key feature of Mode 2 research is that researchers carefully listen to, and are guided by, the questions raised by

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end-users. In agricultural research, the main end-users are farmers, and so the questions they raise are primarily directed at the farm and paddock levels. A more inclusive approach to researching with farmers rather than conducting research on farms is therefore closely associated with the rise of a farming systems perspective (Bawden 1990). A range of frameworks have been proposed for these collaborative investigations where synergies are sought between farmer knowledge and scientific knowledge (e.g. Martin *et al*. 1996; Carberry 2001).

In Australia, the notion of farming systems was rapidly adopted to cover integration (Squires and Tow 1991; Dillon 1992; Carberry 2001), modelling (for a review, see Robertson and Carberry 2010), and an emphasis of agriculture and farming as a human activity (Russell *et al*. 1989; Bawden 1990). The emphasis on farming as a human more than a technical activity in farming systems research led to hard systems analysis being challenged by soft systems and sociology (McCown 2002). One of the responses to this challenge has been embedding hard systems analysis, such as crop models, within participatory research and development (R&D) with farmers and advisers (Hochman *et al*. 2009). Importantly, this tradition of integrating hard and soft models provides an invaluable basis for climate change adaptation, which similarly demands that 'hard' information and models about climate is integrated with the broader socio-economic and political flow-on effects of climate change and the strongly social process of adaptation decision-making.

Both terms 'farming systems' and 'climate change' are relatively elastic, which can lead to a situation where almost any activity can be construed to be under the heading. Nevertheless, there are good reasons for close interaction between farming systems and climate change and for research to be conducted at this level:

- There is a strong link between farming systems and climate. This is reflected in agro-climatic zones (Williams *et al*. 2002; Hutchinson *et al*. 2005). This is evident in farming systems groups that identify as a 'low rainfall region' or 'high rainfall' region, and in the legal notion of regions for the wine industry. The notion of zones shifting in a changing climate (e.g. Webb and Barlow 2008) has grabbed the attention of industry and policy makers.
- The impact of climate change and subsequent risk makes more sense at the farm-enterprise level than the plant, animal, or paddock level (Malcolm 1990; John *et al*. 2005). Many of the adaptation options for a warmer, drier climate, such as adjusting the ratio of livestock to cropping or crop area, or improving the fit between management approach and soil type, are systems-level questions. Likewise, as discussed below, many of the currently available actions to reduce greenhouse gases (GHG) focus on improving overall efficiency and are questions at farm systems level.
- Analysis of livestock management has always required a whole farm analysis, as partial analysis on one part of the flock or herd in a single paddock can be misleading (Cullen *et al*. 2009). A farming systems approach is essential when analysing the cascading effects of climate change and the positive and negative feedbacks of adaptation actions, including the influence of such actions on livestock emissions.
- There has been a move from studying the soil water balance and water-use efficiency of a single plant or crop to trying to understand the role of rotations, including the fallow period (Kirkegaard and Hunt 2010; Oliver *et al*. 2010) and whole farm water-use efficiency (Routley *et al*. 2010).
- Climate change demands that we become more adept at thinking and acting in terms of systems at all levels (Ison 2010). This includes being able to move flexibly between scales (Adger *et al*. 2005; Armson 2011), including but not restricted to 'the farming systems level'.

As noted in the last point, while much climate change adaptation and mitigation activity can usefully be focussed at the farming systems level, this cannot be to the exclusion of other levels of analysis. As shown in Table 1 and other papers in this special issue, RDE on climate adaptation and mitigation can also be usefully targeted at the plant and animal level (e.g. physiology of heat stress or methanogenesis in the rumen), which is a more fundamental or foundational level than farming systems. Similarly, RDE can be targeted at higher integrative levels than farming systems, and other papers in this special issue reflect on such processes, including the building of adaptive capacity at a community and regional level, planning for future landscapes, or transformational adaptation. Terms such as resilience will be more meaningful if the scale and goals of the system being discussed are explicitly stated (Klein *et al*. 2003; Adger *et al*. 2005; Walker and Salt 2006). The challenges of adaptation to and mitigation of climate change in Australian farming systems demands RDE at all levels and clear thinking on how to move between them.

The systems concept of hierarchies and how farming systems fit into this hierarchy (Table 1) is more than just semantics or a form of disciplinary demarcation. It is central to our ability to have a meaningful discussion about RDE on adaptation and mitigation. Passioura (1979) uses a version of Table 1 to indicate that what happens at one level is 'explained' by the level below and is 'given meaning' by the level above. He uses this notion to warn plant physiologists that unless their research could be related to higher levels of agronomy, they risked conducting research that was potentially redundant. He also cautions that research that has no relationship with lower levels is likely to be descriptive, superficial, and unscientific. Carberry (2001) makes a similar point about the need to balance rigor and relevance in farming systems research. Passioura's framework was used by Hearne (1996) to guide agronomists developing and using crop models

Table 1. The need for research at the farming systems level to relate to that at lower and higher levels of organisation in order to improve explanation and meaning, respectively (modified from Passioura 1979, Hearne 1996, and Cornish 2010)

Significance or meaning (level n + 1)	Future landscapes and rural communities, regional adaptive capacity, regional policy and planning
Level of study (level n)	Farming systems—enterprise mix, crop and pasture sequencing, integrated weed disease and pest management
Explanation (level n – 1)	Crop and animal physiology, soil science, weed science, plant pathology, entomology, and climate science

and by Cornish (2010) in an overview of applying research to farming systems.

Applying Passioura's framework to the issue of climate change adaptation and mitigation on Australian farms, it is apparent that RDE at a farming systems level runs the risk of being descriptive and superficial unless it is backed up by sound component science. At the same time, integrative research on farming systems needs to consider farms in a changing landscape, changing policy initiatives, changing rural communities, commodity prices, and agricultural industries. Addressing agronomists, Hamblin (1996) notes that many of the environmental questions asked by policy makers are at a higher scale than most agricultural scientists are trained at, or comfortable, answering. Similarly, Lane *et al*. (2009) note that there has been a considerable shift of responsibility for natural resource management to a regional catchment and farm level and question whether this model is appropriate for every problem. Those authors go on to cite climate change as an example of where there is a mismatch between the scale of the environmental issue and the farm management or even catchment management level, highlighting the need for climate change research on farming to accommodate higher level processes. In a recent paper revisting the framework, Passioura (2010) points to success of working from lower levels such as herbicide tolerance and the insertion of the *Bt* gene in cotton to kill caterpillars. He contrasts the success of these genetic solutions that target alien organisms (e.g. *Bt* genes) or molecules (e.g. glyphosate resistance) with challenges such as heat or drought tolerance. Further, he argues that dialogues between all levels have been essential to the success of insect control and weed management.

Four key questions

While farmers and advisers, like the rest of the community, are asking fundamental questions about the science of climate change, many have moved beyond the basic question of what is climate change and is it real, to asking the more applied question of what should be done. Adapting to climate change and reducing GHG raise many questions at the farming systems level. Some of those frequently posed by farmers and their advisers can be summarised as variants on the following:

(*1*) What are the climate change *projections* relevant for the farm and regional scale?
(*2*) What are the *impacts* of climate change on the farming system?
(*3*) What are *adaptation options* at the farming system level?
(*4*) What are the risks and opportunities for the farming system from *policies to reduce greenhouse gases*?

These questions are similar to those posed in the Climate Change Research Strategy for Primary Industries (CCRSPI) Phase 1 report (LWA 2008, p.14), which emerged through stakeholder consultation and is used as a filter for the research strategy. Different aspects of these questions have been refined and addressed in the Farming Future program of the Department of Agriculture Forests and Fisheries Australia, and various strategies from Rural Development Corporations, CSIRO, universities, and state departments. The focus on projections, impacts, adaptation, and mitigation is also consistent with Intergovernmental Panel on Climate Change (IPCC) working groups and reporting. In the following section, we use these questions to provide a framework to discuss recent developments and emerging issues about the implications of climate change at the farming systems level. A focus on questions raised by key stakeholders is consistent with Mode 2 science (Gibbons *et al*. 1994) and research on farming systems (Dillon 1992).

What are the climate change projections at the farming system scale?

The information-seeking Australian farmer has access to broad-scale climate change projections from the third and fourth assessment rounds of the IPCC. An authoritative summary of projections with an interactive website is provided by CSIRO and the Bureau of Meteorology (www.climatechangeinaustralia.gov.au) (CSIRO and BoM 2007). Across Australia, temperatures are projected to rise by 0.6–1.5°C by 2030 and by 1–5°C by 2070, with an increase in the frequency, intensity, and duration of extreme heat events. The rainfall projections are more uncertain and vary across the country. By 2030, projections range from –10 to +5% across northern Australia and from –10% to no change in southern Australia, while under 2070 high emission scenarios (A1FI), projected changes are for –30 to +20% annual rainfall in northern, central, and eastern Australia, and –30 to +5% annual rainfall across southern Australia. The frequency and extent of droughts are projected to increase over most of southern Australia.

Holper (2010) gives an overview of the 20-year history of the Australian Climate Change Science Program and describes the high level positive reviews it has received. Despite this positive feedback, as in other countries and other areas of climate science, there is a mismatch between the spatial and temporal scale provided by climate change projections and that desired by decision makers. Farmers, agricultural scientists, and policy makers are frequently disappointed in the spatial resolution (150–200 km) available and the wide range of possible futures presented, especially in relation to precipitation. As pointed out by Schiermeier (2010): 'the sad truth of climate science is that the most crucial information [local projections] is the least reliable'. An early response to the question of climate change projections at a scale relevant to farming systems has been an emphasis on higher spatial resolution. Most states in Australia have embarked on some form of downscaling of climate-change projections as a means of narrowing the range of projected changes. Even with downscaling, the narrowing of rainfall projections remains problematic and users are faced with high levels of irreducible uncertainty.

Besides trying to improve climate projections and tools, it is also vital to look for alternatives to prediction. The 'wicked' complexity and 'deep uncertainty' that characterises how the broad phenomena of climate change may manifest at any one time or place means that projections will always be limited (Kandlikar *et al*. 2005). This means that our conventional reliance on prediction as the basis of management needs to be moderated (Hulme *et al*. 2009). Sarewitz (2010) warns that an overemphasis on climate change projections, especially at a fine scale, can be an impediment to adaptation action, firstly because it could delay action as decision makers wait for the next report, and secondly because it can lead to planning for an unrealistically narrow range of future climates. Although decision makers prefer a narrow range, there is the danger that the narrowing is an artefact of which climate models are used rather than an accurate representation of possible futures, which can result in maladaptation if acted on (cf. Barnett and O'Neill 2010). Hennessey *et al*. (2010) conclude their description of climate change projections for Australian agriculture by acknowledging the uncertainty, warning against delay, and recommending agriculturists work on options which are robust over a likely range of future climates. Others similarly argue that we need to aim for robust adaptation decisions (i.e. appropriate over a wide range of conditions) rather than optimal ones (Lempert *et al*. 2004; Hallegatte 2009; Wilby and Dessai 2010).

This is not an argument against investing in climate science. There are substantial national and international resources invested in downscaling and identifying the best set of climate models, and these will continue to provide a better understanding of climate drivers and valuable information for managers of farming systems. Indeed, one of the challenges for Australian agriculture is to gear into substantial R&D on extreme events such as heat waves and bushfires and the substantial effort on understanding the drivers of climate variability as a means of better quantifying both year-to-year variability and climate change (Murphy and Timbal 2008; Timbal *et al*. 2010). Nevertheless, an increasing number of agricultural decision makers are starting to prepare for a warmer and water-constrained future, rather than waiting for the next round of projections. Some of this involves supplementing projections with sensitivity analysis, which investigates how a given farm system would cope with 5%, 10%, or 20% drying and different levels of warming. For example, in low-rainfall farming systems, the use of deciles (Hayman and Alexander 2010) can identify a threshold of 15% decline in rainfall because it shifts the chance of being in the driest three deciles from 30% in the current climate to ~50%. This means that the chance of two bad seasons in a row changes from one season in nine to one season in four. As shown in an economic analysis by Peck and Adams (2010) and social analysis by Rickards (2011) and King *et al*.(2009), and known by generations of farmers, it is the clustering of droughts and their intersection with other climatic and non-climatic pressures that can be catastrophic for an enterprise, especially if it has low adaptive capacity on account of being at a vulnerable time, such as expansion.

Projections can also be supplemented with the use of temporal and spatial analogues (Ford *et al*. 2010; Hayman and Alexander 2010; Wilby and Dessai 2010). Many groups in Australia have used the recent drought as a temporal analogue for a drier future, for example, as has also been done elsewhere (e.g. McLeman *et al*. 2008; Mortimore 2010). The run of very dry seasons on the upper Eyre Peninsula in South Australia was used to identify characteristics of farm enterprises that were sources of resilience (Doudle *et al*. 2009). Ecologists have also long used spatial analogues for future changes, and farmers and advisers naturally look to drier, warmer locations as windows into the future. Comparisons such as this are regularly made in the wine industry, where Coonawarra is ~2°C cooler than the Barossa, which is ~2°C cooler than the Riverland. Temporal and spatial analogues are imperfect, however, and need to be used carefully. While the advantage of temporal analogues relative to spatial analogues is that the soil and farming system is held constant, a limit to this approach is that it is very dependent on the particular run of seasons and how these have interacted with commodity prices. An advantage of a spatial analogue is that it allows comparisons of farming systems, and importantly, because it is in the present day, there are farmers who can be questioned.

What are the impacts of climate change on the farming system?

The actual impacts of a given climatic stimulus depends not only on the characteristics of that stimulus or how exposed a farming system is to it, but on 'internal' characteristics of the farming system, namely its sensitivity to a given type of climate change risk and adaptive capacity (Nelson *et al*. 2010; Steffen *et al*. 2010). Critically, all of these elements—exposure, sensitivity, and adaptive capacity—are, like other elements of the farming system (Lev and Campbell 1987), dynamic and so need to be assessed at any point in time. The importance of the 'soft' system issues of sensitivity and adaptive capacity, as well as the 'hard' system issue of exposure to adaptation, illustrates the importance of an integrating framework like farming systems research.

As a discipline, farming systems research prides itself on accommodating dynamism in the system, until recently it has only had to deal with a variable but stationary climate. This is evident in the widespread use of historical deciles for future planning (Hayman and Alexander 2010). Adjusting farming systems thinking to a variable and trending climate and identifying how various climatic stimuli affect different components of the system over short- to long-term time scales is thus a new and important challenge. A farming systems perceptive also helps to provide a more realistic perspective on climate change impacts than that provided by climate science or agronomic studies alone. As discussed by Eckard (2008) and Bryan *et al*. (2010), climate change impacts involve more than just climatic stimuli or physical changes. Climatic impacts cascade through existing systems to create waves of non-climatic impacts, some of which may be more influential on a farming system than the climatic stimulus itself (Cork 2010).

In an overview of the costs of climate change on the Australian economy, Garnaut (2008) highlights this cascade by referring to four types of impacts. In Table 2, the examples used by Garnaut (2008) are matched with specific examples for farming systems. Estimating the relative costs of the impact of climate change and balancing this against the cost of mitigation is conceptually, ethically, and empirically difficult (Spash 2007; Stern 2007; Garnaut 2010). Garnaut (2008, 2010) notes that while Type 1 impacts are relatively easy to value in a market economy (although the initial damage may be hard to estimate), each subsequent impact type is harder to estimate and cost. This does not, however, make them less important. While it is beyond the scope of this paper to look in detail at the issue of costs, the framework of impacts at the level of a whole economy or society presented by Garnaut (2010) helps to broaden our discussion here of the impacts on farming systems.

Table 2. Framework for considering impacts of climate change on the Australian economy (Garnaut 2008) and examples relevant to farming systems

Four types of climate change impacts	Example from general economy and society	Example from farming systems
Type 1. Impacts easily measured in a market economy	Property loss from storm surges and sea level rise	Reduction of crop and livestock production from water and heat stress leading to reduced farm production and productivity
Type 2. Impacts that are more difficult to measure in a market economy due to uncertainty of estimate and complex interactions	Losses from tourism	Indirect loss in wheat yields due to disease and weeds from farmers dropping break crops from rotations
Type 3. Costs incurred for insurance against low frequency but high impact events	Income foregone and cost of protection of buildings in bush fire prone areas	General loss in confidence in adopting new technologies due to uncertain climate. Uncertainty about spring heat events leading to low inputs on cereals
Type 4. Non-market impacts	Loss of rare species, environmental amenity, access to suburban parks and playing fields	Changes to nature of rural communities and farm enterprises, issues of food sovereignty

Garnaut (2010) emphasises that a major cost of climate change is the structural uncertainty it creates (Type 3). He challenges those who, when considering the range of possible outcomes, focus on the middle of the distribution and ignore the 'bad fat tail'. The negative impact on farmer investment and productivity of increased uncertainty (due to climate change and policies to reduce GHG emissions) should not be underestimated. One attempt by Hafi *et al*. (2006) to value the costs of uncertainty used the economics of Real Options and concluded that it was rational for farmers to delay adopting irrigation technology in the face of climate and policy risk.

Garnaut (2010) also emphasises the importance of Type 4 impacts, which are also far more obtuse than, but equally as important as, more direct climate change impacts on farming. Examples listed by Garnaut (2008) are the loss of rare species or decline in suburban quality of life with easy access to parks and playing fields. Barr (2009) has written eloquently of changes occurring in rural communities as a result of a range of different stresses. Climate change is likely to interact with and exacerbate these pre-existing stressors, as well as introducing new ones (Rickards 2011). Some of the non-market aspects of climate change on the health and wellbeing of rural communities and farming families have started to be documented (King *et al*. 2009; Kiem *et al*. 2010; Hogan *et al*. 2011; Rickards 2011), including the anxiety induced by the very idea of climate change (Fritze *et al*. 2008). Such impacts cannot be ignored, not the least because they negatively affect the human capital and thus adaptive capacity of those involved.

The modelling of the impact of climate change has greatly benefited from the extensive effort in modelling the impact of climate variability in Australia that had been fostered under the Managing Climate Variability Program (Hammer *et al*. 2000; McKeon *et al*. 2004; Meinke and Stone 2005; Robertson and Carberry 2010). Over the last decade or so, simulation models such as APSIM (Keating *et al*. 2003), Grassgro (Moore *et al*. 2009), and the SGS pasture model (Cullen *et al*. 2009) have been used extensively to model the impacts of different future climates. These models use modified climate files and changes to water-use efficiency and radiation-use efficiency due to carbon dioxide fertilisation to simulate crop and pasture growth under future climates. Not only is there uncertainty in the climate change projections, but there is also uncertainty in the way that simulation models translate the changes to rainfall, temperature, and carbon dioxide into impacts (e.g. O'Leary and Anwar 2008; Rötter *et al*. 2011).

In a review of modelling the impact of ENSO, which recognised the many advances by Australian agricultural scientists, Hansen (2002) noted that there was a tendency to focus on the impacts that were easiest to model, for example water productivity of wheat, at the expense of impacts that may be as significant or greater, but are more difficult to model. One of these is the impacts of climatic and related changes on agricultural pests and diseases. There is no doubt, for example, that weed type and density will be significantly influenced by climate change. Weed biology and management are influenced by a range of climatic factors including temperature, rainfall (quantity and distribution), and frost, which are predicted to become more variable with climate change. Weed growth, reproduction potential, and rates of spread are therefore likely to change. Predictions of the impact of climate change on the potential spread of weeds have been modelled with varied complexity (e.g. Sutherst *et al*. 2007; Kriticos and Leriche 2010). Weed dispersal can be short- or long-distance, depending on the mechanism of spread. Floods and wind, for example, are important for long-distance dispersal for many weeds species and the creation of new infestations. It is expected that as summer rainfall increases, combined with elevated summer temperatures, summer weeds will become more widespread and difficult to control. Many tropical and subtropical weeds are expected to move south. Whatever changes occur, weeds will no doubt adapt and continue to spread.

The ability of farmers to effectively manage weeds with herbicides, cultural techniques, or biological controls is also influenced by environmental factors. The efficacy of many chemicals is reduced by adverse conditions such as high temperatures, and very dry or very wet conditions. Likewise, environmental factors such as temperature will strongly influence the success of biological control agents such as rusts for widespread, intractable weed problems such as blackberry. Furthermore, changes in farming systems in response to climate change will also influence the distribution and abundance of weeds, diseases, and insect pests. For example, growing continuous cereals without the disease and weed break from broadleaf crops that may increase the risks of these problems.

What are the adaptation options at the farming system scale?

Adaptation involves far more than understanding possible climate change impacts. Although there have been calls for two decades to move beyond 'impact studies' to looking at opportunities for adaptation, particularly in relation to farming systems (Parry and Carter 1988), our understanding of adaptation options is still poorly developed (Adger and Barnett 2009; Martens *et al*. 2009). According to Schneider *et al*. (2000), early impact studies of agriculture ignored adaptation (so-called 'dumb farmer scenarios'), while some of the next generation of work assumed that, in a variable and changing climate, farmers would optimise adaptation (dubbed 'clairvoyant farmer scenarios'). Schneider *et al*. (2000) argue for a more realistic approach that acknowledges that farmers have both considerable adaptive capacity and challenges, as discussed below.

Part of the reason that 'adaptation science' has been relatively slow to develop is that, as described by Meinke *et al*. (2009), it is distinctly different from the conventional, disciplinary-based science that characterises impact studies. Adaptation science is a solution-oriented, scientific endeavour to facilitate adaptation actions, not by generating more data, but by identifying and helping to develop adaptation pathways or processes in a broadly participatory mode. Although still an emerging field, the above characteristics indicate that it is naturally aligned with the approach taken in farming systems work.

It is broadly acknowledged that RDE is a crucial part of adaptation in all sectors. In agriculture, the Australian National Adaptation Research Plan for Primary Industries (Barlow *et al*. 2010) describes adaptation RDE as: '*fundamentally about generating information*, *knowledge and tools concerned with determining which primary industry systems or parts of systems are vulnerable to climate change*, *why they are vulnerable*, *what their adaptive capacity is*, *how this adaptive capacity can be increased*, *how an enterprise can move from adaptive capacity to adaptation actions and what adaptation technologies*, *options and understanding are needed to implement these actions.*' A broader systems perspective highlights that many of the categories used in the above statement are dynamic and will themselves change in response to climate change and adaptation efforts. Some of this change will be positive. Farmers are well known to be capable of extensive adaptation and learning. For this reason, Pannell (2010) optimistically warns against an over-investment in adaptation to climate change, as he considers that much would occur in any case by smart, adaptive farming communities supported by conventional RDE. The strong, existing, adaptive capacity of Australian farmers is illustrated by the way many have already adapted to (increasing) climatic variability, despite being highly exposed and sensitive to climate (Allen Consulting Group 2005; Garnaut 2008; Howden and Stokes 2010; Pannell 2010). For example, the recent crisis in water has led to innovations of water trading and feed management among dairy farmers (AusVet 2005), while the heatwaves over the last 5 years have led to many clever innovations among viticulturists (Hayman *et al*. 2009; Webb *et al*. 2009).

If one of the best ways to prepare for future climate change is to manage current variability with sound agronomy, this leads to the question of what is new or additional for climate change adaptation R&D. Additionality is a concept commonly associated with mitigation. This is the notion that an action that might sequester carbon needs to be shown as being additional to what was already being done. The discussion on additionailty and adaptation has political overtones in developing countries, based on the United Nations Framework Convention on Climate Change (UNFCCC), which stipulated that assistance from developed countries to developing countries for adaptation to climate change should be new and additional to what was already needed for sustainable development (Schipper 2007). However, it will always be difficult to separate activities that address adaptation to climate change from those that address development. In a study of 135 adaptation projects in developing countries, McGray *et al*. (2007) found that a perspective of adaptation to climate change led to changes in how problems were defined and priorities set but the solutions implemented were rarely different from those in other development projects.

While existing adaptation successes are important starting points for further adaptation, they may be necessary but not sufficient for future success. Some studies also suggest that some 'disaster responses', such as those used to respond to past climatic extremes, may actually hinder longer term adaptation for the actors involved (e.g. Handmer and Dovers 1996). In Australia, some farmers' responses to recent climatic extremes have severely eroded their financial, physical, and mental reserves (e.g. King *et al*. 2009; Rickards 2011). These and other impacts suggest that there is substantial room for improvement in how adaptation has been tackled in the past. This existing 'adaptation deficit' (cf. Burton 2011) and resultant vulnerabilities need to be tackled as part of adapting to further stressors in the future, adding significantly to the challenge. Overall, while adaptive capacity is uncertain because much of it is latent and only becomes evident as a stress is applied (Adger and Vincent 2005), the stress and different priorities imposed by extremes such as drought and flood to date, plus the increased magnitude and unpredictability of extremes and other impacts under future climate change, suggest that work is needed to develop the adequate level and form of adaptive capacity among Australian farmers in the face of climate change.

The appropriateness and ultimate successfulness of any potential adaptation response depends on the spatial or temporal scale over which it is assessed; what seems like an effective adaptation in the short term may end up being a poor one longer term, or *vice versa* (Adger *et al*. 2005). Adger and Vincent (2005) warn of maladaptation that transfers the problem to another spatial or temporal scale. There are also transfers between the actors involved. For example, 'successful adaptation' for a large wine company or grain-handling organisation may involve a policy of retreat and relocation that is devastating to an individual region, vineyard, or low-rainfall grain farm. To avoid such situations, there are, increasingly, calls for adaptation actions to be limited to those that do not increase social, economic, or environmental vulnerability (Barnett and O'Neill 2010; Eriksen *et al*. 2011).

The increasing severity of climate change over time will also require that the apparent appropriateness and successfulness of adaptation is periodically reassessed. While incremental or practice-level changes may be sufficient for a time, systems-level or transformational changes may be needed longer term. Howden *et al*. (2010) stress that while there are large benefits to current adaptation options, many of these will plateau as warming and drying become moderate to severe. They argue that these limits to adaptation are likely to force more transformational changes, such as a switch from changing land management to changing land use, including the opportunities from carbon sequestration mentioned above. In terms of Table 1, these changes would have major impacts on farming systems, rural landscapes, and communities.

One of the challenges facing farming systems research is to keep working to extend the spatial and temporal scale of research in agriculture, in order to accommodate not only the broad extent and diversity of climate change impacts but also the broad extent and diversity of the changes we need to make in response. Unlike the single-issue focus of most RDE projects to date, RDE for adaptation needs to work towards a constantly changing portfolio of options and actions. It also needs to incorporate the ability to monitor and evaluate the successfulness of actions undertaken, where success is evaluated at a broad systems level to reduce the likelihood of perverse feedbacks.

Howden *et al*. (2010) distinguish between adaptation that involves tweaking an existing farming system, modification of the farming system, and more transformational change (see also Rickards and Howden 2012, this issue). Following the idea of a spectrum of adaptations, from adjustment change through to more transformational changes, Table 3 lists some of the changes that studies with Australian farmers suggest are likely. One of the risks of farming systems research is that the inherent focus on the farming systems level leads to an over-emphasis on incremental, practices-based adaptation and a neglect of the need or opportunities for more transformational adaptation (Howden *et al*. 2010). At the same time, a call for transformational change may overlook the fact that Australian farming systems have already proven repeatedly that they are highly dynamic and capable of great transformation (Barr 2009). As noted by Howden *et al*. (2010), climate change adaptation may prove to be another case of researchers catching up with leading farmers and farm industries. It is important to acknowledge that farmers are continuously adjusting their farming systems to a range of stimuli. All of the changes listed in Table 3 are strongly influenced by non-climatic factors and many of the changes are made in response to year-to-year variability. Nevertheless, this is a series of changes that farmers have suggested as likely responses to a warmer and drier climate.

What are the risks and opportunities for the farming system to reduce greenhouse gases?

One of the key indirect impacts of climate change that agricultural producers will have to manage is the mitigation imperative. Acting to reduce GHG emissions is, in turn, one of the main adaptations that agriculture needs to take, reducing the intensity of future climate change impacts (Jones *et al*. 2007). Garnaut (2010) notes that the Australian economy as a whole, and agriculture in particular, would be a big loser from unmitigated climate change. He also recognised that, in the early stages of a mitigation regime, Australian agriculture would face significant costs that were not balanced by long-term benefits. Garnaut (2011*a*, 2011*b*) also notes the potential for Australian agriculture to take a lead role in not only mitigating emissions but also sequestering carbon. The latter systems change could therefore also become an important aspect of adaptation for many producers.

In a farming systems context, research into greenhouse gas mitigation covers activities that directly reduce energy use, and methane, nitrous oxide, and carbon dioxide released from the soil. RDE relevant to mitigation also include the measurement and accounting of carbon in soil or vegetation and the production of biofuels as alternatives to fossil fuel. In contrast to most other sectors, farm businesses in Australia are both a source and a sink for greenhouse gases. As outlined by Baldock *et al*. (2012), one

Table 3. List of possible changes for a warmer drier future suggested by farmers (Rebbeck and Duffield (2008), Robertson *et al*. (2009), Doudle *et al*. (2009), and Howden *et al*. (2010))

The third column (level of change) should not be read as hard boundaries, rather the changes are ranked from higher to lower transaction costs

Response to a warmer drier future	Example	Level of change
Change land use	Change from conventional agriculture to ecotourism, ecosystem services, agroforestry	Transformational changes with higher transaction costs
Shift enterprise	Leave one region and move farming enterprise to a region with more favoured climate	
Change production system	Change from dryland to irrigation to try to increase predictability of water supply in existing area	
Buy land in different region	Diversifying land ownership rather than expanding locally	
Change farming enterprise	E.g. move from cropping to 100% livestock	Changes with moderate transaction costs
Adjust enterprise mix	Change the mix of cropping and livestock	
Change business overheads	Spread the cost of capital and labour between farm enterprises	
Buy more land	Expand farm area within the same region	
Change rotations and crop sequences	Introduce fallowing and or longer pasture phase	Adjustment changes with lower transaction costs
Change crop species	Reduce high input and climatically risky crops like pulses and canola	
Change crop varieties	Increase reliance on shorter season wheat varieties to escape drought and heat stress	
Adjust inputs	Fine tune fertiliser rates and or delay application to later in season	

of the complexities of soil carbon is that climate variability can lead to a paddock being a sink for GHG one year and a source the next. In fire-prone areas, trees can switch from a sink to a source of emissions. The difficulty of GHG accounting is highlighted by the fact that farmers who embark on an audit can end up not being clear about whether their farm is a net sink or source.

While much research is focussed on achieving a net reduction in enteric methane and nitrous oxide and in storing more carbon in trees and soil, significant opportunities are available to reduce emissions per unit of production through improving whole farm systems efficiency, which is a farming systems management issue. In some cases, there are synergies between mitigation actions and improving productivity. For example, the application of current best practices for nitrogen fertiliser rate, source, timing, and placement, in addition to improving nitrogen efficiency, have been shown to reduce nitrous oxide loss (de Klein and Eckard 2008). Soil management to reduce compaction, reducing tillage, and retaining stubble all reduce the potential for nitrous oxide loss and increase soil carbon, while also improving productivity. Likewise for livestock, strategies that reduce the number of unproductive animals on farm, such as earlier finishing of beef cattle in feedlots, and improving reproductive and weaning rates through improved health and genetics and extended lactation in dairy, also reduce emissions from the farm as a whole (Eckard *et al*. 2010). Collectively, these strategies mean less nitrogen input, fewer replacement stock, or fewer breeding stock required for the same output, thus improving efficiency and reducing both emissions and emissions per unit product.

However, some mitigation actions are also in potential conflict with existing goals. In terms of productivity, some current technologies do risk reducing productivity in the process of reducing emissions. To address this, there is substantial R&D investment in enteric methane and nitrous oxide abatement, for example; but many of the technologies under research will take one to two decades before being fully tested and adopted into farming systems.

While at a global scale there appears to be some synergy between adaptation and mitigation actions in agriculture (Smith and Olesen 2010), there are also tensions between some specific adaptation and mitigation measures at a farm systems level. Negative feedbacks can flow in both directions. Some mitigation measures may have negative impacts on the adaptive capacity of farming systems (Smith and Olesen 2010). For example, efforts to improve farm efficiency as a means of mitigation (discussed above) run counter to resilience thinking, which, as noted in relation to robust decision making, advocates for a move away from goals of efficiency and optimisation towards allowing for systems to include some redundancy (spare reserves) to enhance their flexibility and range of adaptation options in the face of highly unpredictable conditions (Anderies *et al*. 2006; Cork 2010). Crucially, some adaptation measures may have a negative effect on mitigation. For example, increasing nitrogen fertiliser use in warmer winters to compensate for longer, hotter, and drier summers would lead to increase nitrous oxide in future climates (Eckard and Cullen 2011). There is potential for ingress of more heat-tolerant C4 pastures into temperate areas (e.g. kikuyu), resulting in more methane per unit product due to lower forage quality. While perhaps justifiable in the short-term, by worsening anthropogenic climate change, these adaptation options are technically 'maladaptive' (Barnett and O'Neill 2010). There are also synergies between some specific mitigation and adaptation actions, such as planting trees to increase shade and shelter for stock while also sequestering carbon on-farm. Likewise, increasing soil carbon in soils has significant biological, physical, and chemical benefits for productive healthy soils.

Finally, it is important to note that mitigation options are shrouded with uncertainty as a result of policy and technology uncertainty. The balance between adaptation and mitigation will vary depending on the imminence of policies relating to GHG reduction and enthusiasm for bio-fuels and carbon credits. With the current policy environment developing a price for carbon, there is potential for conflicts between short-term mitigation and sequestration objectives and long-term adaptation and productivity outcomes. Whole farm systems analysis is therefore critical to identify and avoid the conflicts while maximising the synergies.

Concluding remarks

Farming systems research with its focus on integration and interaction between components is well suited to helping agriculture adapt to and mitigate climate change, including the four questions on projections, impacts, adaptation, and mitigation discussed in this paper. Although the science of climate change adaptation and mitigation is relatively new, there have been shifts in emphasis. Not surprisingly, the issue of climate change was initially dominated by climate science and a desire for better projections, or at least consistent projections. Now many people accept a level of irreducible uncertainty in regional projections and recognise that we cannot allow this to act as a barrier to beginning the process of adapting, being mindful to maintain flexibility and robustness, aim for a broad target, tackle underlying vulnerabilities, and increase resilience.

Impacts are starting to be well understood and we need to move increasingly onto participatory research to explore farming systems adaptation options. Studies are progressing beyond simply applying simulation models with adjusted climate states to recognising some of the complexities of farming systems, including pests, weeds, and diseases and the essential participation of those who have to implement any adaptations on-farm. Hulme (2011) argued that progress on adaptation and mitigation of climate change has been limited because hard sciences have been overemphasised and social science has been limited to economics. Farming systems RDE draws on a rich tradition internationally and nationally of productive multi-disciplinary efforts. These efforts have not always been easy and are far from perfect but provide an important base level of adaptive capacity. Climate change presents further needs and opportunities for disciplines to learn from each other. As we have argued in this paper, researchers working in farming systems need to build on fundamental soil, plant, and animal sciences and acknowledge the social fabric and landscapes in which farms occur. However, there is much to be studied and learnt at the farm level. Some of this will come from on-farm biophysical research and some from models, but most will be learnt in partnership with farmers, many of whom have already demonstrated extraordinary expertise at managing complexity and uncertainty at this level.

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