CSIRO PUBLISHING

Crop & Pasture Science, 2012, **63**, 240–250
http://dx.doi.org/10.1071/CP11172

Transformational adaptation: agriculture and climate change

L. Rickards[A,C] *and S. M. Howden*[B]

[A]Melbourne School of Land and Environment, University of Melbourne, Level 1, 221 Bouverie Street, Carlton, Vic. 2010, Australia.
[B]Adaptive Primary Industries, Enterprises and Communities, Climate Adaptation National Research Flagship, CSIRO, Canberra 2911, ACT, Australia.
[C]Corresponding author. Email: lauren.rickards@unimelb.edu.au

Abstract. Climate change presents the need and opportunity for what the Stern report called 'major, non-marginal change'. Such transformational adaptation is rapidly emerging as a serious topic in agriculture. This paper provides an overview of the topic as it applies to agriculture, focusing on the Australian situation. It does so by first defining transformational adaptation, distinguishing it from other more incremental but overlapping modes of climate change adaptation and positing its emergence in agriculture as a response to both drivers and opportunities. The multiple dimensions of transformational adaptation are highlighted before two types or cases are focussed upon in order to tease out issues and highlight two major examples of transformation in agriculture in the past. Four key issues about climate change adaptation in agriculture particularly pertinent for transformational adaptation are then reviewed: the identification, level, distribution and management of the costs of adaptation; the definition, potential for and need to avoid maladaptation; the capacity demands that this level of adaptation presents; and the role of government in adaptation. Overall, transformational adaptation poses potential great gains but also great risks. It reinforces the realisation that agricultural research can no longer remain insulated from off-farm, non-science or non-agricultural knowledge or processes. Support and guidance of transformational adaptation requires that we understand how Australian agriculture is currently, and could be, positioned within the landscape, rural communities, and broader social, political and cultural environment.

Additional keywords: adaptation, agriculture, climate change, transformation.

Received 6 July 2011, accepted 20 March 2012, published online 28 May 2012

Introduction

Climate change adaptation is widely accepted as a necessity and opportunity but remains an ambiguous topic and task. Numerous definitions and types exist. An emerging focus is on 'transformational' change as an adaptive response (e.g. Howden *et al.* 2007; O'Brien 2011; Pelling 2011). This paper examines what transformational adaptation means in the context of agriculture. It defines transformational climate change adaptation in agriculture as major, purposeful action undertaken at the farm or supra-farm level in response to potential or actual climate change impacts and opportunities in the context of other drivers.

A recent comprehensive definition of climate change adaptation highlights the many questions that adaptation raises about what adapts, what is adapted to, how adaptation occurs and how effective it is:

> 'Adaptation involves changes in social-ecological systems in response to actual and expected impacts of climate change in the context of interacting nonclimatic changes. Adaptation strategies and actions can range from short-term coping to longer-term, deeper transformations, aims to meet more than climate change goals alone, and may or may not succeed in moderating harm or exploiting beneficial opportunities' (Moser and Ekstrom 2010).

In agriculture in Australia and elsewhere, research and action to date has been more in keeping with the Intergovernmental Panel on Climate Change definition, which frames adaptation as a question of 'adjustment' (Parry *et al*. 2007). Yet, as the definition above usefully highlights, adaptation also encompasses more radical change: 'longer-term, deeper transformations'. Such transformational change is increasingly on the agenda both by necessity and design (e.g. Cork *et al*. 2010; O'Brien 2011; Pelling 2011; WGBU 2011). For example, the Stern report in the UK highlights that climate change presents the need and opportunity for 'major, non-marginal' change (Stern 2007: 1). In agriculture, the scale of the climate change challenge and the growing influence of outside interests mean that transformation is both especially likely and desired. *Transformational* adaptation in and of agriculture was recently recognised as a priority by the Australian Primary Industries National Adaptation Research Plan (http://piarn.org.au/about-piarn/national-adaptation-research-plan, accessed 30 March 2012) and is an emerging field of research (e.g. Walker *et al*. 2009; Park *et al*. 2012).

This paper provides an introductory overview of transformational adaptation (TA) to climate change in agriculture. Given the nascent stage of thinking on the topic and space limitations, it is necessarily conceptual and exploratory. It consists of three main parts. First, the question of what TA is in relation to agriculture is discussed, highlighting the multiple dimensions involved, the relative nature of the concept and the need to think about both *in situ* and migratory change in land use. Second, two historical examples of transformation in agriculture are reviewed to highlight agriculture's experience with transformation and illustrate different types of transformation. Third, four inter-related issues of climate change adaptation of particular pertinence to TA of agriculture are discussed before conclusions and implications for further research are presented.

Pressures for transformation: two frameworks of adaptation

Adaptation as 'fitting to' the environment: a focus on thresholds

A range of biophysical and social drivers are contributing to the rising interest in TA. These include how climate change adaptation is intellectually framed. Two major frameworks focus on need and opportunity, respectively. In terms of need, adaptation is typically conceived as a process of 'fitting to' an altered set of external circumstances, reflecting the bio-physical origins of much of the early literature on adaptation. Illustrated by the growing literature on 'limits', 'tipping points' and 'thresholds' (e.g. Russill and Nyssa 2009; Kwadijk *et al*. 2010; McNeall *et al*. 2011), this interpretation of adaptation has reminded society of humans' biological nature and the climatic, ecological and other natural limits we exist within. Such limits and the potential for major changes in socio-natural systems have been investigated over many years in numerous fields including disturbance ecology and disaster risk management. But it is the growing evidence of the potential for substantial and/or rapid changes in future climate as a result of anthropogenic climate change that has most powerfully underlined that transformational change in human systems may be necessary. As the projected degree and pace of climate change accelerates (Rahmstorf *et al*. 2007; New *et al*. 2011) alongside the exacerbation of other biophysical-based limits such as less land, water, fossil fuels, phosphorus and biodiversity and rising demand for agricultural products, the likely need for more systemic, powerful adaptation of agriculture is increasingly being realised (e.g. Alexandra and Riddington 2007; Howden *et al*. 2007; Campbell 2008; Brussaard *et al*. 2010; Cork 2010*a*; Horlings and Marsden 2011; Sounness 2011). The aim of such transformational change is to maintain sets of activities, products (*sensu lato*), values and processes in the sector or region. In particular, transformative adaptators either seek to: (1) pro-actively avoid, uncertain and severe challenges in order to avoid transformational change of a more involuntary, uncontrolled and negative character; or (2) be 'first movers' so as to take full advantage of what they see as emerging opportunities (Howden *et al*. 2007; Park *et al*. 2012).

Adaptation as 'fitting with' the environment: a focus on proactive action

While the above is an important interpretation and driver of transformational change in agriculture, it does not capture the full situation. Reflecting the coupled nature of social-ecological systems such as agriculture, adaptation needs to be viewed not just as 'fitting to' biophysical limits of the sort discussed above, but 'fitting with': a process of co-evolving with one's system (Collins and Ison 2009*a*, 2009*b*; Ison 2010). This alternative framework – which in itself represents a mental adaptation – is particularly suitable for perceiving and conceiving of transformational change for three reasons. First, it better acknowledges ongoing 'background' change in the environment we are part of. Here, transformational change is a recognisable shift in the *type* of change occurring rather than the introduction of change to a stable setting. Second, in this frame, humans have a greater degree of agency over what can be influenced and changed, including the climate itself. A co-evolutionary perspective allows for a proactive as well as reactive approach to adaptation and broadens the scope of what can be changed, reframing accepted 'inevitabilities' such as infrastructure limitations, economic arrangements, agricultural policies or mental frameworks as a question of choice. This reframing helps move the debate from a negative perspective (cost-avoidance) into a potentially positive perspective (increased environmental or economic sustainability and opportunity) (Howden *et al*. 2007). As well as reducing harm, TA may be pursued as a way of creating new and better systems, consistent with the move in adaptation circles towards low-regrets strategies (where benefits exist regardless of whether projected impacts eventuate) and win-win options (in which all stakeholders benefit) (UNDP 2009). Adaptation in general is increasingly understood as a response to multiple drivers and a source of multiple benefits (e.g. Pittock 2009) and this is especially true of TA (Pelling 2011; Park *et al*. 2012).

A target of low-regrets strategies is to address the long-standing ecological, social and economic vulnerabilities that climate change exposes, such as soil degradation, biodiversity losses, dependence on declining oil reserves, low financial equity, and an aging farmer population (Green *et al*. 2003; Anderies *et al*. 2006; Walker and Salt 2006; Campbell 2008; Fresco 2009; PHAA 2009; Robinson 2009; Cribb 2010; Fedoroff *et al*. 2010). Research on agriculture's 'social licence' to operate suggests that there is a related growing pressure on agriculture to demonstrate it is a legitimate and preferred user of a land, water, biodiversity and atmospheric base progressively strained by climate change (Martin and Williams 2011) where there are alternative land uses such as for biofuel production, carbon sequestration, biodiversity conservation and other ecosystem services. This includes political and social pressure on agriculture to reduce greenhouse gas emissions. This brings us to the fourth advantage of a co-evolutionary interpretation of adaptation, which is that, like others, farmers need to adapt to the full suite of indirect and direct impacts of climate change, including the full range of its social, cultural, political, financial and physical effects, as well as other concurrent situations and threats. As a response to and source of significant flow-on effects, transformational change requires a perspective that accommodates this breadth and dynamism, as a co-evolutionary perspective does.

Conceptualising transformational climate change adaptation in agriculture

Multiple dimensions of potential transformational change

Given that TA is being and increasingly will be demanded of agriculture in the face of climate change, work is needed to clarify the concept. This requires accepting its heuristic, subjective and relative character. Different perspectives on what counts as transformational change exist and are not reducible to one another. This is for two reasons. First of all, there are many dimensions over which TA to climate change can be conceived (Table 1). While a large spatial scale is one possible dimension, TA can also be thought of differently in relation to smaller scales, from an individual to a family to a community, or from a single farm business or property, to a sector or region.

Second, across any one dimension, the level of change that counts as 'transformational' is subjective and relative. It is relative in two ways. First it is a question of the difference between the deliberate versus background change. Climate change adaptation is essentially about 'persistence through change', which raises the questions of what persists (subject to pre-existing trajectories or variability) and what changes (in a desired, deliberate or obvious way). In TA, this ratio between persistence and change is low; more of the system is changed than is continued as is. Second, this ratio is relative to less transformational forms of change. Adaptation as adjustment (incremental adaptation) infers that the ideal 'ratio' of what remains relatively constant to what is deliberately changed is high. Most of the existing system remains on its pre-existing trajectory. Park *et al*. (2012) note that the central aim of incremental adaptations is to maintain 'the essence and integrity of an incumbent system or process at a given scale' (p. 5).

This second element of relativity is emphasised in the diagram by Howden *et al*. (2010) (Fig. 1) that brought the concept of TA to prominence in the agricultural sector. It presents 'transformational adaptation' as the more radical end of a spectrum of change that begins with incremental adaptation (changes in practices and technologies within an existing system such as planting times or row spacing) and extends through systems adaptation (changes to an existing system, such as major change in the focus between livestock and cropping, new crop types or the adoption of precision agriculture), mapped against an increasing degree of climate change.

The third point to note about TA is that it does not exist in a vacuum: the three types of adaptation in Fig. 1 overlap conceptually and in practice. The adaptation being pursued in any situation depends in part on the type of decision being faced. For some decisions (e.g. the amount of fertiliser to apply to a crop), reducing the decision horizon will likely always be the more rational way of proceeding. For other decisions (e.g. where to purchase a property), TA will be needed. Here, incremental adaptation alone may act as a blockage for necessary change by increasing investment in the existing system or locale and narrowing down alternatives for change: what the resilience, transition and policy literatures refer to as 'lock in trap', 'incrementalism' and 'negative resilience' (e.g. Handmer and Dovers 1996; Allison and Hobbs 2004; Anderies *et al*. 2006).

While the need for some degree of TA will likely become more indispensable and involuntary as climate change increases, it is not always necessary or desirable to wait for such pressures to accumulate. TA is already being pursued earlier to capture various benefits, address pre-existing structural issues, pre-empt possible problems or to accommodate the long lead times on associated decisions and actions (Howden *et al*. 2010; Park *et al*. 2012). TA will also always need to be accompanied by more incremental forms of change to allow for adjustments to fine-tune systems to ongoing change. The earlier decision makers act the more uncertainty and variability needs to be accommodated. This requires making decisions 'robust' across a range of possible future conditions future (Wilby and Dessai 2010; Stafford Smith *et al*. 2011) rather than focusing too narrowly on one climatic signal such as dryness. It also requires building in capacity for monitoring, learning and adjustment (Howden *et al*. 2007). If robustness and flexibility are taken seriously, deliberately acting early on some dimensions to alter the system (e.g. addressing pre-existing vulnerabilities, or adaptation to climate change) is likely to allow for a greater range of options and more influence over circumstances than non-action (Smit *et al*. 1996). How the

Table 1. Possible characteristics of transformational adaptation (TA) across different dimensions of change at the farm and regional scales

Dimension of change	Characteristic of TA	Example for farm system	Example for regional system
Depth of change	Relatively profound change in the system (may be interpreted as the creation of a 'new system')	Move from cereals to farm forestry for carbon sequestration	Change from being a dryland region to an irrigated region, or vice versa
Generality of change	General or intangible change in direction	Shift in goals from optimising productivity to more sustainable, long-term systems	Rezoning of land from agricultural to residential or conservation
Spatial scale of change	Change across whole system of interest	Conversion of a farm from a conventional to an organic system	Establishment of conservation corridors across all farmland in a region to facilitate species migration
Effect on the system	Even if action taken seems minor, has a relatively profound effect on the system	Adoption of substantial off-farm work by farmer to increase income, affecting many aspects of farm management and life	Closure of local abattoir due to reduced level and reliability of local production
Permanence of change	Change is not necessarily permanent, but difficult to reverse	Revegetate pasture with native vegetation Large financial investment in new land	Extension of rail system into new cropping region

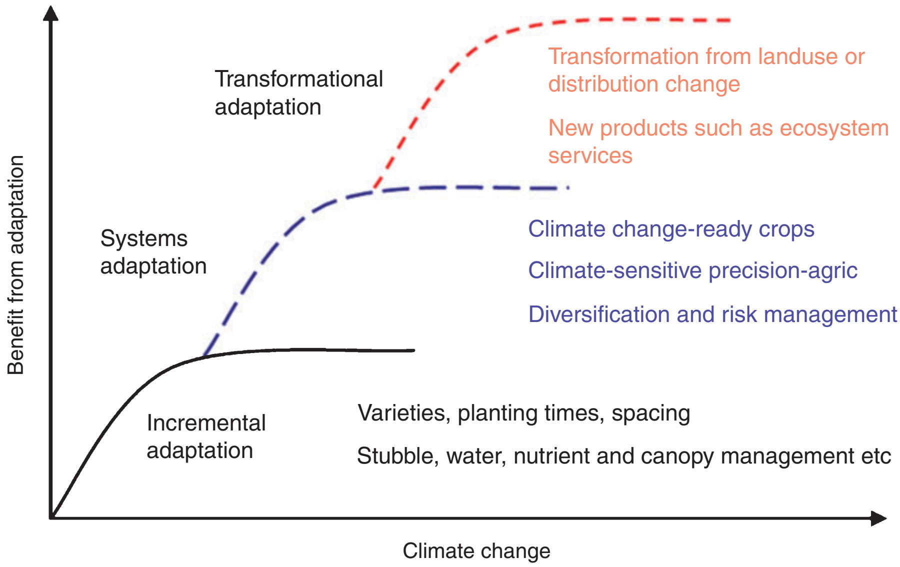

Fig. 1. Levels of adaptation in relation to benefits from adaptation actions and degree of climate change, with illustrative examples (from Howden *et al*. 2010).

different types of adaptation relate to each other in practice is a topic of ongoing research (Park *et al*. 2012). Depending on how TA is defined, incremental adaptations may accumulate on one farm or across a region to create or trigger a transformational change. Park *et al*. (2012) provide examples from the wine industry about how incremental and TA by actors operating at different scales interact, with transformational change at either the farm scale or sectoral scale enabling incremental adaptation at the opposite scale.

Two illustrative types of TA in agriculture

Further insight into TA in agriculture can be gained by considering two illustrative and potentially influential cases:

(1) Changes in goal (for example resulting in a major change in land use and/or employment through trying to do more or something different); and/or
(2) Changes in location (of an agricultural activity and/or agriculturalists) (Fig. 2).

Both strategies are directed at reducing adaptors' vulnerability to climate change impacts (broadly defined), where vulnerability is understood as a combination of sensitivity and exposure to impacts and capacity to adapt (Smit *et al*. 1996). The main difference between them is their relative focus on sensitivity and exposure. Where the anticipated change is negative, an *in situ* change in land use or occupation primarily aims to reduce the adaptors' sensitivity to impacts by shifting to a less climate-sensitive mode of operating, while a spatial relocation primarily aims to reduce the adaptors' exposure to impacts by seeking out a new area anticipated to be more amenable to the continuance of their original activity or occupation. These transformational processes of replacement and displacement may result in the maintenance of agricultural activity, even if there is a shift from food- to non-food-based agriculture in some places. They may also involve a shift out of agriculture, particularly when combined. In contrast, if the perception of climate change is net positive, then the change in land use or location could aim to increase the sensitivity of the operation to capitalise on the anticipated benefits.

The choices involved in such changes highlight the importance of willingness to adapt as well as capacity to adapt (Moser and Ekstrom 2010). The strategies contrast those farmers who are strongly attached to their land and will go to great lengths (including working off-farm, planting it with Blue Gums etc.) to maintain ownership of it, and those who are strongly attached to their farming occupation (and perhaps particular enterprise types such as livestock or cropping) but do not care deeply about where

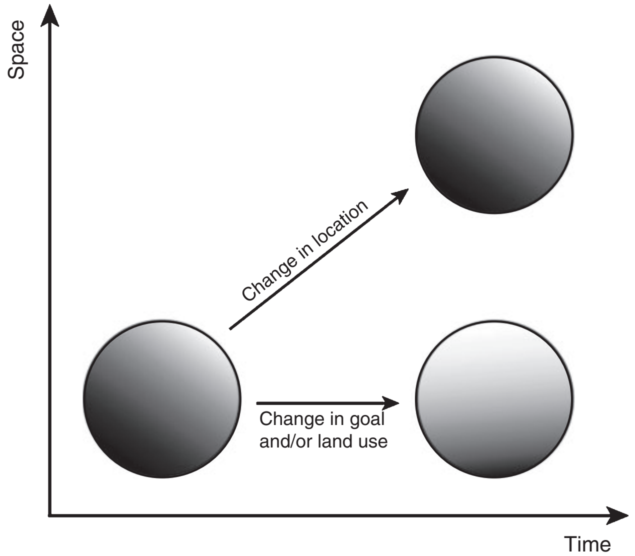

Fig. 2. Schematic diagram of the two main forms of transformational adaptation in agriculture: (*a*) a major *in situ* change; (*b*) a change in spatial location, with minor accompanying *in situ* changes.

they practice it. In this and other ways, TA intersects with identity issues within farming (e.g. see Marshall 2010), including the different ideals of agricultural masculinity dominant in different settings (e.g. Ferrell 2011).

Changes in goal and location presuppose and intersect with other adaptations and broader change processes, both in the landscape and socio-economically, technically and politically. This includes adaptations at the sub-farm level, which are defined here as system changes and not considered in detail. That said, a farmer purchasing an additional property in a new area in order to avoid projected climate impacts in the original area (i.e. partially relocating) could count as transformation, as would substituting a significant amount (not necessarily all) of their agricultural work with off-farm employment. Evidence is emerging of both of these adaptation strategies at work, some in explicit response to climate change (e.g. Park *et al*. 2012; Rickards 2012). Like more definitive changes in goal or location, these adaptation processes at the farm level may aggregate over time and space to create large-scale change. Such a high level view is now taken to describe major transformations within agriculture in the past.

Past and present transformational processes in agriculture

Not only are agriculturalists familiar with the idea of and need for climate adaptation (Kandlikar and Risbey 2000; Howden and Stokes 2009), but so too are they familiar with major transformations (Lobao and Meyer 2001; Barr 2009). These past and ongoing transformations boost the slim evidence base for transformational climate change adaptation by providing temporal and spatial analogues. As for climate change adaptation in general (Ford *et al*. 2010; McLeman and Hunter 2010), these can be used to gain insights into change processes and identify their possible characteristics and constraints.

Eras of agricultural production: an example of changes in goal

At a broad scale, an analogue of the first form of transformational change in agriculture identified above – a change in goal – is provided by the emergence of different eras of agriculture. At a very coarse scale, there was first a shift from traditional agriculture to ‘modern’ science and market-based agriculture, substituting at least at the sectoral level subsistence-based goals and values with ones associated with productivity and professionalism (Rickards 2006). More recently, ‘productivist’ agriculture has been replaced in part by ‘multifunctional’ or ‘post-productivist’ agriculture in Britain and the European Union through alterations to the Common Agricultural Policy arising from changing societal values (Potter and Tilzey 2005; Wilson 2007, 2008). Seen to a far lesser extent in Australia, this shift represents the formal addition of goals associated with land stewardship, biodiversity conservation and ecosystem services to those to do with productivity (Cocklin *et al*. 2006). This insertion of environmental sustainability goals and policies into the agricultural arena is likely to increase under climate change, especially in relation to the mitigation and sequestration imperative that agriculture increasingly seems expected to respond to (Bebbington *et al*. 2011). More generally, the farm business has been decoupled to a degree from farm production *per se* as the goal of increasing productivity has been replaced by that of profitability. This has led to a range of diversifications of farm income, in the most extreme cases involving a complete replacement of farm production income and an exit from farming (in most cases involving a concomitant shift in location for the farm members). As growing numbers of farmers have taken the latter option, farmer numbers have declined significantly in Australia and elsewhere. The resultant ‘Great Transformation’ of agriculture, as Lobao and Meyer (2001) call it in relation to the United States, provides a further analogue of potential TA under climate change, not just as a generic transformational change but as one that is likely to specifically feature among climate change adaptations.

The importation of British agriculture to Australia: an example of a change in land use/location

‘British’ agriculture in its increasingly scientific form was exported to Australia with colonialism in the eighteenth and nineteenth centuries. Indeed, expansion of agricultural land was a key tool of British colonialisation of the ‘empty landscape’ of *Terra Nullius* (Anderson 2003). This relocation or expansion of sedentary agriculture provides an analogue of the second form of transformational change in agriculture identified above and can illustrate significant lessons about such changes in location. First, in contrast to the frontier mentality that accompanied the clearing of land for agriculture, we now know that rather than inserting agriculture into a vacuum, the process was one of replacing existing land uses, people and values, including indigenous ‘fire stick’ farming (Jones 1969). The same holds for any relocation of agriculture today: it will always be in replacement of another set of attributes, values and goals, and thus necessitates careful consideration of costs, trade-offs and power issues. In this way, the processes of displacement and replacement are intricately linked. They are also linked to the extent that no agricultural system can be ‘imported’ to a new location wholesale without significant modifications. Pointing to the interaction of the TA process of relocation with incremental and systems adaptations, farmers and extension agents are acutely aware of the need to adjust generic advice to the local biophysical context (Pannell *et al*. 2006). While the point of relocating agriculture under climate change is to better match an existing agricultural system to a local climate elsewhere, this match will not be perfect, the climate will change in the new location also, and numerous other biophysical factors will be different from the original location (Park *et al*. 2012), requiring *in situ* changes to the agricultural system in its new location, as illustrated in Fig. 2 above. Understanding how the ‘new’ agricultural system interacts with the local environment is essential for identifying, avoiding and managing negative externalities such as habitat loss and water pollution, which is another critical lesson that has emerged from the importation of British agriculture into the Australian context.

Issues for transformational adaptation

The above discussion of some major past transformational changes in agriculture illustrate that such change can involve serious challenges, risks and benefits. It also reinforces that climate change and adaptation are not happening in isolation;

there is already a complex collection of change processes in play. Climate change impacts, adaptation efforts, and the impacts of adaptation itself will interact with these processes, and will likely exacerbate the complexity and uncertainty involved.

In this section, we turn to the climate change adaptation literature to present four general climate change adaptation issues of particular pertinence to TA in agriculture. Bridging literatures in this way is important for facilitating interdisciplinary, social learning of the sort needed to respond to climate change (Collins and Ison 2009*a*; Ison 2010). These issues – costs, maladaptation, adaptive capacity, and role of government – are discussed in turn below.

The costs of transformational adaptation

Common to all change, adaptation to climate change can involve some significant costs. Five are considered here. First are transaction costs, which is the toll on resources (mental, emotional, physical, financial, social etc) that the *process* of change exacts. Transaction costs are largely independent of the positive value or rationality of the change; a point that agricultural extension has come to realise following decades of frustration at farmers' seemingly illogical recalcitrance (Pannell *et al*. 2006). For a farmer, even learning about and considering the applicability of a potential change takes precious time and energy (Pannell *et al*. 2006). Climate change adaptations can involve particularly significant transaction costs, in part because of the uncertainty surrounding what adaptation is needed in response to what potential changes, what the options are and what is most appropriate: the contingency cost can be high. Transaction costs and risks can also be high because the expected benefits of action may not be realised for a long time, or even ever, and the actions can contest with existing norms and values (Howden *et al*. 2008; Orlove 2009). In the case of TA, the retarding influence of uncertainty is greatly exacerbated as the longer time scale, larger spatial and social scale, and greater magnitude of action increases the degree of uncertainty and the deliberation needed. As Stafford Smith *et al*. (2011) discuss, adaptation decisions with long life times (long lasting effects) usually also have long lead times.

The second type of cost to note is opportunity cost. The path dependency of adaptation decisions and especially TA decisions means that this form of cost is also particularly significant in the context of climate change. Path dependency refers to the way in which decisions taken now – particularly transformative ones – may constrain the options available at a later point (Inderberg and Eikeland 2009). As the uncertainty surrounding conditions under climate change demands a flexible or robust approach in which options are kept open (Hallegatte 2009; Wilby and Dessai 2010), this path dependency is especially problematic and requires that strenuous efforts are made to reduce 'lock in' (Allison and Hobbs 2004) and other opportunity costs. TA also highlights the potential for positive change and wider benefits under the guise of adaptation. A further opportunity cost is that which emerges when action is not taken to seize such potential. This appears to be a key motivation for current transformative climate change adaptations in the wine, peanut and rice industries (Park *et al*. 2012).

Opportunity costs can be accepted consciously or unconsciously. The latter unintended consequences are the third form of cost of relevance to climate change adaptation: those costs arising out of the unexpected, often long-term and long distance risks created by our actions, epitomised by climate change itself (Beck 2006) that can be systematically hidden from view if a narrow conceptualisation of value is used in economic framing (Costanza 2001). As Eriksen *et al*. (2011) note, 'not every response to climate change is a good one' (p. 7). For example, a climate adaptation that increases greenhouse gas emissions would be difficult to justify as being internally consistent (Howden *et al*. 2007). TA is particularly vulnerable to creating unintended consequences because the complexity of change involved is beyond the limits of our scientific capacity to predict or trace, as illustrated in the cases of transformational change in agriculture above. That said, avoidance of the unintended consequences of inadequate action is also a major motivator for TA (see Handmer and Dovers 1996).

The fourth type of cost is that which arises out of the incompleteness of adaptation, as adaptation will never fully compensate for climate change losses where the change is negative (Easterling *et al*. 2007). There will therefore always be residual losses and in some cases enhanced gains. Some of these losses may be intended. Economists focussed on cost-efficiency, for example, advocate for *a priori* acceptance of a certain level of damage (Fankhauser 2010). The rationale is that there is an economically optimal level of adaptation, represented by where the cost of adaptation action intersects with the projected cost of climate change impacts at a particular point in time (the latter being the fifth type of cost to note). Although seriously marred by the ignorance within and static nature of the predictions on which the calculations are based (Hulme *et al*. 2009), this approach has popularised the notion of 'over-adaptation': the idea that it is possible to act too soon or too vigorously. TA is especially vulnerable to criticism of over-adaptation, given that the long lead time and opportunity-focus of much such adaptation can require acting in advance of a necessitating degree of climate change (Stafford Smith *et al*. 2011). To the extent that TA involves preventative action, it is further vulnerable to this criticism, as the very successfulness of prevention can diminish public awareness of the reality of the problem at which such action is directed, leading to assertions that such actions are 'over the top' (Zaalberg *et al*. 2009). Nevertheless, there are already examples of farmers making transformative changes in response to the climate trends that are already occurring (Park *et al*. 2012). Ongoing evaluation of the success of these will hopefully inform the discussions in relation to over-adaptation. Hindsight will also inform us whether the costs incurred by reactive, incremental adaptation justified an earlier, staged approach to more systemic and transformational change.

The upshot of the above discussion is that where climate change is negative, adaptation is likely to reduce the size of the losses rather than remove them. Decision makers therefore need to address the types, level and distribution of losses they want to aim for. While TA carries the risk of significant losses, it also has a unique potential to avert potentially greater losses. Rising calls for radical change and action (Bailey and Wilson 2009) indicate that, as discussed by (Jones 2010) and implied by Fig. 1 above, across sectors people are increasingly willing to take a risk in order to try to reduce the extent to which we are at risk under climate change. Agriculture is no exception.

Maladaptation

Whether society will succeed in reducing the extent to which we are at risk from climate change is an open question. Adaptation efforts that fail in this way, or involve excessive costs in the process, are a form of maladaptation. In addition to how effective and efficient adaptation actions are, 'good adaptation' is increasingly assessed, at least in theory, according to other more searching criteria, notably: equity (distributional justice, including future generations); social legitimacy (procedural justice); and sustainability (including inter-species justice) (Adger *et al*. 2005; Barnett and O'Neill 2010; O'Brien *et al*. 2009; Orlove 2009; Eriksen and Brown 2011) as well as risk of increased greenhouse gas emissions which would operate as a positive feedback to climate change (Howden *et al*. 2007).

The systems perspective associated with TA is crucial for attempting to trace the consequences of potential and actual adaptation actions across time, space and social settings in order to try to avoid maladaptation for one's self or others. The high order change that TA involves is also posited as a way of avoiding maladaptation, given the existing problems of inequity and unsustainability that currently exist and potentially may be exacerbated by climate change (Leichenko and O'Brien 2008). It is also in response to concerns about the perceived inadequacy of current proposed adaptation and mitigation actions that calls for TA have been initiated. Calls for consideration of TA are escalating, whether based on the ongoing failure to initiate effective mitigation (e.g. Ayers and Huq 2009), a concern about the long-term ineffectiveness of specific adaptation approaches (e.g. Stokes and Howden 2010), or a desire to address pre-climate change vulnerability (e.g. O'Brien and Wolf 2010).

Of particular pertinence to agriculture is debate about how adaptive the existing responses to climate variability are in the long term. Responding to the impacts of climatic extremes and natural disasters is unavoidable and therefore a stepping stone to longer term adaptation (e.g. McKeon et al. 1993). Failure to acknowledge this can lead to unrealistic and callous expectations of those recovering from disasters (McKeon *et al*. 2004). Recovery processes can also involve many of the same approaches needed for climate change adaptation, particularly when the climatic extreme involved is aligned with changes in average conditions, as is the case for drought in Australia (Howden *et al*. 2010). Yet, research also indicates that responses to variability may in the longer term prove maladaptive. In a study of graziers in Queensland, for example, Marshall (2010) concludes that: 'Enhanced strategies for coping with climate variability will provide a way for encouraging gradual, incremental adjustments for climate adaptation' but may also lead to over-confidence among producers and 'in fact, make them vulnerable to more extreme and frequent climate events predicted for the future (p. 40). Importantly, the consequences of these extreme events may be effectively irreversible and thus reactive, incremental adaptation based on historical experience of extremes and post-hoc learning will potential degrade future production options (McKeon *et al*. 2004). Similarly Handmer and Dovers (1996) stress that 'change at the margins' can create a false sense of security and delay needed transformational change and (Davies 2009) argues that perpetuating a state of mere 'coping' is no substitute for genuine adaptation. Overall, the relationship between adaptation to climate variability and climate change is complex, highly pertinent to agriculture, and in need of in-depth research.

Adaptive capacity

TA requires a higher level of adaptive capacity than incremental or systems-scale adaptation due to the greater risks and complexity arising from the change. To the extent that it can involve collective, voluntary action (a common mode of change in agriculture), it also requires an especially high level of willingness to adapt, which is determined in part by the potential benefits to be gained and the perceived legitimacy of the adaptation process. In many cases TA also requires substantial resources.

The attributes required for transformation may be somewhat different from those required for incremental adaptation. Cork (2010*b*) lists the characteristics of transformability as: experimentation; support for change; trust (social capital); human, built and natural capital; and cross-scale awareness. These characteristics are important in incremental or systems adaptations as well as in change processes more generally, but it could be argued that they are more crucial in transformative climate adaptation. More generally, the five types of capital identified by Nelson *et al*. (2010*a*, 2010*b*) – human capital (e.g. health, education), social capital (within-group and between-group connectedness), financial capital (assets, cash), physical capital (infrastructure, technology) and natural capital (soil, water, biodiversity) – are needed for the perpetuation and improvement of rural livelihoods in general and adaptation to climate change in particular. Empirical research on farming families' decision making experiencing drought and other pressures (Greenhill *et al*. 2009; King *et al*. 2009; Rickards 2012) suggests that the accumulative effects of climate change and other issues erode their net level of these 'capitals' or assets and may encourage maladaptive substitution between them (e.g. exploiting one's human health and energy to substitute for a lack of financial capital by taking on more work). At the level of human capital, transformative learning research with producers suggests that critical reflection on the relationship between practices, the environment, roles, responsibilities and social norms can lead to the kind of transformative change needed for major adaptation to climate change (Tarnoczi 2011). A wealth of research also highlights the importance of social and human capital in enabling the sort of positive, enduring, collective action TA will involve (e.g. Meert *et al*. 2005; Gooch and Rigano 2010; Burton and Paragahawewa 2011).

Role of government

The final issue to highlight in relation to TA in agriculture is the role of government. This is shaped by broader debates about the role of government both in relation to climate change mitigation and adaptation, agriculture and society more generally. In terms of the former, it is acknowledged that climate change can be framed as an unprecedented market failure (Stern 2007), and therefore legitimates government intervention. Yet, the form this intervention could most effectively take is less certain, especially in relation to adaptation which is often misconceived as a mere local-level, private-good concern that will happen autonomously (Nelson *et al*. 2011). Sensitivity to the private benefits of adaptation is enhanced in Australian agriculture, where since the 1970s there has been a move to more precisely distinguish private good from public good activities in agriculture in order to help reduce and justify government expenditure in the sector (Simpson and Dargusch 2010), including in relation to climate-related disasters (Botterill 2003). While this stance remains strongly influential, climate change and associated food security concerns are prompting growing calls to redress some of the consequent reduction in government investment in agricultural research, development and extension (RDE), both in Australia and beyond (e.g. Cribb 2010; PMSEIC 2010). The case for such investment seems particularly strong in support of transformational adaptation, with Pannell (2010) for example arguing that government RDE investment should be focussed on supporting 'decisions that are larger and indivisible, such as land purchase or the decision to exit from agriculture' (unpaginated). Nelson *et al*. (2011) argue that there is a key role of government in identifying and implementing policies that foster pro-active and anticipatory adaptation especially addressing market failures such as moral hazard and adverse selection of risk management approaches.

The appropriate type as well as quantum of agricultural RDE is needed to support TA in agriculture. Information is needed that provides flexible options for farmers and others to use, monitor and evaluate. To be effective, particularly at a transformational level, it is crucial that the underpinning research is cross scale, cross sectoral and integrated with mitigation (Nelson 2009), the latter being a major policy and societal shift that agriculture needs to adapt to. Research to support transformational change therefore needs to be interdisciplinary and engage with relevant insights from diverse areas, including futures thinking (Inayatullah 2008), innovation studies and socio-technical transitions studies (e.g. Geels and Schot 2007; Dolata 2009; Leggewie and Welzer 2010), rural and political geography (e.g. Gibson *et al*. 2010), resilience thinking (e.g. Cork 2010*b*; Gelcich *et al*. 2010), and the mainstream climate risk management literature, including that on migration and climate change adaptation (e.g. Black *et al*. 2011). As pointed out elsewhere, conventional insular agricultural research is increasingly inadequate in the face of growing complexity and uncertainty (see, for example, PMSEIC 2010). More than interdisciplinary, such research also needs to be transdisciplinary, which refers to the integration of non-academic knowledge through participatory processes and in developing systems of adaptive governance (Nelson *et al*. 2008). CSIRO, for example, is starting to work with farmers undertaking transformational changes to better understand and help assess the consequences of different transformation options, in part to avoid problems of the past and the issues of over- or maladaptation discussed above (Park *et al*. 2012). Policy makers, agricultural organisations, agribusiness, agricultural advisors and rural community groups are other important 'end users' and shapers of research into TA of and in agriculture. Effort is needed to bring these different perspectives together to discuss the cross-scale and cross-sectoral shifts that may eventuate under climate change and increase the social learning that is needed for appropriate adaptation.

Conclusion

TA is a crucial and increasingly relevant aspect of agriculture's adaptation to climate change. It is also little studied and poorly understood. This paper has sought to provide an introductory overview of the topic in relation to agriculture. It has highlighted that it is a multidimensional, relative and critical concept, which can be understood more easily by focusing on two major types of change: changes in the goals and/or location, including the option for farmers of exiting the industry. Historical and ongoing examples of other transformational change processes in agriculture provide important insights into what TA under climate change may involve, and further research is required in this area. Further research is also needed to engage the agricultural research community with the broader learning emerging out of the mainstream climate change adaptation literature and other disciplines. TA reinforces the realisation that agricultural research can no longer remain insulated from off-farm, non-science or non-agricultural knowledge or processes. Just as support and guidance of TA requires that we understand how Australian agriculture is currently, and could be, positioned climatically, we need to understand its position within the landscape, rural communities, and broader social, political and cultural environment. It is only by building our capacity in adopting such a broad systems perspective that TA will avoid the maladaptations of the past and enable opportunities for positive change to be realised.

Acknowledgement

The authors would like to thank the Primary Industries Adaptation Research Network for facilitating the production of this paper.

References

Adger WN, Arnell NW, Tompkins EL (2005) Successful adaptation to climate change across scales. *Global Environmental Change* **15**, 77–86. doi:10.1016/j.gloenvcha.2004.12.005

Alexandra J, Riddington C (2007) Redreaming the rural landscape. *Futures* **39**, 324–339. doi:10.1016/j.futures.2006.04.002

Allison HE, Hobbs RJ (2004) Resilience, adaptive capacity, and the 'Lock-in trap' of the Western Australian agricultural region. Ecology and Society 9. Available at: www.ecologyandsociety.org/vol9/iss1/art3 (accessed 30 March 2012)

Anderies J, Ryan P, Walker P (2006) Loss of resilience, crisis and institutional change: lessons from an intensive agricultural system in southeastern Australia. *Ecosystems* **9**, 865–878. doi:10.1007/s10021-006-0017-1

Anderson K (2003) White natures: Sydney's Royal Agricultural Show in post-humanist perspective. *Transactions of the Institute of British Geographers* **28**, 422–441. doi:10.1111/j.0020-2754.2003.00102.x

Ayers J, Huq S (2009) The value of linking mitigation and adaptation: a case study of Bangladesh. *Environmental Management* **43**, 753–764. doi:10.1007/s00267-008-9223-2

Bailey I, Wilson GA (2009) Theorising transitional pathways in response to climate change: technocentrism, ecocentrism, and the carbon economy. *Environment & Planning A* **41**, 2324–2341. doi:10.1068/a40342

Barnett J, O'Neill S (2010) Maladaptation. *Global Environmental Change* **20**, 211–213. doi:10.1016/j.gloenvcha.2009.11.004

Barr N (2009) 'The house on the hill: the transformation of Australia's farming communities.' (Land and Water Australia and Halstead Press: Canberra)

Bebbington J, Asaduzzaman M, Fernandez A, Clark M, Guillou M, Jahn M, Erda L, Mamo T, Van Bo N, Nobre CA, Scholes RJ, Sharma R, Wakhungu J (2011) Achieving Food Security in the Face of Climate Change: summary for policy makers from the Commission on Sustainable Agriculture and Climate Change. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark. Available at: www.ccafs.cgiar.org/commission (accessed 30 March 2012)

Beck U (2006) Living in the world risk society. *Economy and Society* **35**, 329–345. doi:10.1080/03085140600844902

Black R, Kniveton D, Schmidt-Verkerk K (2011) Migration and climate change: towards an integrated assessment of sensitivity. *Environment & Planning A* **43**, 431–450. doi:10.1068/a43154

Botterill LC (2003) Uncertain climate: the recent history of drought policy in Australia. *The Australian Journal of Politics and History* **49**, 61–74. doi:10.1111/1467-8497.00281

Brussaard L, Caron P, Campbell B, Lipper L, Mainka S, Rabbinge R, Babin D, Pulleman M (2010) Reconciling biodiversity conservation and food security: scientific challenges for a new agriculture. *Current Opinion in Environmental Sustainability* **2**, 34–42. doi:10.1016/j.cosust.2010.03.007

Burton RJF, Paragahawewa UH (2011) Creating culturally sustainable agri-environmental schemes. *Journal of Rural Studies* **27**, 95–104. doi:10.1016/j.jrurstud.2010.11.001

Campbell A (2008) 'Paddock to plate: food, farming and Victoria's progress to sustainability. ACF's Future Food & Farm Project.' (Australian Conservation Foundation: Melbourne)

Cocklin C, Dibden J, Mautner N (2006) From market to multifunctionality? Land stewardship in Australia. *The Geographical Journal* **172**, 197–205. doi:10.1111/j.1475-4959.2006.00206.x

Collins K, Ison R (2009*a*) Jumping off Arnstein's ladder: social learning as a new policy paradigm for climate change adaptation. *Environmental Policy & Governance* **19**, 358–373. doi:10.1002/eet.523

Collins K, Ison R (2009*b*) Living with environmental change: adaptation as social learning. *Environmental Policy and Governance* **19**, 351–357. doi:10.1002/eet.520

Cork S (2010*a*) 'Resilience and transformation: preparing Australia for uncertain futures.' (CSIRO Publishing: Melbourne)

Cork S (Ed.) (2010*b*) Resilience of social-ecological systems. In 'Resilience and transformation: preparing Australia for uncertain futures'. pp. 131–142. (Australia 21 and CSIRO: Melbourne)

Cork S, Eckersley R, Walker B (2010) 'Rapid and surprising change in Australia's future: anticipating and preparing for future challenges and opportunities on the way to a sustainable Australia.' (Australia 21: Canberra). www.australia21.org.au/oldsite/pdf/Tipping2007.pdf

Costanza R (2001) Visions, values, valuation, and the need for an ecological economics. *Bioscience* **51**, 459–468. doi:10.1641/0006-3568(2001)051[0459:VVVATN]2.0.CO;2

Cribb J (2010) 'The coming famine: the global food crisis and what we can do to avoid it.' (CSIRO Publishing: Melbourne)

Davies S (2009) Are coping strategies a cop out? In 'The Earthscan Reader on adaptation to climate change'. (Eds ELF Schipper, I Burton) pp. 99–116. (Earthscan: London)

Dolata U (2009) Transformative capacity, adaptability, patterns of change: an analytical framework. *Research Policy* **38**, 1066–1076. doi:10.1016/j.respol.2009.03.006

Easterling WE, Aggarwal PK, Batima P, Brander K, Erda L, Howden SM, Kirilenko A, Morton J, Soussana JF, Schmidhuber J, Tubiello FN (2007) Food, fibre and forest products. Climate Change 2007: impacts, adaptation and vulnerability. In 'Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change'. (Eds ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson) pp. 273–313. (Cambridge University Press: Cambridge, UK)

Eriksen S, Brown K (2011) Sustainable adaptation to climate change. *Climate and Development* **3**, 3–6. doi:10.3763/cdev.2010.0064

Eriksen S, Aldunce P, Bahinipati CS, Martins RD, Molefe JI, Nhemachena C, O'Brien K, Olorunfemi F, Park J, Sygna L, Ulsrud K (2011) When not every response to climate change is a good one: identifying principles for sustainable adaptation. *Climate and Development* **3**, 7–20. doi:10.3763/cdev.2010.0060

Fankhauser S (2010) The costs of adaptation. *WIREs Climate Change* **1**, 23–30. doi:10.1002/wcc.14

Fedoroff NV, Battisti DS, Beachy RN, Cooper PJM, Fischhoff DA, Hodges CN, Knauf VC, Lobell D, Mazur BJ, Molden D, Reynolds MP, Ronald PC, Rosegrant MW, Sanchez PA, Vonshak A, Zhu JK (2010) Radically rethinking agriculture for the 21st Century. *Science* **327**, 833–834. doi:10.1126/science.1186834

Ferrell AK (2011) Doing masculinity: gendered challenges to replacing burley tobacco in central Kentucky. *Agriculture and Human Values*, in press. doi:10.1007/s10460-011-9330-1

Ford JD, Keskitalo ECH, Smith T, Pearce T, Berrang-Ford L, Duerden F, Smit B (2010) Case study and analogue methodologies in climate change vulnerability research. *WIREs Climate Change* **1**, 19.

Fresco LO (2009) Challenges for food system adaptation today and tomorrow. *Environmental Science & Policy* **12**, 378–385. doi:10.1016/j.envsci.2008.11.001

Geels FW, Schot J (2007) Typology of sociotechnical transition pathways. *Research Policy* **36**, 399–417. doi:10.1016/j.respol.2007.01.003

Gelcich S, Hughes TP, Olsson P, Folke C, Defeo O, Fernandez M, Foal S, Gunderson LH, Gundersong LH, Rodríguez-Sickert C, Scheffer M, Steneck RS, Castilla JC (2010) Navigating transformations in governance of Chilean marine coastal resources. *Proceedings of the National Academy of Sciences of the United States of America* **107**, 16794–16799. doi:10.1073/pnas.1012021107

Gibson K, Cahill A, McKay D (2010) Rethinking the dynamics of rural transformation: performing different development pathways in a Philippine municipality. *Transactions of the Institute of British Geographers* **35**, 237–255. doi:10.1111/j.1475-5661.2009.00378.x

Gooch M, Rigano D (2010) Enhancing community-scale social resilience: what is the connection between healthy communities and healthy waterways? *The Australian Geographer* **41**, 507–520. doi:10.1080/00049182.2010.519698

Green K, Harvey M, McMeekin A (2003) Transformations in food consumption and production systems. *Journal of Environmental Policy and Planning* **5**, 145–163. doi:10.1080/1523908032000121175

Greenhill J, King D, Lane A, MacDougall C (2009) Understanding resilience in South Australian farm families. *Rural Society* **19**, 318–325. doi:10.5172/rsj.351.19.4.318

Hallegatte S (2009) Strategies to adapt to an uncertain climate change. *Global Environmental Change* **19**, 240–247. doi:10.1016/j.gloenvcha.2008.12.003

Handmer J, Dovers S (1996) A typology of resilience: rethinking institutions for sustainable development. *Organization & Environment* **9**, 482–511. doi:10.1177/108602669600900403

Horlings LG, Marsden TK (2011) Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernisation of agriculture that could 'feed the world'. *Global Environmental Change* **21**, 441–452. doi:10.1016/j.gloenvcha.2011.01.004

Howden SM, Stokes CJ (2009) Introduction. In 'Adapting agriculture to climate change: preparing Australian agriculture, forestry and fisheries for the future'. (Eds CJ Stokes, SM Howden) pp. 1–12. (CSIRO: Melbourne)

Howden SM, Soussana JF, Tubiello FN, Chhetri N, Dunlop M, Meinke H (2007) Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 19691–19696. doi:10.1073/pnas.0701890104

Howden SM, Crimp SJ, Stokes CJ (2008) Climate change and Australian livestock systems: impacts, research and policy issues. *Australian Journal of Experimental Agriculture* **48**, 780–788. doi:10.1071/EA08033

Howden SM, Crimp S, Nelson RN (2010) Australian agriculture in a climate of change. In 'Managing Climate Change: Papers from GREENHOUSE 2009 Conference'. (Eds I Jubb, P Holper, W Cai) pp. 101–112. (CSIRO Publishing: Melbourne)

Hulme M, Pielke R Jr, Dessai S (2009) Keeping prediction in perspective. *Nature* **3**, 2.

Inayatullah S (2008) Six pillars: futures thinking for transforming. *Foresight* **10**, 4–21. doi:10.1108/14636680810855991

Inderberg TH, Eikeland PO (2009) Limits to adaptation: analysing institutional constraints. In 'Adapting to climate: thresholds, values and governance'. (Eds W Adger, I Lorenzonin, K O'Brien) pp. 433–447. (Cambridge University Press: Cambridge, UK)

Ison R (2010) 'Systems practice: how to act in a climate change world.' (The Open University and Springer: London)

Jones R (1969) Fire-stick farming. *Australian Natural History* **16**, 224.

Jones R (2010) The use of scenarios in adaption planning: managing risks in simple to complex settings. Report for the Victorian Centre for Climate Change Adaptation Research. Scenarios for Climate Adaptation Program. Available at: www.vcccar.org.au/files/vcccar/Jones%20scenarios%20presentation%2011-11-10.pdf

Kandlikar M, Risbey J (2000) Agricultural impacts of climate change: if adaptation is the answer, what is the question? *Climatic Change* **45**, 529–539. doi:10.1023/A:1005546716266

King D, Lane A, MacDougall C, Greenhill J (2009) The resilience and mental health and wellbeing of farm families experiencing climate variation in South Australia. Report for the National Institute of Labour Studies Incorporated, Adelaide, Australia.

Kwadijk JCJ, Haasnoot M, Mulder JPM, Hoogvliet MMC, Jeuken ABM, van der Krogt RAA, van Oostrom NGC, Schelfhout HA, van Velzen EH, van Waveren H, de Wit MJM (2010) Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. *WIRES Climate Change* **1**, 729–740. doi:10.1002/wcc.64

Leggewie C, Welzer H (2010) Another 'great transformation'? Social and cultural consequences of climate change. *Journal of Renewable and Sustainable Energy* **2**, 031009. doi:10.1063/1.3384314

Leichenko RM, O'Brien KL (2008) 'Environmental change and globalization: double exposures.' (Oxford University Press: Oxford, UK)

Lobao L, Meyer K (2001) The great agricultural transition: crisis, change, and social consequences of Twentieth Century US farming. *Annual Review of Sociology* **27**, 103–124. doi:10.1146/annurev.soc.27.1.103

Marshall NA (2010) Understanding social resilience to climate variability in primary enterprises and industries. *Global Environmental Change* **20**, 36–43. doi:10.1016/j.gloenvcha.2009.10.003

Martin P, Williams J (2011) Renegotiating farmers' social licence. In 'Defending the social licence of farming: issues, challenges and new directions for agriculture'. (Eds J Williams, P Martin) pp. 195–202. (CSIRO Publishing: Melbourne)

McKeon GM, Howden SM, Abel NOJ, King JM (1993) Climate change: adapting tropical and subtropical grasslands. In 'Grasslands for our world'. (Ed. MJ Baker) pp. 426–435. (SIR Publishing: Wellington, New Zealand)

McKeon G, Hall W, Henry B, Stone G, Watson I (Eds) (2004) 'Pasture degradation and recovery in Australia's Rangelands: learning from history.' (Queensland Department of Natural Resources, Mines and Energy: Brisbane)

McLeman RA, Hunter LM (2010) Migration in the context of vulnerability and adaptation to climate change: insights from analogues. *WIRES Climate Change* **1**, 450–462.

McNeall D, Halloran PR, Good P, Betts RA (2011) Analyzing abrupt and nonlinear climate changes and their impacts. *WIRES Climate Change* **2**, 663–686. doi:10.1002/wcc.130

Meert H, van Huylenbroeck G, Vernimmen T, Bourgeois M, van Hecke E (2005) Farm household survival strategies and diversification on marginal farms. *Journal of Rural Studies* **21**, 81–97. doi:10.1016/j.jrurstud.2004.08.007

Moser SC, Ekstrom JA (2010) A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences of the United States of America* **107**, 22026–22031. doi:10.1073/pnas.1007887107

Nelson GC (2009) Agriculture and Climate Change: An Agenda for Negotiation in Copenhagen, 2020 Vision for Food. Agriculture and the Environment, International Food Policy Research Institute, Washington, DC.

Nelson R, Howden M, Smith MS (2008) Using adaptive governance to rethink the way science supports Australian drought policy. *Environmental Science & Policy* **11**, 588–601.

Nelson R, Kokic P, Crimp S, Martin P, Meinke H, Howden M (2010*a*) The vulnerability of Australian agriculture to climate variability & change: Part I – reconciling the supply and demand for integrated assessments. *Environmental Science & Policy* **13**, 8–17. doi:10.1016/j.envsci.2009.09.006

Nelson R, Kokic P, Crimp S, Martin P, Meinke H, Howden M, Devoil P, McKeon G, Nidumolu U (2010*b*) The vulnerability of Australian agriculture to climate variability & change: Part II – vulnerability assessments that support adaptation. *Environmental Science & Policy* **13**, 18–27. doi:10.1016/j.envsci.2009.09.007

Nelson R, Byron N, Stafford Smith M (2011) Towards economic and policy analysis of adaptation to climate change. In 'Paper presented at the Australian Economics Society Annual Conference'. 11–14 July, Canberra, ACT. Available at: http://publicpolicy.anu.edu.au/coombs/workshops/climate_change_adaptation_in_australia/Adaptation%20-%20towards%20eco%20&%20policy%20analysis.pdf

New M, Liverman D, Schroder H, Anderson K (2011) Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications. *Philosophical Transactions of the Royal Society A* **369**, 6–19. doi:10.1098/rsta.2010.0303

O'Brien K (2011) Global environmental change II: from adaptation to deliberate transformation. *Progress in Human Geography*, in press. doi:10.1177/0309132511425767

O'Brien KL, Wolf J (2010) A values-based approach to vulnerability and adaptation to climate change. *WIRES Climate Change* **1**, 232–243.

O'Brien K, Hayward B, Berkes F (2009) Rethinking social contracts: building resilience in a changing climate. *Ecology and Society* **14**. Available at: www.ecologyandsociety.org/vol14/iss2/art12/

Orlove B (2009) The past, the present and some possible futures of adaptation. In 'Adapting to climate change: thresholds, values, governance'. (Eds WN Adger, I Lorenzoni, K O'Brien) pp. 131–163. (Cambridge University Press: Cambridge, UK)

Pannell DJ (2010) Policy for climate change adaptation in agriculture. In 'Paper presented at the 54th Annual Conference of the Australian Agricultural and Resource Economics Society'. Adelaide, 10–12 February 2010.

Pannell DJ, Marshall G, Barr N, Curtis A, Vanclay F, Wilkinson R (2006) Understanding and promoting adoption of conservation practices by rural landholders. *Australian Journal of Experimental Agriculture* **46**, 1407–1424. doi:10.1071/EA05037

Park SE, Marshall NA, Jakku E, Dowd AM, Howden SM, Mendham E, Fleming A (2012) Informing adaptation responses to climate change through theories of transformation. *Global Environmental Change* **22**, 115–126. doi:10.1016/j.gloenvcha.2011.10.003

Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (2007) Climatic change: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK.

Pelling M (2011) 'Adaptation to climate change: from resilience to transformation.' (Routledge: London)

PHAA (2009) 'A future for food: addressing public health, sustainability and equity from paddock to plate.' (Public Health Association of Australia: Canberra) www.phaa.net.au/documents/PHAA%20Report.pdf

Pittock J (2009) Lessons for climate change adaptation from better management of rivers. *Climate and Development* **1**, 194–211. doi:10.3763/cdev.2009.0021

PMSEIC (2010) 'Australia and food security in a changing world.' (The Prime Minister's Science, Engineering and Innovation Council: Canberra)

Potter C, Tilzey M (2005) Agricultural policy discourses in the European post-Fordist transition: neoliberalism, neomercantilism and multifunctionality. *Progress in Human Geography* **29**, 581–600. doi:10.1191/0309132505ph569oa

Rahmstorf S, Cazenave A, Church JA, Hansen JE, Keeling RF, Parker DE, Somerville RCJ (2007) Recent climate observations compared to projections. *Science* **316**, 709. doi:10.1126/science.1136843

Rickards L (2006) Capable, enlightened and masculine: constructing English agriculturalist ideals in formal agricultural education, 1845–2003. PhD Thesis, School of Geography and Environment, University of Oxford, UK.

Rickards L (2012) Critical breaking point? The effects of climate variability and other pressures on farm households. Final Report for the Birchip Cropping Group, Birchip, Australia. Available at: www.bcg.org.au/cb_pages/Social_and_Comm_Dev.php

Robinson GM (2009) Towards sustainable agriculture: current debates. *Geography Compass* **3**, 1757–1773. doi:10.1111/j.1749-8198.2009.00268.x

Russill C, Nyssa Z (2009) The tipping point trend in climate change communication. *Global Environmental Change* **19**, 336–344. doi:10.1016/j.gloenvcha.2009.04.001

Simpson S, Dargusch P (2010) Classifying public benefit in Australian agricultural research. *Australasian Agribusiness Review* **18**, 13.

Smit B, McNabb D, Smithers J (1996) Agricultural adaptation to climatic variation. *Climatic Change* **33**, 7–29. doi:10.1007/BF00140511

Sounness C (2011) Five big questions: assisting broadacre agriculture to face the need for transformational change. In 'Climate Change Research Strategy for Primary Industries Conference'. Feburary 2011, Melbourne. Available at: www.theccrspiconference.com.au/viewStory/Presentations

Stafford Smith M, Horrocks L, Harvey A, Hamilton C (2011) Rethinking adaptation for a 4°C world. *Philosophical Transactions of the Royal Society A* **369**, 196–216.

Stern N (2007) 'Stern Review: the economics of climate change.' (Cambridge University Press: Cambridge, UK)

Stokes CJ, Howden SM (Eds) (2010) 'Adapting agriculture to climate change: preparing Australian agriculture, forestry and fisheries for the future.' (CSIRO Publishing: Melbourne)

Tarnoczi T (2011) Transformative learning and adaptation to climate change in the Canadian Prairie agro-ecosystem. *Mitigation and Adaptation Strategies for Global Change* **16**, 387–406. doi:10.1007/s11027-010-9265-7

UNDP (2009) A climate risk management approach to disaster reduction and adaptation to climate change. In 'The Earthscan Reader on adaptation to climate change'. (Eds ELF Schipper, I Burton) pp. 229–248. (Earthscan: London)

Walker B, Salt D (2006) 'Resilience thinking: sustaining ecosystems and people in a changing world.' (Island Press: New York)

Walker B, Abel N, Anderies J, Ryan P (2009) Resilience, adaptability and transformability in the Goulburn-Broken catchment, Australia. *Ecology & Society* **14**, Article No. 12.

WGBU (2011) World in transition: a social contract for sustainability. Report by the German Advisory Council on Global Change (WGBU), Berlin.

Wilby RL, Dessai S (2010) Robust adaptation to climate change. *Weather* **65**, 180–185. doi:10.1002/wea.543

Wilson G (2007) 'Multifunctional agriculture: a transition theory perspective.' (CABI: Wallingford, UK)

Wilson GA (2008) From 'weak' to 'strong' multifunctionality: conceptualising farm-level multifunctional transitional pathways. *Journal of Rural Studies* **24**, 367–383. doi:10.1016/j.jrurstud.2007.12.010

Zaalberg R, Midden C, Meijnders A, McCalley T (2009) Prevention, adaptation, and threat denial: flooding experiences in the Netherlands. *Risk Analysis* **29**, 1759–1778. doi:10.1111/j.1539-6924.2009.01316.x