available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/envsci

Review

The vulnerability of Australian rural communities to climate variability and change: Part I—Conceptualising and measuring vulnerability

R. Nelson [a,*], P. Kokic [a], S. Crimp [a], H. Meinke [b], S.M. Howden [a]

[a] CSIRO Climate Adaptation Flagship, GPO Box 284, Canberra, ACT 2601, Australia
[b] Centre for Crop Systems Analysis, Wageningen University, P.O. Box 430, NL 6700 AK, Wageningen, The Netherlands

ARTICLE INFO

Published on line 8 November 2009

Keywords:
Vulnerability
Adaptive capacity
Climate
Policy
Hazard
Impact modelling

ABSTRACT

Vulnerability is a term frequently used to describe the potential threat to rural communities posed by climate variability and change. Despite growing use of the term, analytical measures of vulnerability that are useful for prioritising and evaluating policy responses are yet to evolve. Demand for research capable of prioritising adaptation responses has evolved rapidly with an increasing awareness of climate change and its potential impacts on rural communities. Research into the climate-related vulnerability of Australian rural communities is only just beginning to emerge. Current research is dominated by hazard/impact modelling, drawing on a heritage of managing the risks posed by seasonal climate variability. There is a natural tendency to use the same risk management approach to understand the emergent nature of vulnerability. In this paper, we explore the consequences for policy advice of imperfectly examining vulnerability through the lens of an impact/hazard modelling approach to risk management. In a second paper in this series, we show how hazard/impact modelling can be complemented with more holistic measures of adaptive capacity to provide quantitative insights into the vulnerability of Australian rural communities to climate variability and change.

1. Introduction

Vulnerability is a term increasingly used in policy to describe the risks posed to rural communities by climate variability and change. Despite its frequent use, the concept of vulnerability is rarely converted into analytical measures that can be used to prioritise policy interventions and evaluate their impact. Demand for research to prioritise adaptation policy throughout society has arisen from an increasing awareness of the potential threat posed by a changing climate. Climate-related research and extension in Australia since the 1980s has focused on applications of seasonal climate forecasting to manage the production risks associated with climate variability within existing farming systems (Meinke and Stone, 2005). At the time of writing, the types of science available to inform rural policy associated with adaptation to climate change in Australia were continuing to build on this heritage of hazard and impact modelling (Hennessy et al., 2008). Both these streams of research continue to pursue greater predictive skill over longer time horizons using new generations of global climate models. The paradox that we address in this paper is whether adhering to this approach risks

* Corresponding author. Current address: Department of Climate Change, GPO Box 854 Canberra ACT 2601, Australia. Tel.: +61 0 26159 7465.
E-mail address: rohan.nelson@climatechange.gov.au (R. Nelson).

1462-9011/$ – see front matter. Crown Copyright © 2009 Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.envsci.2009.09.006

stranding adaptation policy in the multi-dimensional uncertainty surrounding climate change.

We begin by reviewing the policy context within which the demand for vulnerability research in Australia has been evolving. This provides preliminary insights into the policy issues and trade-offs that vulnerability research needs to address in order to be policy relevant. We then explore options for conceptualising and measuring vulnerability and adaptive capacity from a rapidly expanding international literature. In a second paper (Nelson et al., 2010), we show how hazard and impact modelling can be combined with an holistic measure of adaptive capacity to provide quantitative insights into the vulnerability of Australian rural communities to climate variability and change. This builds on research by Nelson et al. (2005), who used the rural livelihoods analysis framework of Ellis (2000) to create a vulnerability index for Australian broadacre agriculture.

2. Background

2.1. International policy environment

International climate policy is on the cusp of an unprecedented transition in two important dimensions. First, it has begun to move from an almost exclusive focus on mitigating greenhouse gas emissions, toward adapting to the changes in climate that we are already experiencing (Burton, 2003). This is in response to a growing recognition that the world's climate has already changed due to human activity, and that significant future climate change is inevitable even if an unusual degree of collective action results in immediate reductions in global greenhouse gas emissions (Fussel and Klein, 2006; IPCC, 2007). Authoritative reports such as Stern (2006) and Garnaut (2008) have begun to translate climate change projections into potential economic impacts. This has raised the priority given to climate change within the political agendas of governments around the world.

Second, while there is a high degree of confidence that our climate will continue to change in significant ways, the exact nature and consequences of these changes are highly uncertain (IPCC, 2007). The uncertainty surrounding the impacts of climate change is forcing a rethink of traditional risk management approaches to climate policy, especially in agriculture. Climate-related policy in agriculture and the science used to support it has tended to focus on scientific systems for predicting extreme events such as droughts, floods and storms and their impacts on agriculture (Kundzewicz et al., 2002; Wilhite, 2002). The extent to which the management of climate variability is intrinsic to agricultural policy and practice should provide a natural foundation from which adaptation to climate change can evolve (Howden et al., 2007). However, this advantage may prove difficult to realise. This is because adaptation to climate variability and change has often been conceptualised as a linear sequence of technical responses to clearly identified and predictable sources of risk. A narrow focus on forms of risk that can be quantified and predicted can have the unintended consequence of under-emphasising longer term and more holistic opportunities to build adaptive capacity. It also overlooks fundamental limits to predictability in the global climate system (Barnston et al., 2005), and tends to focus on the drivers of climate variability and change which cannot be influenced by decision makers (Meinke et al., 2006; Nelson et al., 2007a).

2.2. Australian policy environment

Although the terms *vulnerability* and *adaptive capacity* were rarely used in the past, the goal of Australian agricultural policy has ostensibly been to enhance the capability of farmers and rural communities to self-manage climate risk (DAFF, 2005). Historically, the focal point of climate policy in Australian agriculture has been drought. Australia's national drought policy was comprehensively reviewed by Botterill (2005), while the earlier history of drought policy was reviewed by James (1973). Prior to 1989, drought was treated as a natural disaster attracting emergency relief. This form of drought policy was widely suspected of undermining incentives for farmers to self-manage climate risk. In policy development since the early 1990s, drought has been considered a natural characteristic of Australia's variable and changing climate. This means that successful management of climate risk is recognised as a definitive characteristic of farming excellence (see for example Blackadder, 2005). With this focus on self-reliance, the rationale for providing drought support has been to ensure that farmers with long-term prospects for viability are not forced to leave their land due to short-term adverse events (DAFF, 2005).

As has been the case internationally, policies relating to climate variability and change in Australian agriculture have tended to adopt approaches to risk management that focus on selected risks in existing systems that can be quantified and predicted. The result has been an emphasis on technical solutions to maintaining current farming systems and patterns of land use. The joint Australian/New Zealand Standard on Risk Management, for example, defines risk management as the systematic application of management policies, procedures and practices to the tasks of identifying, analysing, assessing, treating and monitoring risk (Hardaker et al., 2004, p.13). This type of risk management has been promoted as the basis for managing adaptation to climate change in Australia by Clark et al. (2006). This approach to risk management attempts to focus policy and decision making on minimising the occurrence and impact of risky events, something that is all but impossible with climate extremes. Institutionalising this approach to risk management has two unintended consequences. First, it diminishes the value of science in the eyes of the policy makers because it provides the right answers to the wrong questions (Nelson et al., 2007a). Second, it risks immobilising scarce research funds in the design and development of ill-fated policy support tools (Nelson et al., 2008).

Although somewhat aspirational, the need for more innovative and holistic approaches to understanding the vulnerability of Australian rural communities to climate variability and change was recognised in Australia's National Agriculture & Climate Change Action Plan (NACCAP) (DAFF, 2006). The action plan begins by recognising the uncertainty surrounding future climate change: *The size and scope of the impacts of climate change are still beyond our grasp but the threat is very real* (DAFF, 2006, p. iii). The NACCAP goes on to envision a policy framework that builds on, but transcends, traditional risk management and sustainable farming practices to promote a culture of innovation and responsiveness in addressing global change. The action plan identifies four areas for transformative science and policy:

- adaptation strategies to build resilience into agricultural systems;
- mitigation strategies to reduce greenhouse gas emissions;
- research and development to enhance the agricultural sector's capacity to respond to climate change; and
- awareness and communication to inform decision-making by primary producers and rural communities.

The NACCAP framework was one early step in a policy transition surrounding adaptation to climate change in Australia. The Australian Government elected in November 2007 created a Department of Climate Change, and is establishing processes for coordinating national adaptation policy. A National Climate Change Research Strategy for Primary Industries was developed jointly by Australia's Rural Research and Development Corporations, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), as well as State and Federal governments (http://www.lwa.gov.au/ccrspi/). The Council of Australian Governments provided CSIRO with an additional $44 million funding over 4 years to establish a Climate Adaptation Flagship. The Flagship is a large-scale, multidisciplinary research partnership designed to enable Australia, including the agricultural sector, to adapt more effectively to the impacts of climate variability and change. The Australian Government has also committed up to $126 million over 5 years to establish a National Climate Change Adaptation Research Facility managed by Griffith University. The goal of this facility is to improve understanding of the impacts of climate change and to develop adaptation responses. It will also establish research networks to enhance communication and integration.

An analysis of these policy initiatives reveals a common set of goals. Shared priorities include identifying vulnerable industries and regions, exploring why they are vulnerable, and prioritising policies and programs to build their adaptive capacity. A key difference lies within their scope. Different policy programs focus on different and/or multiple communities, industries or regions, spanning in some cases the full diversity of Australian rural communities or society more generally.

2.3. *Applications to Australian agriculture*

Most climate-related research and extension in Australian agriculture has focused on impact modelling using seasonal climate forecasts to manage the production impacts of climate variability within existing farming systems. This research has been comprehensively reviewed by Hammer (2000), McKeon et al. (2004) and Meinke and Stone (2005). Statistical forecasting systems that provide probabilistic forecasts of seasonal rainfall have been combined with models of crop and pasture production to evaluate potential changes in farm management. Seasonal climate forecasting has been applied across multiple scales from production in individual farmers' fields to crop and pasture production across Australia (Stephens et al., 1989; Carter et al., 2000; Potgieter et al., 2005). These in turn have been combined with economic models to predict the impact of climate variability on farm incomes for the coming season (Kokic et al., 2007), with potential to revolutionise the types of science used to support drought and other rural policy (Nelson et al., 2007a).

At the time of writing, the science available to support climate adaptation policy in Australian agriculture was also dominated by climate impact modelling. A review by Pearson et al. (2008) found that most existing research has focused on modelling the potential impacts of climate change on agricultural production. Much less attention has been given to adaptive management responses with potential to reduce the impacts of climate change on production. In a paper currently being updated, Howden et al. (2003) reviewed potential adaptive management responses within a wide array of agricultural industries at farm, regional and national scales. This type of broad sectoral adaptation analysis is rare, if not unique, with most studies focusing on impacts on particular industries such as grazing (Crimp et al., 2002), grains (Potgieter et al., 2008), wool (Harle et al., 2007) and wine (Webb et al., 2008). Kokic et al. (2005) made a preliminary attempt to translate the production-related impacts of climate change into changes in land values. Kingwell (2006) drew on this type of quantitative analysis to provide a descriptive review of potential economic impacts and adaptation options in agriculture. Initial attempts have been made to predict the impacts of climate-induced changes in agricultural productivity on regional economic output and employment using macroeconomic models (Heyhoe et al., 2007).

Preliminary attempts have also been made to explore the cross-sectoral impacts of climate change in agriculture, partially based on macroeconomic models (Garnaut, 2008). Other cross-sectoral studies referring to agriculture have provided qualitative assessments of vulnerability based on industry and community consultation to guide preliminary thinking on adaptation (Allen Consulting Group, 2005).

3. Vulnerability research

3.1. *Diverse disciplinary perspectives*

Vulnerability is a contested concept, and there is little agreement about how to convert it into policy relevant measures for priority setting. The concept of climate-related vulnerability has been comprehensively reviewed by many authors (Adger, 2006; Adger et al., 2007; Adger and Vincent, 2005; Alwang et al., 2001; Eakin and Luers, 2006; Eriksen and Kelly, 2007; Fussel and Klein, 2006; Gallopin, 2006; Nelson et al., 2007b). Most, but not all of these reviews, have set out to compare and/or reconcile the diverse perspectives of vulnerability held by different academic disciplines. For example, Adger (2006) identified four prominent schools of thought within political science, ecology and ecological economics, adaptive management and sustainable livelihoods analysis that have contributed conceptual understandings of vulnerability. Alwang et al. (2001) compared perspectives from economics, social science and anthropology, disaster management, environment science as well as health and nutrition.

Within this diversity of disciplinary perspectives, there is growing convergence around at least the generic attributes of vulnerability. In a comprehensive review, Nelson et al. (2007b) defined vulnerability as the *susceptibility of a system to disturbances determined by exposure to perturbations, sensitivity to perturbations, and the capacity to adapt* (p. 396). Consistent with this definition, the vulnerability of human–environment systems to climate risk is widely agreed to depend on their relative exposure to climate variability and change, their sensitivity to exposure and capacity to adapt. There is growing agreement surrounding the conceptualisation of vulnerability as susceptibility to harm, rather than as a measure of harm itself (Gallopin, 2006), and as a state of being independent of whether it is actually triggered by exposure to threats or drivers of change (Sen, 1981; Gallopin, 2006). This view is consistent with common use of the word. It is displacing narrower technical concepts of vulnerability as specific to individual drivers of change, and their probability of occurring, derived from hazard assessment and engineering approaches to risk management. Vulnerability is sometimes defined in terms of its opposites, such as entitlement (Sen, 1981) and security (Chambers, 1989) from a socioeconomic perspective, or robustness and resilience from an ecological perspective (Anderies et al., 2004; Gallopin, 2006).

A common logical fallacy in the emerging field of vulnerability research in Australia is to confuse definitions of vulnerability with conceptual frameworks. This began with an initial cross-sectoral assessment of climate change vulnerability by the Allen Consulting Group (2005). The simple schematic used to define vulnerability has been confused as a conceptual framework in a series of vulnerability assessments (Hobday et al., 2008; Preston et al., 2008; Johnson and Marshall, 2007). Definitions describe the components of vulnerability, such as exposure, sensitivity and adaptive capacity, whereas conceptual frameworks give meaning to the emergent properties of these concepts so that they can be analysed in ways that are objective and repeatable. Definitions are not conceptual frameworks, they simply shift the conceptual debate to the subcomponents of vulnerability—what are exposure, sensitivity and adaptive capacity, and how can they be measured?

3.2. *Hazard/impact assessment*

While there is growing consensus about the components of vulnerability, there is much less agreement about how to refine conceptual definitions into operational metrics that can be used to inform policy and decision making (Adger, 2006; Gallopin, 2006). This disagreement arises from differences between disciplinary perspectives, and the diversity of contexts in which these ideas are applied (Adger, 2006).

While more holistic applications are clearly possible (Blaikie et al., 1994), most applications of hazard or impact modelling tend to conceptualise vulnerability as the residual impact of change once adaptation has occurred—the *end-point* of the analysis (Eriksen and Kelly, 2007; Fussel and Klein, 2006). This approach works forwards inductively from a hazard to investigate who and what is affected, how they are affected and to what extent. The hazard forms the primary unit of analysis, followed by the physical infrastructure potentially affected by hazards, and lastly the socioeconomic impacts on communities dependent on this infrastructure. Biophysical or macroeconomic models are often used to model the risk of exposure of an asset or community to a specific hazard, and the risk of damage or sensitivity to that hazard. Viewing vulnerability as the *end-point* of the analysis tends to focus assessment on technical solutions to cope with predicted impacts of risk in well-defined systems. Vulnerability in systems assumed to be closed or at least well-defined is often analysed using modelling approaches that predict impacts in terms of proxies such as mortality (Brooks et al., 2005; Eriksen and Kelly, 2007; Fussel and Klein, 2006).

Hazard assessment shares some of the limitations of the narrowly conceived types of risk management science that have tended to dominate analytical support for climate-related policy in the agricultural sector. Analysis of immediate coping capacity within existing patterns of activity in closed systems can overlook the multiple drivers of vulnerability and sources of adaptive capacity arising from transformational change (Eriksen and Kelly, 2007). A focus on quantitative prediction using simulation models can overlook limits to the predictability of global climate systems, and disempower decision makers by focusing on biophysical drivers of change such as rainfall and temperature that are beyond their immediate influence (Nelson et al., 2007a).

A common methodological fallacy is confusing hazard assessment with integrated vulnerability assessment. For hazard assessment, the use of proxies for vulnerability such as mortality or an economic damage function is common. In the extreme, vulnerability is implicitly equated to simple model outputs without any attempt to conceptualise or measure its emergent properties, consequences or potential adaptations. Vincent (2007) noted that this creates a paradox within data driven approaches to measuring and modelling vulnerability. These analyses are typically motivated by a need to measure the intangible multiple dimensions of vulnerability, and yet can be reduced to subjectively choosing a single dimensional proxy to represent vulnerability due to data availability. This is similar to the problem of drought science focusing on rainfall and temperature variability, rather than the impact of climate variability on production, incomes and rural livelihoods (Nelson et al., 2007a). The same fallacy is expressed through the use of macroeconomic models to analyse vulnerability in terms of economic output and employment (such as Fischer et al., 2002; Heyhoe et al., 2007).

An alternative to the hazard/risk management approach is to view vulnerability as an emergent property of complex human–environmental systems, often measured using social vulnerability indices. From this perspective, risk management strategies to avert or cope with specific, measurable drivers of change within current patterns of activity merge with more transformative opportunities to adapt to multiple and interacting drivers of change. Vulnerability is conceptualised as the *starting point* of the analysis (Eriksen and Kelly, 2007), a latent characteristic of human populations with generic attributes that may be shared between drivers of change, with attributes specific to particular drivers of change (Kelly and Adger, 2000). From this perspective, the concepts of vulnerability and adaptive capacity are inextricably linked (Grothmann and Patt, 2005). Vulnerability depends not so exclusively on the precise nature of the hazard, but also on the latent characteristics of human–environment systems that enable them to cope with change in their current form, or undergo more transformative adaptation to maintain important functions (Folke et al., 2005; Nelson et al., 2007b).

3.3. *Entitlements*

The more holistic and integrated perspectives of vulnerability and adaptive capacity on which social vulnerability indices have been built have arisen from two main sources: socio-economic and institutional analysis of resource entitlement (Sen, 1981), and evolutionary ecology (Holling, 1973). Entitlements approaches focus on the welfare of individuals, households and businesses that are subject to multiple hazards and opportunities in a changing world. They draw attention to the elements of coping and adaptation that are independent of specific hazards. Sen (1981, p. 154) directly challenged the central premise of hazard assessment, that famines were primarily caused by biophysical events such as drought, flood and pests. He demonstrated that a number of major famines in history had taken place without a substantial decline in food availability. He then proposed an entitlements approach that conceptualised vulnerability to famine in terms of the actual and potential resources available to individuals based on their own production, assets and reciprocal access to the resources of others (Adger, 2006, p. 270).

The entitlements approach focuses on the influence of politics, institutions and culture on individuals' access to resources, noting that the social conventions governing these rights can be complex (Sen, 1981, p. 46). Seeking explanations for famine that transcend hazards such as climatic events enabled Sen to identify a range of trade, governance and agricultural policy principles with potential to directly reduce the vulnerability of rural communities. However, this focus on politics, institutions and cultures has been criticised for downplaying ecological or physical risk (Adger, 2006). This has been partially overcome in subsequent developments of the approach to create a more integrated conceptual framework for analysing the vulnerability of rural communities. Following Chambers (1989), Scoones (1998) and Ellis (2000) have transformed the entitlements approach into rural livelihoods analysis which integrates the social, economic and biophysical elements of vulnerability. The entitlements approach and rural livelihoods analysis have both been applied to create social vulnerability indices (e.g. Kelly and Adger, 2000; Nelson et al., 2005).

3.4. *Socio-ecological systems*

Another integrated perspective of vulnerability and adaptive capacity arises from evolutionary ecology and ecological economics, although the opportunity to translate these approaches into operational metrics remains largely aspirational. From this perspective, human activity is inextricably embedded within complex and open socio-ecological systems (Gallopin, 2006; Nelson et al., 2007b). Vulnerability and adaptive capacity are expressed in terms of resilience—the ability of socio-ecological systems to reconfigure themselves when subject to change without significant changes in function (Folke et al., 2005; Nelson et al., 2007b). The socio-ecological systems perspective has made a significant contribution to understanding the dynamic aspects of vulnerability and adaptation, and highlighted the importance of thresholds in defining resilience (Nelson et al., 2007b). Adger (2006) has drawn attention to the role that the pressure-and-release model of Blaikie et al. (1994) has played in spanning the ecology and hazards traditions which have contributed to the evolution of this perspective.

A key theme of the socio-ecological systems perspective is that human–environment systems are in a constant state of change, with multiple possible states, requiring flexible and adaptive management. This concept of passing through multiple states helps to define and focus attention on the importance of transformative versus incremental change and adaptation. It also highlights the potential for rigid governance systems to undermine adaptive capacity (Eakin and Luers, 2006), and focuses attention on designing systems of governance that enhance adaptive capacity (Anderies et al., 2004; Nelson et al., 2008). Focusing on the dynamic and integrated nature of adaptation also assists with conceptualising the possible trade-offs that specific forms of adaptation can imply for increased vulnerability in other parts of a system (Nelson et al., 2007b). This includes the idea that resilience, or adaptation within particular states of the system, can actually inhibit more transformational adaptation necessary to achieve less vulnerable and more adaptive states (Folke, 2006; Gallopin, 2006).

The potential for the socio-ecological systems paradigm to incorporate the complexity and uncertainty surrounding vulnerability and adaptive capacity make it an apparently attractive theoretical foundation for future research. However, it is an approach that has proven difficult to translate into operational measures of vulnerability that inform policy. Socio-ecological systems are an abstract unit of analysis, which are difficult or unhelpful to define too narrowly because of the importance of cross-scale interactions (Holling et al., 2002). The complexity with which socio-ecological systems research describes the processes influencing vulnerability and adaptive capacity makes empirical application difficult with the kinds of data that are currently available. Most applications, such as those described by Allison and Hobbs (2004) and Walker and Lawson (2006), describe the dynamic interactions between governance and ecosystem function in specific regional or catchment contexts. This type of research tends to focus on the benefits of enhancing resilience, while overlooking the potential costs (Howden et al., 2007). The result is that resilience thinking has yet to result in broader scale operational measures of vulnerability.

3.5. *Theory or data driven?*

There are two basic philosophical approaches to measuring vulnerability that are relevant to policy and decision making: *deductive* and *inductive*, often described as *theory* versus *data* driven approaches (Adger, 2006; Adger and Vincent, 2005; Vincent, 2007). Both of these ideological approaches can be applied through a diverse array of methods. Common methods include hierarchical impacts modelling associated with traditional forms of hazard assessment. The more integrative approaches described above, including entitlements-based approaches, have most often been applied via vulnerability and adaptive capacity indices.

Deductive approaches base the selection of methods and indicators on a rigorous conceptual understanding of vulnerability or adaptive capacity. Conceptual frameworks that are logically and intuitively robust provide a common language for communicating measures to policy audiences in order to assist with prioritising intervention (Downing, 2003). Adhering to a conceptual framework ensures that the assumptions used to select methods and indicators are transparent, stable and intuitively meaningful to users. It also guides the selection of a minimal, focused and therefore efficient set of indicators. This combination of intellectual rigour and efficiency contributes to the repeatability, comparability and verification of vulnerability measures, which in turn facilitates their expansion, updating, communication and interpretation (Eriksen and Kelly, 2007).

By contrast, the concept of vulnerability associated with inductive approaches tends to be a by-product of the analysis. Thus hazard modelling tends to define vulnerability by default as the outputs of pre-existing physical or economic modelling systems—often confined in practice to the exposure and sensitivity dimensions of vulnerability (see for example Fischer et al., 2002; Heyhoe et al., 2007). Similarly, inductive approaches to index construction use statistical analyses to relate large numbers of variables to proxy measures of vulnerability in an attempt to determine those that are statistically significant. The less focused expressions of this method are sometimes referred to as *hoovering* (Downing, 2003).

The indiscriminate use of model outputs or data associations to define vulnerability can result in the goals of vulnerability assessment being directed down pathways that are interesting for scientists but of low policy relevance. We have previously documented the potential subversion of policy goals through *centralised expert management* in relation to Australian drought policy (Nelson et al., 2008). This is often compounded by a lack of transparency in the model structure or processes of data transformation essential for appropriately interpreting the outcomes of the analysis. Aggregation, for example, can alter the correlation between the variables contributing to vulnerability indices, making it difficult to interpret important causal relationships implied by the analysis. Merging data from unrelated sampling frames can also pose a significant threat to the validity of inferences drawn from the resulting index or analysis. These phenomena are captured in popular science discourse through terms such as *GIS disease* or *data dumping*—though these phenomena are by no means intrinsic or confined to the spatial sciences.

3.6. *Convergence in application*

In reality, deductive and inductive approaches are not the polar opposites that they are sometimes made to appear, because they tend to merge in the messy process of application. The apparent theoretical purity of deductive approaches tends to break down if conceptual frameworks are poorly described or applied, or as data limitations compel pragmatism in indicator selection (Pelling, 2006). Even when conceptual frameworks are rigorously adhered to, statistical analysis can be a useful way of validating indicator selection. Similarly, conceptual understanding usually plays at least some role in even the loosest inductive data trawls. Induction can also be the source of new theory, as statistical relationships supported by growing empirical evidence lead to the formation of new conceptual frameworks. So complex can these interactions be that it can be difficult to distinguish whether particular vulnerability studies are deductive or inductive (Eriksen and Kelly, 2007).

For example, Kelly and Adger (2000), Adger and Vincent (2005) and Vincent (2007) declare a strong theory-driven approach to constructing Social Vulnerability Indices (SVIs). The conceptual framework used to define and measure vulnerability in the earliest of these papers is clear. Kelly and Adger (2000) used an architecture of entitlements based on Sen (1981) as a conceptual framework populated with primary data to analyse the vulnerability of coastal communities in Vietnam to the threat of cyclones. In contrast, Adger and Vincent (2005) and Vincent (2007) explore the *uncertainties* of using secondary data to create operational measures of vulnerability at broader regional and national scales. At these larger scales, the unit of analysis is no longer a specific community in a well-defined geographical context, and it is much less obvious which conceptual framework(s) can and/or should be used to define and measure vulnerability.

The availability of data has had a significant influence on whether particular methods can be used to support action to reduce vulnerability or build adaptive capacity. For example, most authors acknowledge that the strongly contextual nature of vulnerability is reflected in significant regional variation. However, the availability of data has tended to limit the construction of vulnerability indices to a national scale using data from national accounts and related development indicators. Data quality issues, inconsistent results between studies and a related lack of verification has led Eriksen and Kelly (2007) to conclude that national scale vulnerability indices are of low relevance to policy advisers. This is partly because the conceptual frameworks of deductive studies have tended to be weakly applied, while the potential contribution to theory by inductive studies is rarely drawn out. Haddad (2005) has pointed out that most national scale vulnerability assessments tend to reproduce wealth rankings, because economic development is implicitly assumed to be the primary goal of national governments. This research demonstrated that alternative assumptions about national aspirations can lead to starkly divergent rankings of national vulnerability to climate change. This inconsistency makes it difficult to use national indices to support coordinated policy action on climate change.

4. Discussion and conclusions

4.1. *Resolving alternative perspectives*

The emergent and integrative nature of vulnerability and adaptive capacity means that the values of the analyst strongly influence the choice of conceptual frameworks and methods. According to Sarewitz (2004), even the most apparently apolitical, disinterested scientist may, by virtue of disciplinary orientation, view the world in a way that is more amenable to some value systems than others (p. 392). The choice between conceptual frameworks and methods is intrinsically subjective and value laden, and one that is often made tacitly. One approach in this field has been for disciplinary specialists to equate the concepts of vulnerability and adaptive capacity with the outputs of disciplinary-specific models and methods. This risks overlooking the emergent nature of these concepts, resulting in choices informed by analyses of vulnerability and adaptive capacity that are incomplete or arbitrary in potentially surprising ways. The emergent nature of vulnerability and adaptive capacity means that meaningful concepts and methods are only likely to be found by spanning disciplinary boundaries to select methods appropriate to specific contexts from a diverse array of options. Making these choices explicit and transparent reveals the underlying values so that they can be acknowledged, debated and resolved if necessary. Making explicit choices also enables the concepts and methods selected to be aligned with the needs of decision makers through participatory processes.

The value of conceptualising and measuring vulnerability and adaptive capacity derives from the potential support that doing so adds to the political processes through which individuals, communities, industries and governments choose appropriate actions to reduce their vulnerability. Chambers (1989) has argued that the primary goal of applied vulnerability assessment should be to create contextually relevant measures of vulnerability that trigger action to reduce it. Maxwell (2008) has gone further arguing that dissociating scientific knowledge from tackling the practical problems of living has become a massive, institutionalised blunder, and that much more attention is needed to proposing possible solutions and actions. This need to resolve choices over concepts and methods based on their capability to support societal action is consistent with a well established notion that there are limits to the extent to which even well integrated forms of science can support the political processes through which contended values are resolved (Sarewitz, 2004). This suggests that vulnerability research needs to be use-oriented, and capable of being integrated into the participatory and adaptive governance processes via which the contended values surrounding public choice are resolved.

4.2. *Beyond hazard/impact modelling*

This review suggests a number of reasons why hazard or impact modelling should not be confused with more integrated approaches to vulnerability research when providing policy advice. There is growing consensus among different disciplinary perspectives that vulnerability includes both exposure and sensitivity to multiple drivers of change, as well as the capacity to adapt to change. Contrary to this conceptual understanding, vulnerability research has been dominated by applications of hazard/impact modelling that tend to focus on exposure and sensitivity, especially applications that define exposure and sensitivity in narrow technical terms. Narrowly defining exposure and sensitivity as the basis of adaptation to predictable sources of risk within existing patterns of activity overlooks fundamental limits to predictability in the global climate system. As Pielke and Sarewitz (2003) have pointed out, this has led to repeated overinvestment in climate prediction at the expense of research creating mitigation and adaptation options. They provide a striking analogy:

> 'The types of knowledge we have been emphasizing for the past decade or so, despite their significant scientific value, are not those we will most need in dealing with the challenge of climate change. It's as if the National Institute of Health focused its research on making better projections of when people will die, rather than seeking practical ways to increase health and life expectancy.' (p. 28)

A tendency for hazard/impact modelling to focus on an arbitrary and narrow subset of the multiple emergent dimensions of vulnerability seems to be a feature of past applications rather than an intrinsic limitation of the method. Understanding the emergent nature of vulnerability and integrating appropriate interdisciplinary solutions is difficult. The pressure to respond to rapidly evolving policy demand has led to vulnerability being equated with a narrow set of mostly biophysical or economic impacts predicted using pre-existing modelling systems. Selectively and arbitrarily equating vulnerability with default model outputs tends to create a relevance gap between this type of science and the types of information required to prioritise adaptation responses throughout society. A focus on narrow technical responses can overlook more transformative and holistic opportunities to adapt, and disempower decision makers by focusing on drivers of change beyond their immediate influence.

There is an urgent need to broaden the application of hazard/impact modelling, and to complement it with methods capable of identifying and enhancing diverse and transformative sources of adaptive capacity throughout society. This review suggests that indices designed deductively from integrated conceptual frameworks have potential to illuminate the multiple and emergent dimensions of vulnerability and adaptive capacity. In the next paper in this series (Nelson et al., 2010), we combine hazard and impact modelling with an holistic measure of the adaptive capacity created using rural livelihoods analysis. This approach is then used to provide preliminary insights into the vulnerability of Australian rural communities to climate variability and change.

Acknowledgements

The authors acknowledge partial funding for this research from the National Land & Water Resources Audit (NLWRA), and the Australian Government Department of Agriculture, Fisheries & Forestry (DAFF). Nadine Marshall and Alistair Hobday provided insightful comments on earlier drafts, which were edited by Marianne Nelson and Pauline Simonetti. We are grateful for informal comment from colleagues in policy agencies on evolving policy demand, particularly members of the Climate in Agriculture and Natural Resource Management (CLAN) sub-committee of the Natural Resource Policies & Programs Committee (NRPPC). The views expressed in this

paper are those of the authors, and should not be attributed to the Australian Government.

REFERENCES

Adger, W., 2006. Vulnerability. Global Environmental Change 16, 268–281.

Adger, W., Vincent, K., 2005. Uncertainty in adaptive capacity. Comptes Rendus Geoscience 337, 399–410.

Adger, W., Agrawala, S., Mirza, M., Conde, C., O'Brien, K., Pulhin, J., Pulwarty, R., Smit, B., Takahashi, K., 2007. Assessment of adaptation practices, options, constraints and capacity. In: , M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, C.E. Hanson (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 717–743.

Allen Consulting Group, 2005. Climate Change Risk and Vulnerability—Promoting an Efficient Adaptation Response in Australia. Australian Government Department of Environment and Heritage Australian Greenhouse Office, Canberra.

Allison, H., Hobbs, R., 2004. Resilience, adaptive capacity and the ''lock-in trap'' of the Western Australian agricultural region. Ecology and Society 9, 3–27.

Alwang, J., Siegel, P., Jorgensen, S. 2001. Vulnerability: a view from different disciplines. Social Protection Discussion Paper Series No. 0115. The World Bank, Washington.

Anderies, J., Janssen, M., Ostrom, E., 2004. A framework to analyse the robustness of socio-ecological systems from an institutional perspective. Ecology and Society 9, 1–18.

Barnston, A.G., Kumar, A., Goddard, L., Hoerling, M., 2005. Improving seasonal prediction practices through attribution of climate variability. Bulletin of the American Meteorological Society 86, 59–72.

Blaikie, P., Cannon, T., Davis, I., Wisner, B., 1994. At Risk: Natural Hazards, People's Vulnerability and Disasters. Routledge, London.

Blackadder, J., 2005. Masters of the Climate: Innovative Farmers Coming Through Drought. Managing Climate Variability Research and Development Program, Land & Water Australia, Canberra.

Botterill, L., 2005. Late twentieth century approaches to living with uncertainty: the national drought policy. In: Botterill, L.C., Wilhite, D. (Eds.), From Disaster Response to Risk Management: Australia's National Drought Policy. Springer, Dordrecht.

Brooks, N., Adger, W., Kelly, P., 2005. The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. Global Environmental Change 15, 151–163.

Burton, I., 2003. Do we have the adaptive capacity to develop and use the adaptive capacity to adapt? In: Smith, J., Klein, R., Huq, S. (Eds.), Climate Change, Adaptive Capacity and Development. Imperial College Press, London.

Carter, J., Hall, W., Brook, K., McKeon, G., Day, K., Paull, C., 2000. Aussie GRASS: Australian grassland and rangeland assessment by spatial simulation. In: Hammer, G., Nicholls, N., Mitchell, C. (Eds.), Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems—the Australian Experience, vol. 21. Atmospheric and Oceanographic Sciences Library, Kluwer Academic Publishers, Dordrecht.

Clark, A., Barratt, D., Munro, B., Sims, J., Laughlin, G., Poulter, D., 2006. Science for Decision Makers: Climate Change: Adaptation for Agriculture. Bureau of Rural Sciences, Canberra. , http://affashop.gov.au/product.asp?prodid=13352.

Chambers, R., 1989. Editorial introduction: vulnerability, coping and policy. Institute for Development Studies Bulletin 20, 1–7.

Crimp, S., Flood, N., Carter. J., Conroy, J., McKeon, G. 2002. Evaluation of the potential impacts of climate change on native pasture production—implications for livestock carrying capacity. Final Report for the Australian Greenhouse Office, 60 pp.

DAFF, October 2005. Information Handbook: Exceptional Circumstances Assistance. Australian Government Department of Agriculture, Fisheries and Forestry, http://www.affa.gov.au/content/publications.cfm?ObjectID=D43AC96E-FEB9-42A0-9A6BBCD98FA5A401.

DAFF, 2006. National Agriculture & Climate Change Action Plan 2006–2009. Department of Agriculture, Fisheries and Forestry, Canberra.

Downing, T., 2003. Lessons from famine early warning and food security for understanding adaptation to climate change: toward a vulnerability/adaptation science? In: Smith, J., Klein, R., Huq, S. (Eds.), Climate Change, Adaptive Capacity and Development. Imperial College Press, London.

Eakin, H., Luers, A., 2006. Assessing the vulnerability of social-environmental systems. Annual Review of Environment and Resources 31, 365–394.

Ellis, F., 2000. Rural Livelihoods and Diversity in Developing Countries. Oxford University Press, Oxford.

Eriksen, S., Kelly, P., 2007. Developing credible vulnerability indicators for climate adaptation policy assessment. Mitigation and Adaptation Strategies for Global Change 12, 495–524.

Fischer, G., Shah, M., van Velthuizen, H., 2002. Climate change and agricultural vulnerability. Special Report by the International Institute for Applied Systems Analysis to the World Summit on Sustainable Development, Johannesburg.

Folke, C., 2006. Resilience: the emergence of a perspective for socio-ecological systems analyses. Global Environmental Change 16, 253–267.

Folke, C., Hahn, T., Olsson, P., Norberg, J., 2005. Adaptive governance of socio-ecological systems. Annual Review of Environment and Resources 30, 441–473.

Fussel, H., Klein, R., 2006. Climate change vulnerability assessments: an evolution of conceptual thinking. Climatic Change 75, 301–329.

Gallopin, G.C., 2006. Linkages among vulnerability, resilience, and adaptive capacity. Global Environmental Change 16, 293–303.

Garnaut, R., 2008. The Garnaut Climate Change Review. Cambridge University Press, Cambridge.

Grothmann, T., Patt, A., 2005. Adaptive capacity and human cognition: the process of individual adaptation to climate change. Global Environmental Change 15, 199–213.

Haddad, B., 2005. Ranking the adaptive capacity of nations to climate change when socio-political goals are explicit. Global Environmental Change 15, 165–176.

Hammer, G., 2000. Applying seasonal climate forecasts in agricultural and natural ecosystems—a synthesis. In: Hammer, G., Nicholls, N., Mitchell, C. (Eds.), Applications of seasonal climate forecasting in agricultural and natural ecosystems—the Australian experience, vol. 21. Atmospheric and Oceanographic Sciences Library, Kluwer Academic Publishers, Dordrecht.

Hardaker, J., Huirne, R., Anderson, J., Lien, G., 2004. Coping with Risk in Agriculture, 2nd edition. CABI Publishing, Wallingford.

Harle, K., Howden, S.M., Hunt, L., Dunlop, M., 2007. The potential impact of climate change on that Australian wool industry by 2030. Agricultural Systems 93, 61–89.
Hennessy, K., Fawcett, R., Kirono, D., Mpelasoka, F., Jones, D., Bathols, J., Whetton, P., Stafford Smith, M., Howden, S.M., Mitchell, C., Plummer, N., 2008. An Assessment of the Impact of Climate Change on the Nature and Frequency of Exceptional Climatic Events. CSIRO and the Australian Bureau of Meteorology, Melbourne. , 31 pp.,http://www.bom.gov.au/climate/droughtec/
Heyhoe, E., Kim, Y., Kokic, P., Levantis, C., Ahammad, H., Schneider, K., Crimp, S., Nelson, R., Flood, N., Carter, J., 2007. Adapting to climate change. Australian Commodities 14 (1), 167–178.
Hobday, A.J., Poloczanska, E.S., Matear, R., 2008. Implications of Climate Change for Australian Fisheries and Aquaculture: A Preliminary Assessment. Report to the Department of Climate Change, Canberra, Australia. August 2008.
Holling, C., Gunderson, L., Ludwig, D., 2002. In quest of a theory of adaptive change. In: Gunderson, L., Holling, C. (Eds.), Panarchy: Understanding Transformations in Human and Natural Systems. Island Press, Washington.
Holling, C., 1973. Resilience and stability of ecological systems. Annual Review of Ecological Systems 4, 1–23.
Howden, S.M., Ash, A., Barlow, E., Booth, C., Cechet, R., Crimp, S., Gifford, R., Hennessy, K., Jones, R., Kirschbaum, M., McKeon, G., Meinke, H., Park, S., Sutherst, R., Webb, L., Whetton, P., 2003. An Overview of the Adaptive Capacity of the Australian Agricultural Sector to Climate Change—Options, Costs and Benefits. Report to the Australian Greenhouse Office, Canberra.
Howden, S.M., Soussana, J.-F., Tubiello, F., Chhetri, N., Dunlop, M., Meinke, H., 2007. Adapting agriculture to climate change. PNAS 104, 19691–19696.
IPCC, 2007: Climate Change 2007: Synthesis Report. In: Core Writing Team, Pachauri, R.K., Reisinger, A. (Eds.), Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 104 pp.
James, P., 1973. Economic policy for drought. In: Lovett, J. (Ed.), The Environmental, Economic and Social Significance of Drought. Angus and Robertson, Sydney.
Johnson, J., Marshall, P. (Eds.), 2007. Climate Change and the Great Barrier Reef: A Vulnerability Assessment. Great Barrier Reef Marine Park Authority and Australian Green House Office, Australia.
Kelly, P., Adger, W., 2000. Theory and practice in assessing vulnerability to climate change and facilitating adaptation. Climatic Change 47, 325–352.
Kingwell, R., 2006. Climate change in Australia: agricultural impacts and adaptation. Australasian Agribusiness Review 14 (Paper 1).
Kokic, P., Heaney, A., Pechey, L., Crimp, S., Fisher, B., 2005. Climate change. Predicting the impacts on agriculture: a case study. Australian Commodities 12, 161–170.
Kokic, P., Nelson, R., Meinke, H., Potgieter, A., Carter, J., 2007. From rainfall to farm incomes – transforming advice for Australian drought policy: Part I – Development and testing of a bioeconomic modelling system. Australian Journal of Agricultural Research 58 (10), 993–1003.
Kundzewicz, Z., Budhakooncharoen, S., Bronstert, A., Hoff, H., Lettenmaier, D., Menzel, L., Schulze, R., 2002. Coping with variability and change: floods and droughts. Natural Resources Forum 26, 263–274.
Maxwell, N., 2008. Are philosophers responsible for global warming? Philosophy Now 65, 12–13.
McKeon, G., Hall, W., Henry, B., Stone, G., Watson, I., 2004. Pasture Degradation and Recovery in Australia's Rangelands. Queensland Department of Natural Resources, Mines and Energy, Brisbane.
Meinke, H., Nelson, R., Kokic, P., Stone, R., Selvaraju, Baethgen, W., 2006. Actionable climate knowledge—from analysis to synthesis. Climate Research 33, 101–110.
Meinke, H., Stone, R., 2005. Seasonal and inter-annual climate forecasting: the new tool for increasing preparedness to climate variability and change in agricultural planning and operations. Climatic Change 70, 221–253.
Nelson, D., Adger, W., Brown, K., 2007b. Adaptation to environmental change: contribution of a resilience framework. Annual Review of Environment and Resources 32, 395–419.
Nelson, R., Kokic, P., Crimp, S., Martin, P., Meinke, H., Howden, S.M., Devoil, P., Nidumolu, U., 2010. The vulnerability of Australian agriculture to climate variability and change: Part II—integrating impacts with adaptive capacity. Environmental Science & Policy 13, 18–27.
Nelson, R., Howden, S.M., Stafford Smith, M., 2008. Using adaptive governance to rethink the way science supports Australian drought policy. Environmental Science & Policy 11, 588–601.
Nelson, R., Kokic, P., Meinke, H., 2007a. From rainfall to farm incomes – transforming advice for Australian drought policy: Part II – forecasting farm incomes. Australian Journal of Agricultural Research 58 (10), 1004–1012.
Nelson, R., Kokic, P., Elliston, L., King, J., 2005. Structural adjustment: a vulnerability index for Australian broadacre agriculture. Australian Commodities 12 (1), 171–179.
Pearson, L., Nelson, R., Crimp, S., Langridge, J. 2008. Climate change vulnerability assessment: review of agricultural productivity. CSIRO Climate Adaptation Flagship Working Paper 08.1.
Pelling, M., 2006. Measuring urban vulnerability to natural disaster risk: benchmarks for sustainability. Open House International 31, 125–132.
Pielke Jr., R.A., Sarewitz, D., 2003. Wanted: scientific leadership on climate. Issues in Science and Technology 27–30.
Potgieter, A.B., Hammer, G.L., Meinke, H., Stone, R.C., Goddard, L., 2005. Three putative types of El Nino revealed by spatial variability in impact on Australian wheat yield. Journal of Climate 18, 1566–1574.
Potgieter, A., Doherty, A., Crimp, S., Rodriguez, D., Hammer, G., Meinke, H., Fairweather, H., 2008. Shire scale impacts and adaptation options for Australian cereal crops affected by climate change. In: 14th Australian Agronomy Conference, Adelaide.
Preston, B., Smith, T., Brooke, C., Gorddard, R., Measham, T., Withycombe, G., Beveridge, B., Morrison, C., McInnes, K., Abbs, D., 2008. Mapping Climate Change Vulnerability in the Sydney Coastal Councils Group. CSIRO, Melbourne.
Sarewitz, D., 2004. How science makes environmental controversies worse. Environmental Science & Policy 7, 385–403.
Scoones, I., 1998. Sustainable rural livelihoods: a framework for analysis. IDS Working Paper No. 72. University of Sussex, Brighton.
Sen, A., 1981. Poverty and Famines: An Essay on Entitlement and Deprivation. Oxford University Press, Oxford.
Stephens, D., Lyons, T., Lamond, M., 1989. A simple model to forecast wheat yield in Western Australia. Journal of the Royal Society of Western Australia 71, 77–81.
Stern, N., 2006. Stern Review on the Economics of Climate Change. UK Government Economic Service, London. , http://www.sternreview.org.uk/.
Vincent, K., 2007. Uncertainty in adaptive capacity and the importance of scale. Global Environmental Change 17, 12–24.

Walker, B., Lawson, R., 2006. Case studies in resilience: fifteen socio-ecological systems across continents and societies. In: Walker, B., Anderied, J., Kinzig, A., Ryan, P. (Eds.), Exploring Resilience in Socio-Ecological Systems—Comparative Studies and Theory Development. CSIRO Publishing, Melbourne.
Webb, L., Whetton, P., Barlow, E., 2008. Climate change and wine grape quality in Australia. Climate Research 36, 99–111.
Wilhite, D., 2002. Combating drought through preparedness. Natural Resources Forum 26, 275–285.

Rohan Nelson is director of Agriculture with the Australian Government Department of Climate Change. This paper was written while he was a research group leader and resource economist with CSIRO, designing science and governance systems that support rural communities, industries and governments in their ongoing efforts to adapt to global change.

Philip Kokic is a senior statistician with CSIRO developing innovative approaches to the statistical analysis of climate risk.

Steven Crimp is a research team leader and senior scientist with CSIRO evaluating options to increase resilience of Australian cropping systems to climate variability and change.

Holger Meinke is professor and head of the Centre for Crop Systems Analysis at Wageningen University. The group researches and designs climate robust agricultural systems and analyses risks and opportunities created by global change.

Mark Howden is leader of the adaptive primary industries and enterprises theme within CSIRO's Climate Adaptation Flagship. Mark works with farmers, farmer groups and policymakers building their capacity to deal more effectively with climate variability and change.