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The vulnerability of Australian rural communities to climate variability and change: Part II—Integrating impacts with adaptive capacity

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ABSTRACT

In the first paper in this series [Nelson, R., Kokic, P., Crimp, S., Martin, P., Meinke, H., Howden, S.M. (2010, this issue)], we concluded that hazard/impact modelling needs to be integrated with holistic measures of adaptive capacity in order to provide policy-relevant insights into the multiple and emergent dimensions of vulnerability. In this paper, we combine hazard/impact modelling with an holistic measure of adaptive capacity to analyse the vulnerability of Australian rural communities to climate variability and change. Bioeconomic modelling was used to model the exposure and sensitivity of Australian rural communities to climate variability and change. Rural livelihoods analysis was used as a conceptual framework to construct a composite index of adaptive capacity using farm survey data. We then show how this integrated measure of vulnerability provides policy-relevant insights into the constraints and options for building adaptive capacity in rural communities. In the process, we show that relying on hazard/impact modelling alone can lead to entirely erroneous conclusions about the vulnerability of rural communities, with potential to significantly misdirect policy intervention. We provide a preliminary assessment of which Australian rural communities are vulnerable to climate variability and change, and reveal a complex set of interacting environmental, economic and social factors contributing to vulnerability.

1. Introduction

Our previous paper in this series (Nelson et al., 2010) showed that the concept of vulnerability is rarely converted into analytical measures that can be used to prioritise policy interventions and evaluate their impact. An increasing awareness of climate change and its potential impacts on rural communities is driving demand for research capable of prioritising adaptation responses. The types of science available to inform rural adaptation in Australia continue to build on a

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long heritage of hazard and impact modelling. Selectively or arbitrarily equating vulnerability to disciplinary-specific model outputs risks creating a relevance gap between hazard/impact modelling and the information required to inform the emergent dimensions of vulnerability. Conceptualising vulnerability as a linear sequence of technical adaptations to predictable sources of risk overlooks more transformative opportunities to adapt, and disempowers decision makers by focusing on drivers of change that are beyond their immediate influence. It also overlooks fundamental limits to predictability in the global climate system, leading to over-investment in climate prediction relative to research that supports adaptation actions throughout society. We concluded that there is an urgent need to complement hazard/impact modelling with methods capable of identifying and enhancing diverse and transformative sources of adaptive capacity throughout society.

This paper combines hazard and impact modelling with an holistic measure of adaptive capacity created using rural livelihoods analysis to analyse the vulnerability of Australian rural communities to climate variability and change. It builds on two previous streams of research to inform an holistic, outcome-focused conceptualisation of vulnerability. First, it builds on the work of Kokic et al. (2007) and Nelson et al. (2007a) who showed that bioeconomic modelling could be used to transform climate impact modelling to inform the economic outcomes important to rural communities, industries and governments. Second, we show that impact modelling alone is insufficient and can be misleading for informing policy options unless combined with holistic measures of adaptive capacity. We do this by building on the research of Nelson et al. (2005), who used the rural livelihoods analysis framework of Ellis (2000) to create a vulnerability index for Australian broadacre agriculture. The appeal of this earlier vulnerability index to rural policy advisers and the community generally was demonstrated by its publication on the front page of a national newspaper (The Australian Newspaper, Monday 6 June, 2005), its adoption in standard reporting systems (Martin et al., 2007) and funding to assess its expanded application (Nelson et al., 2007b; Sheng et al., 2008). However, its almost spontaneous evolution and adoption was presumptive of some key elements of its scientific design, which we address in this paper.

2. Method

2.1. Exposure to climate variability and change

Building on related research by Kokic et al. (2007) and Crimp et al. (2008), we compared three measures of the exposure and sensitivity of rural communities to climate variability and change. Adopting standard practice, current exposure to climate variability was measured using a coefficient of variation for: (1) historical rainfall; (2) simulated pasture growth; and (3) historical farm income data over a 10-year period from 1996–97 to 2005–06 (see Table A1 for details). Rainfall variability was measured using historical climate data from the Australian Bureau of Meteorology. The Aussie Grass model (Carter et al., 2000) was used to simulate pasture growth across Australia at a 5 km^2 resolution for this 10-year period using historical rainfall, temperature and other climate data. Aussie Grass integrates the impact of climate variability with regional differences in soils, pasture types and livestock management. The combined influence of variability in agricultural input and output prices, farm management, climate and other drivers of physical and economic productivity were captured through historical farm income data provided by Australian farmers via ABARE's Agricultural and Grazing Industry Survey (ABARE, 2003).

The exposure of Australian rural communities to climate change was measured using models to project expected changes in rainfall, pasture growth and farm incomes to 2030 (see Table A2 for details). A limitation of current climate change models is that they model average annual changes in rainfall and temperature, rather than the inter-annual or inter-seasonal variability upon which the productivity of agricultural systems depends. Consequently, we compared projected trends in rainfall, pasture growth and farm incomes to their average value over a base period. For the biophysical measures of rainfall and pasture growth, we conformed to the IPCC practice of using 1980–1999 as a base period (IPCC WG1, 2007). Due to structural changes in Australia's agricultural sector (see Kokic et al., 2007), we used the shorter but overlapping period of 1996–97 to 2005–06 as the base period for the bioeconomic modelling (Table A2). The potential beneficial effects of increased carbon dioxide levels in the atmosphere were captured in the pasture growth modelling using the method described by Crimp et al. (2002). The spatial definition of climate projections continues to be relatively coarse in agricultural terms, and hence the analysis was conducted using average values for Australia's statistical divisions (www.abs.gov.au).

At the time of writing, the IPCC was using 23 climate models to project future climate change across a set of 40 emission scenarios (IPCC WG1, 2007). Future emission scenarios are derived from assumptions about the pace of economic development and technological innovation. However, it is well known that not all climate models perform equally well when predicting Australia's climate (CSIRO, 2007). Similarly, recent research has demonstrated that global CO_2 emissions, atmospheric CO_2 concentrations, sea level rise and global temperatures are already tracking along the upper bounds of the projected range (Canadell et al., 2008; Rahmstorf et al., 2007). We therefore used the MPI-ECHAM5 model (Roeckner et al., 2003) to project annual changes in climate expected by 2030 under the A1FI emission scenario relative to average conditions over the base period from 1980 to 1999 as this model and scenario best represents the observed changes. Following the approach outlined by Crimp et al. (2002) and Kokic et al. (2007), these projections of future climate were then used to project annual changes in pasture growth with the GRASP model, and changes in farm incomes using the AgFIRM bioeconomic model. The AgFIRM model has the advantage of at least partially capturing some of the historically observed adaptation to seasonal climate variability in Australian agriculture (Kokic et al., 2007).

2.2. Adaptive capacity using rural livelihoods analysis

The rural livelihoods framework developed by Ellis (2000) was used as the conceptual framework underpinning deductive construction of an adaptive capacity index (see online Appendix for a more detailed explanation). This framework conceptualises adaptive capacity as an emergent property of the diverse forms of human, social, natural, physical and financial capital from which rural livelihoods are derived, and the flexibility to substitute between them in response to external pressures (Ellis, 2000, Table A3). Farm households with a greater diversity of assets and activities are likely to have greater adaptive capacity because of a greater capacity to substitute between alternative livelihood strategies in times of stress.

Balance between the five capitals is also important, because minimum levels of one capital may be necessary to effectively make use of another. The contribution of diversification and substitution to adaptive capacity is particularly strong when non-farm sources of income less directly affected by climate are available. Diversification at a household or business level often complements economic specialisation within a household, and economic specialisation in any one set of activities can facilitate investment in other forms of capital from which future livelihoods can be derived (Ellis, 2000).

Rural livelihoods analysis provides a view of the potential adaptive capacity of rural households at a point in time. This is a first step toward measuring more dynamic and integrative concepts of resilience for which specific understanding of causal relationships and local thresholds or *tipping points* is required (Holling, 1973; Walker and Salt, 2006).

A composite (see Appendix) index of adaptive capacity was constructed using data provided by farmers through the Australian Agricultural and Grazing Industries Survey (AAGIS) (ABARE, 2003). For this application, the original choice of variables by Nelson et al. (2005) from the AAGIS survey was reviewed and improved against the conceptual framework (Table A4). A detailed explanation of how each of the capitals was interpreted against the rural livelihoods analysis framework in the context of Australian agriculture was provided by Nelson et al. (2007b). Three variables were selected to represent each of the five capitals, in order to preserve their statistical relevance and transparency of interpretation. Conceptually important dimensions of the five capitals were supplemented using data from the Australian Bureau of Statistics (ABS) and National Land & Water Resources Audit (NLWRA) (Table A4).

The three variables selected were weighted to form a farm level measure of each capital type. The measures for each of the five capitals were then weighted together to form an overall index of adaptive capacity. Two weighting methods were used: (1) the proportion of variation explained by each variable using principal component analysis (PCA); and (2) simple (equal) weights. A nested approach to weighting was used to enable the ability to *drill down* through the variables to explore which capitals influence adaptive capacity in a region, and which indicators influence each capital. A detailed explanation of why each weighting procedure was used is provided in the online Appendix.

The results are presented spatially. The farm level measures of each capital and adaptive capacity were smoothed spatially to a grid, each variable independently of the others, using the Kernel smoothing technique described in Cowling et al. (1996). These smoothed data were then mapped using GIS software excluding non-agricultural regions such as national parks. The smoothed data for adaptive capacity were mapped to show regions with low (10th percentile) and moderate (10th–25th percentile) adaptive capacity across Australia. When combined into an integrative analysis of vulnerability to climate change, average values of adaptive capacity for each statistical division were used to conform to projections of average pasture growth and farm incomes at a similar scale.

2.3. *Integrated vulnerability measure*

Rural communities vulnerable to climate variability and change were identified as those for whom high or moderate exposure coincides with low to moderate adaptive capacity (Fig. 1). For climate variability, vulnerable communities were identified using the 10th and 25th percentiles to identify communities with low/moderate adaptive capacity and high/moderate exposure. For climate change, vulnerable communities were identified using terciles of adaptive capacity and exposure because of the lower resolution of the climate change impact modelling. Consequently, each statistical division was ranked as having low, moderate or high vulnerability to climate change. In the absence of transparent and credible methods for projecting the multiple dimensions of adaptive capacity, the convention of Vincent (2007) was followed under which current adaptive capacity is used as a proxy for future adaptive capacity. A capability to project adaptive capacity is a critical dimension of ongoing research.

3. Results

3.1. *Exposure to climate variability*

Farm incomes have been much more variable in northern Australia than they have been in southern Australia (Fig. 2). In earlier papers we provided evidence that Australian rural communities that are most exposed to climate variability are

		Exposure		
		High	Moderate	Low
Adaptive capacity	Low	High	High	Moderate
	Moderate	High	Moderate	Low
	High	Moderate	Low	Low

Fig. 1 – Mapping vulnerability as the intersection of exposure and adaptive capacity.

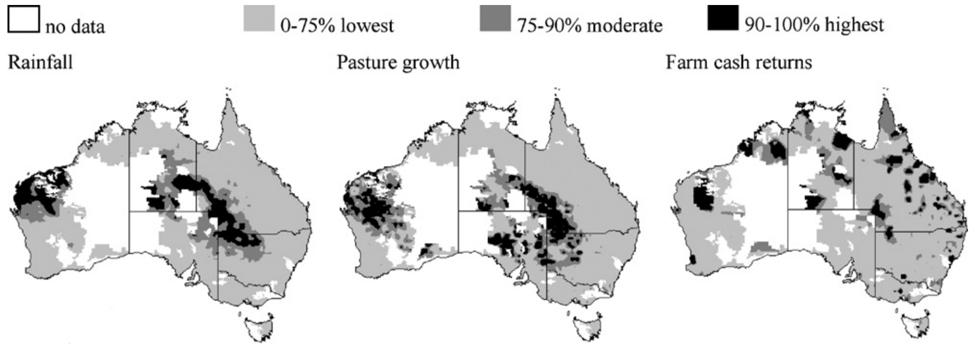

Fig. 2 – The exposure of Australian broadacre farm households to climate variability over the 10 years from 1996–97 to 2005–06 measured using historical data for (a) rainfall, (b) pasture growth and (c) farm cash returns (see Table A1 in online Appendix for methods).

also highly adapted to it (Nelson et al., 2005; Meinke et al., 2006). Similar results have been obtained in Europe (Reidsma, 2007). The Australian evidence is confirmed in Fig. 2, which shows that the rural communities that have experienced the most variable rainfall and pasture growth are not necessarily those that have experienced the most variable farm incomes. This provides tangible evidence that farmers in regions with severe climate variability can and have developed appropriate farming systems to manage this variability. It also demonstrates how misleading it can be to substitute or confuse hazard or impact modelling with more integrated approaches to vulnerability assessment. Even highly integrative biophysical measures of exposure and sensitivity, such as simulated pasture growth, may provide few insights into the adaptive capacity of rural communities.

When farm incomes are used to provide an integrated perspective of the combined impact of physical and economic drivers of change on rural communities, the spatial pattern of exposure is more complex (Fig. 2, panel on the right). In general, farm incomes have been more variable in northern Australia than in southern Australia, and in regions dominated by extensive grazing. There are also pockets of high income variability throughout the wheat-sheep zones of eastern Australia and south–west Western Australia. High income variability along the east coast reflects the pressure of urbanisation on land values, declining farm sizes, slow productivity growth for small beef producers and reduced investment in agriculture as an income source. A detailed regional analysis of the exposure and sensitivity of Australian farms in the wheat-sheep zone to climate variability has previously been provided by Nelson and Kokic (2004).

3.2. *Exposure to climate change*

For the A1FI scenario, the MPI-ECHAM5 climate model projected lower rainfall in 2030 for regions of south-west Western Australia, Victoria and south-east Queensland (Fig. 3). A third of Australia's 58 statistical divisions are projected to experience reductions in rainfall and pasture growth of more than 4 per cent (Fig. 3). More than 10 per cent of

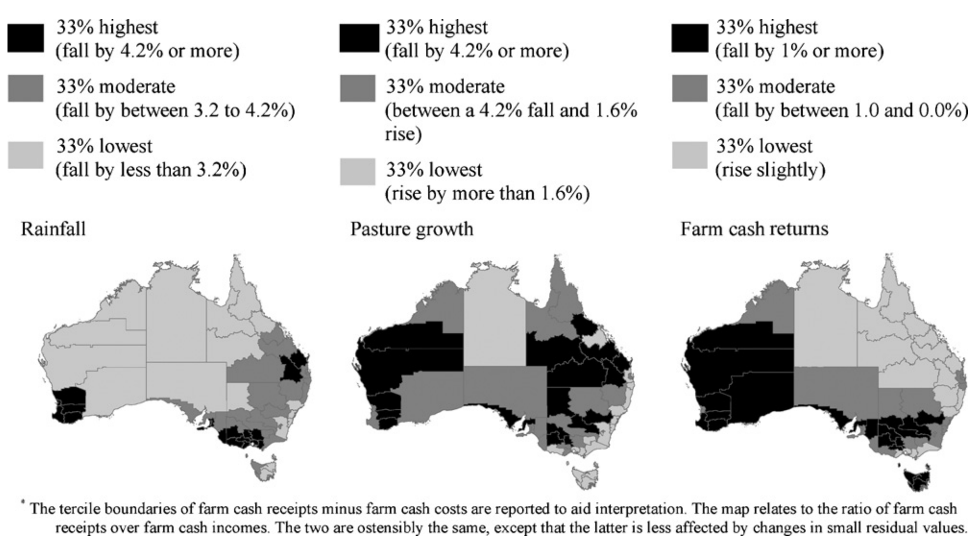

Fig. 3 – The exposure of Australian rural communities to average change in (a) rainfall, (b) pasture growth and (c) farm incomes to 2030 under the A1FI scenario projected using the MPI-ECHAM5, GRASP and AgFIRM models relative to the base period (see Table A2 for methods).

Table 1 – Principal component weights for each capital, and the proportion of variation that they collectively explain in the adaptive capacity index.

Capital	Weights (first principal component)	Variation explained (%)
Adaptive capacity		
Human	0.23	
Social	0.41	
Natural	0.40	45
Physical	0.57	
Financial	0.55	

regions are projected to experience falls in average annual pasture growth of more than 7 per cent by 2030, with south-west Western Australia and western Victoria the worst affected.

The spatial distributions of projected changes in rainfall and pasture growth are significantly different. Pasture growth is projected to increase in more than a third of regions, and increase by around 4 per cent in about 10 per cent of regions across Australia. This is because the pasture growth modelling combines changes in rainfall with changes in temperature and CO_2 concentrations likely to occur under the A1FI scenario. It also integrates regional differences in soils and differences in the physiological response to climate change by different types of pasture. In some regions, changes in temperature, CO_2 and frost incidence are projected to offset declining rainfall and combine to increase pasture growth.

Overall, changes in pasture productivity lead to smaller relative changes in farm incomes (Fig. 3). Farm incomes are projected to fall by 1 per cent or more in a third of Australia's 58 statistical divisions, and are projected to rise slightly in another third. Farm incomes are projected to fall by more than 5 per cent in parts of south-west Western Australia and western Victoria, consistent with projected declines in rainfall and pasture growth. In contrast, farm incomes are projected to rise slightly across central and southern Queensland and Tasmania despite projected falls in pasture growth.

The smaller falls in farm incomes relative to agricultural productivity reflect past adaptive responses to climate variability incorporated into the bioeconomic model used here. However, historical adaptation is only partially represented in the AgFIRM model, and is likely to be underestimated (see Kokic et al., 2007 and Nelson et al., 2007a). Further, past adaptation may poorly reflect the full range of options available to respond to future changes in climate (Howden et al., 2007). This means that the projections in Fig. 3 are likely to overstate the impact of climate change on farm incomes under this particular climate scenario.

3.3. *Adaptive capacity using rural livelihoods analysis*

The weights of the first principal component for each capital and the variation they collectively explain in the overall adaptive capacity index are shown in Table 1. These weights potentially range from −1 to 1, with positive (negative) weights indicating a positive (negative) relationship with the other variables used to represent each capital. The weights for each capital are positive, with physical and financial capital contributing more to adaptive capacity than human or natural capital. The low contribution of human capital reflects a limitation of using secondary data such as formal education and health to represent farm management skill and capability. More specific and contextually relevant measures of farm management skill and capability could produce measures of human capital much more consistent with the social, natural, physical and financial capitals that contribute to resilient farming systems and rural communities.

The weights for the first principal component for each indicator are shown in Table A5.

While providing a rich avenue for ongoing research and improvements in data collection, differences in the contributions of each capital have a relatively minor effect on the robustness of the adaptive capacity index. This is demonstrated by a high degree of consistency between the map of adaptive capacity constructed using PCA weights (Fig. 4, right), and a map constructed using simple weights (Fig. 4, left). This robustness was achieved by rigorously adhering to the rural livelihoods framework when selecting indicators. An ability to use the simpler weighting method makes the analysis easier to interpret and therefore more transparent and accessible to policy advisers.

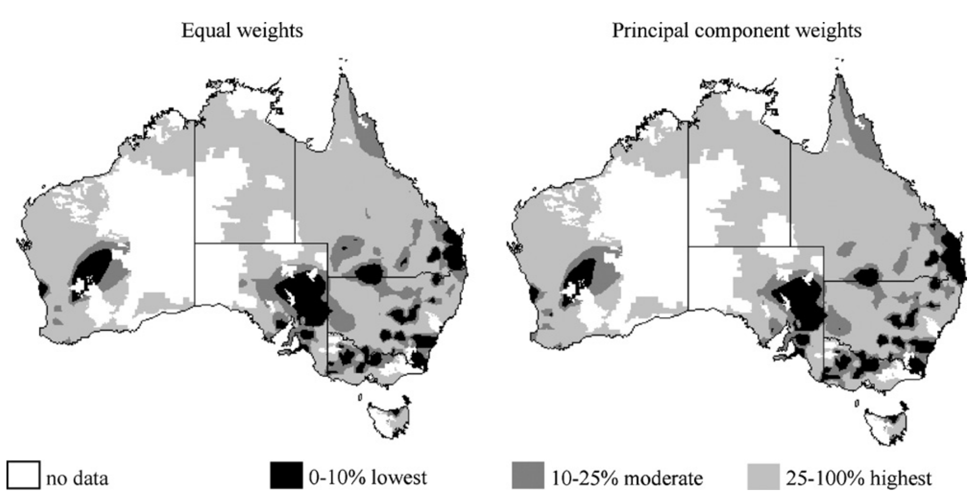

Fig. 4 – The adaptive capacity of Australian rural communities. The map on the left uses simple or equal weighting, while the map on the right uses principal component scores.

The composite indices of the five capitals and their component variables are mapped in Fig. A3. Decomposing each capital into its components highlights regional constraints and opportunities to build adaptive capacity (see Appendix for a detailed analysis). When the five capitals are integrated into a composite index (Fig. 4), they show that adaptive capacity is low across many of Australia's rangeland communities that remain dependent on the wool industry (Fig. 4). The pastoral communities of South Australia and the south-west corners of both Queensland and New South Wales have struggled to adjust to a long term decline in the profitability of wool production since the late 1980s. In other pastoral communities that were dependent on wool production, a greater degree of adjustment has been possible. In the Gascoyne Murchison region of Western Australia for example, a greater emphasis on meat production, live exports, and proximity to the mining industry have contributed to higher levels of adaptive capacity.

Pockets of low adaptive capacity throughout the wheat-sheep zones of eastern Australia and south-west Western Australia are associated with upward pressure on economically viable farm sizes (needed to achieve economies of scale) exerted by declining terms of trade. This is compounded in the high rainfall coastal zones of eastern Australia, Tasmania and Western Australia by the declining productivity growth of small beef properties relative to the extensive beef properties of northern Australia. Urbanisation increases the rates of return required for broadacre agriculture to be economically viable in peri-urban areas, while providing alternative income sources that reduce investment in agriculture.

Low adaptive capacity across Cape York partly reflects the declining emphasis on agricultural productivity in these regions, as the land is increasingly managed for a broader range of indigenous, environmental and mining values.

3.4. *Vulnerability to climate variability*

Even if biophysical impact modelling is integrated with holistic measures of adaptive capacity, the resulting analysis of vulnerability can be misleading. Fig. 5 shows the stark differences in vulnerability assessed using biophysical impact modelling of pasture growth (left), compared to more holistic economic impact modelling of farm incomes (right). Confining the analysis to the impacts on pasture growth would lead to a conclusion that inland Australia is most vulnerable due to high exposure to a variable climate, and low adaptive capacity (Fig. 5, left). Assessments of vulnerability based solely on climate impacts such as rainfall (Fig. 2, left) would be even more misleading. When farm incomes are used as a more integrative measure of exposure to climate variability, the spatial vulnerability of rural communities becomes considerably more complex (Fig. 5, right).

The rural communities across Australia that are both exposed to climate variability and low in adaptive capacity are geographically dispersed and diverse in their social, economic and environmental characteristics. One way to organise this diversity is to consider three broad types of community that are vulnerable. Some of the most vulnerable communities in rural Australia are those that are reliant on extensive sheep grazing in southern and central Australia. These communities have experienced a long term decline in the profitability of wool production, but lack options to diversify into other agricultural industries. This confirms a strong link between income variability and diversification that was revealed in an earlier paper (Nelson et al., 2007a).

Other rural communities vulnerable to climate variability are scattered throughout the wheat-sheep zone, particularly in eastern Australia. These are farming communities strongly affected by declining terms of trade and rural decline, undergoing a slow intergenerational process of farm consolidation that lags well behind the climatic and economic drivers of this change. Another vulnerable group are coastal and peri-urban farming communities. In these communities, the declining relative profitability of small-scale beef production has partially been offset by declining dependence on agriculture as urbanisation advances.

3.5. *Vulnerability to climate change*

The rural communities of Australia that are most exposed to climate change (Fig. 3), are also not necessarily the most

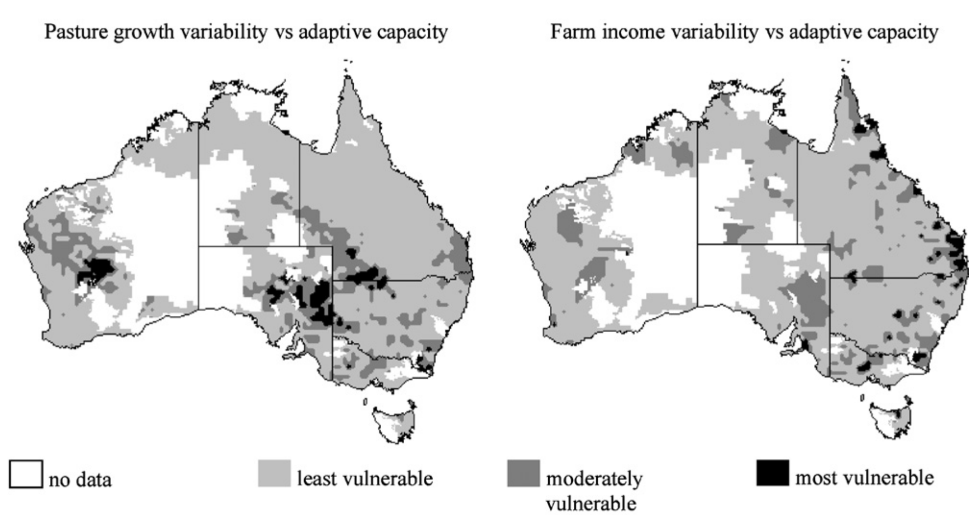

Fig. 5 – The vulnerability of Australian rural communities to climate variability.

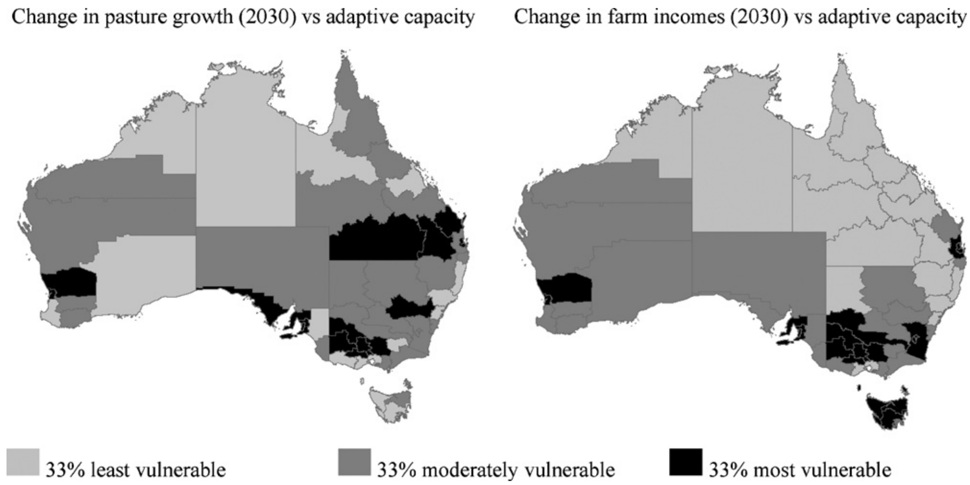

Fig. 6 – The vulnerability of Australian rural communities to climate change.

vulnerable to it (Fig. 6). For example, all of the agricultural areas of Western Australia are either highly or moderately exposed to climate change impacts on pasture productivity and farm incomes (Fig. 3). However, most of these regions except the Midlands east of Perth have high or moderate adaptive capacity (Fig. 4). The result is low to moderate vulnerability, except in the Midlands (Fig. 6). In areas such as south-east New South Wales, moderate exposure combines with low adaptive capacity to create high vulnerability. Coastal and peri-urban rural communities in both south-eastern and south-western Australia that are dependent on small-scale beef production also tend to be moderately to highly vulnerable to climate change. This is due to low adaptive capacity and projected reductions in farm incomes. Pasture productivity in many of these areas is projected to increase under this climate change scenario, and would therefore provide an entirely erroneous measure of the vulnerability of these regions.

Australian rural communities that are vulnerable to climate variability and change are vulnerable for a complex set of environmental, economic and social reasons. Vulnerable communities include those in inland Australia that lack alternative livelihood options to contend with a long term decline in the international demand for wool. For rural communities associated with grain and beef production, multiple drivers of change and constraints on adaptive capacity contribute to vulnerability. For example, in the wheat-sheep zone, climate variability and the prospect of a drier future is likely to accelerate an ongoing process of structural adjustment in response to declining terms of trade. A critical question for future research is whether and under what conditions this combined impetus for change is likely to exceed incremental coping capacity, and require more transformative changes in farming systems, land use and industries. The pressure for transformative change could be made more complex by pervasive climate-induced changes in Australia's comparative advantage in international commodity markets. In smaller coastal farms close to urban areas, low adaptive capacity and vulnerability may be evidence of agricultural systems already undergoing transformative change, as urbanisation reduces dependence on agricultural livelihoods in these regions.

4. Science-policy implications

The science of vulnerability assessment urgently needs to be redirected toward identifying diverse and flexible options for adapting to the multiple, interacting and uncertain dimensions of future climate change. If focused on exclusively, we have demonstrated that hazard/impact modelling can lead to entirely erroneous conclusions about the vulnerability of rural communities. This is because rural communities exposed to climate risk are often highly adapted to it. A focus on optimising management responses to predicted climate conditions can also lead to an unproductive and never-ending quest to remove uncertainty from policy advice on climate variability and change (Nelson et al., 2008). The inevitable science-policy relevance gap that results from this approach could, if repeated, diminish the perceived value of science in adaptation policy. Similarly, unwitting acceptance of this type of science by policy advisers will introduce significant risks into policy processes. This is because at best, reliance on hazard/impact modelling constrains policy analysis to a limited set of incremental adaptation options within existing agricultural systems. At worst, it risks institutionalising inappropriate or counter-productive adaptation options and restricts exploration of new sets of activities that may be better suited to changing climate conditions.

Integrated vulnerability assessment also offers pathways to constructive policy solutions that are not revealed by hazard/impact modelling. Hazard and impact models focus on the drivers of change, often framed as threats, rather than on creating options and opportunities. We have previously shown that there are few policy options capable of reducing the exposure or sensitivity of rural communities to climate variability and change except in the very long term (Meinke et al., 2006; Nelson et al., 2007a). Decomposing adaptive capacity into its components highlights policy opportunities for building it. For example, human capital can be increased through specific investments in education and health services, while social capital can be enhanced through programs that support community development and communication infrastructure, such as Australia's Landcare movement. Policies and programs that accelerate rural and regional development and expand access to world markets can create the physical infrastructure and market opportunities needed to create new agricultural and non-farm livelihood opportunities (Anderson, 2003).

To be policy relevant, vulnerability assessments need to inform action by and on behalf of communities, industries and governments to reduce vulnerability and build adaptive capacity (Chambers, 1989). For climate change this means providing input into immediate policy development on the costs and benefits of various mitigation policy alternatives, and any trade-offs involved in balancing adaptation and mitigation (Howden et al., 2007). It means creating interdisciplinary forms of science that inform policy-relevant outcomes, and embedding these in science-policy engagement processes that support decision making.

Rural livelihoods analysis was used in this paper to create a composite index of adaptive capacity that enables policy advisers to drill into the attributes of adaptive capacity to identify opportunities for addressing limiting factors. An experimental website has been developed enabling community groups, industries and governments to explore the factors limiting adaptive capacity in their region.[1] Research parallel to this is converting rural livelihoods analysis into participatory self-assessment processes that enable community-based natural resource management groups to set priorities for collective action to build their capacity to adapt to global change (Brown et al., forthcoming). This type of adaptive governance process also provides opportunities for communities and governments to work together to address trade-offs between building adaptive capacity and attaining other goals to design co-owned, *no-regrets* actions.

The risk of substituting hazard or impact modelling for integrated vulnerability assessment partly arises from the different pace at which policy and science processes evolve, and partly from institutional constraints. Policy demand for integrated vulnerability assessment has been driven by an urgent need to identify vulnerable industries and regions in order to prioritise policies and programs for building adaptive capacity (Nelson et al., 2010), including strategic assessment of mitigation policy (Garnaut, 2008). This places policy and funding pressure on scientists to draw inferences about vulnerability using existing hazard/impact models that have dominated past climate-related research (Pearson et al., 2008). Part of the solution to this problem is to create science-policy engagement processes that promote the co-evolution of policy demand with scientific capability. However, these processes can only be created through institutional structures and incentives that enable scientists from diverse disciplines and agencies to flexibly and continuously reorganise themselves to create interdisciplinary, outcome-oriented research. The research presented in this paper, for example, was the result of informal collaboration across a community of practice in applied climate science that includes social scientists, economists, statisticians, climatologists, agronomists and ecologists geographically dispersed across several separate agencies.

[1] www.apsim.info/VulnerabilityAssessmentAustralia/.

5. Conclusion

In this series of papers, we have shown that it is no longer acceptable to substitute or confuse hazard or impact modelling with more integrated approaches to vulnerability assessment when providing policy advice. To have any potential for policy relevance, hazard/impact modelling needs to be combined with holistic measures of adaptive capacity to provide insights into the multiple and emergent dimensions of vulnerability. The development and interpretation of vulnerability assessments involves myriad value judgements on the part of scientists, often made tacitly. Each one of these value judgements represents a decision point at which individual scientists can choose to incorporate design criteria elicited from end users to enhance the policy relevance and societal value of their research. Experience shows that this does not always occur serendipitously, and requires innovation in science-policy engagement to create cultures and reward structures in science institutions supportive of interdisciplinary research. Transforming science-policy engagement to a more adaptive model could enable vulnerability assessment to co-evolve with adaptation policy without subverting policy goals to fit science agendas. This would simultaneously maximise the societal value of science and the robustness of policy processes supporting community and industry adaptation to climate variability and change.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.envsci.2009.09.007.

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