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Land degradation and climate change: opportunities for climate resilient agriculture

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Abstract

Land degradation and climate change pose enormous risks to global food security. Land degradation influences the vulnerability of agro-ecological systems to climate change impacts and the effectiveness of adaptation options. However, land degradation has largely been omitted from climate impact assessments and adaptation planning. Here, we critically examine how land degradation can influence climate change impacts and producers' adaptive capacity in agro-ecological systems. We then present novel strategies for climate-resilient agriculture that leverage synergies and integrate responses to the challenges. Forward-looking, climate-resilient agriculture requires: (1) incorporation of land degradation processes, and their linkages with adaptive capacity, into adaptation planning, (2) identification of key vulnerabilities to prioritize adaptation responses, (3) improved knowledge exchange across scales to support strategies for developing adaptive capacity of producers, and (4) innovative management and policy options that provide multiple wins for land, climate and biodiversity, thus enabling global development and food security goals to be achieved.

In a nutshell:

- The interactive effects of land degradation and climate change on global agriculture and food security are underappreciated.
- Land degradation has potential to influence the magnitude and direction of climate impacts and effectiveness of adaptation options.
- Feedbacks between land degradation, climate change, and the adaptive capacity of land users, needs to be understood to identify vulnerable systems and prioritize adaptation actions.
- Improved knowledge exchange across scales, and management and policy responses which focus on 'multi-win' options that reduce land degradation whilst benefiting climate change adaptation and biodiversity, provide significant opportunities for building climate resilience in agriculture.

[Manuscript]

Land degradation and climate change are intensifying challenges that have affected global agricultural production and food security of civilizations for millennia (Diamond 2005). Tackling these challenges is vital for building sustainable agro-ecological systems that can feed the world's rapidly growing population. Although there is extensive knowledge about land degradation and climate change as separate phenomena, less is known about how they are likely to interact in different agro-ecological systems, and critically, how societies must simultaneously adapt to these challenges (Reed and Stringer 2016). The scale of each challenge alone is enormous. Land degradation is estimated to affect >25% (37.25 million km^2) of the global land area, in the form of a reduction or loss of soil quality due to soil physical and chemical changes and erosion, and declining biological and economic productivity (ELD Initiative 2015). These changes are occurring across the world's ecosystems and agricultural lands, including arid and semi-arid rangelands and pasturelands (Bestelmeyer *et al*. 2015), agro-forestry systems (Miettinen *et al*. 2014), and croplands (Karamesouti *et al*. 2015). However, available global assessments of land degradation rates remain highly uncertain (Drenge and Chou 1994; Oldeman 1994; Lepers *et al*. 2005). Approximately 40% of land degradation has occurred in developing countries, which are projected to experience 78% of the global dryland expansion and 50% of the population growth by 2100 (Huang *et al.* 2015). At the same time, the risks of climate change to agriculture, biodiversity and livelihoods are also vast, with some of the greatest risks in developing dryland areas (IPCC 2014). With the increasing challenge of global warming, managing accelerating climate impacts presents an immense and urgent task, while in some cases providing opportunities for land restoration and increasing agricultural production.

Combating land degradation is integral to adaptation planning as land degradation often increases the exposure and sensitivity of agro-ecological systems to climate impacts; reducing system resilience and influencing the adaptive capacity of land users (Gisladottir and Stocking 2005). However, impacts of land degradation and climate change on agriculture have often been masked by technological advances of the past century (Pingali 2012). For example, in Australia, cereal grain yield increases have been reduced by soil degradation, resulting in yield plateaus otherwise hidden by ongoing areal expansion of croplands (Turner *et al.* 2016). Unless soil degradation is addressed, projected declines in rainfall over Australian croplands may compound the soil degradation impacts on grain yields, presenting a risk to food security (CSIRO and BoM 2015). In rangeland systems, and in regions that have not adopted appropriate conservation agriculture, exposure to land degradation risks may be even greater. Shrub encroachment and wind erosion in the Botswana Kalahari has increased the vulnerability of local communities to drought relative to those in neighboring Namibia and South Africa (Figure 1) (Dougill *et al.* 2010). Unless land degradation is addressed now, or alternative land uses and livelihood options sought, rising temperatures and projected rainfall declines are likely to further impact the ability of southern Botswana communities to reach their development goals. Government policies, for example the Tribal Grazing Lands Policy of Botswana (Dougill *et al*. 1999), the European Union's Common Agricultural Policy and US farm bill, directly influence land degradation rates across agro-ecological systems and their resilience to climate change (MA 2005). The potential for land to continue providing ecosystem services under a changing climate is directly impacted by the way in which it is managed. Land degradation can undermine the effectiveness of climate change adaptation.

Novel management and policy options can provide multi-win outcomes for land degradation and climate change, as well as biodiversity. These draw on current understanding of the biophysical, social and economic linkages between land degradation and climate change across scales. They enable identification of key social and biophysical vulnerabilities, and appropriate adaptation strategies. Adaptation planning has become a focus of global science and policy to address climate change risks and identify opportunities (Howden *et al.* 2007). However, pervasive and severe land degradation remains a major barrier to effective adaptation planning for agriculture (Reed and Stringer 2016). Unless land degradation and climate change are addressed together in ways that do not negatively impact biodiversity, we may undermine adaptation efforts, exacerbate food security and development risks posed by climate change, and fail to achieve many of the Sustainable Development Goals (SDGs) (United Nations 2015).

In this paper we critically assess how land degradation can exacerbate the negative impacts of climate change and influence the adaptive capacity of producers. We then outline four core actions, presented as future science, management and policy directions, to improve adaptation planning and the resilience of global agro-ecological systems to climate change.

Links between land degradation, climate change and adaptation planning

Land degradation and climate change are interlinked processes that have biophysical and human drivers, impacts and responses (Herrick *et al.* 2013). Land degradation is defined as a "reduction or loss of biological or economic productivity and complexity of agro-ecological systems as a consequence of land use, or from one or more processes which may arise from human activities including: (i) soil erosion by wind and/or water, (ii) deterioration of the physical, chemical, and biological or economic properties of soil (e.g., due to salinization), and (iii) long-term loss of natural vegetation" (UNCCD 1994). Such changes may be exacerbated directly by land use and land management patterns, and natural phenomena such as drought, heavy rainfall and fire (MA 2005). Land degradation may also be exacerbated by indirect social, economic and political factors that encourage or impose land use pressures that fail to balance the use of ecosystem services with agricultural production demands (D'Odorico *et al*. 2013). Land degradation can therefore manifest in diverse ways across agro-ecological systems; such as structural changes in tropical forest canopy cover and biomass reduction (Miettinen *et al*. 2014), salinization of irrigated drylands (Qadir *et al*. 2014) and soil nutrient decline in croplands due to erosion (Quinton *et al*. 2010). These impacts may be diffuse across landscapes and regions, or occur as hot spots and exhibit large spatial variability.

Given the embedded nature of ecological and social systems, land degradation usually results in a decline in agro-socio-ecosystem resilience; the ability of a system to maintain the structure required to sustain basic system functions through periods of stress or perturbation (Reed and Stringer 2016).

Declining resilience of agricultural and social systems can increase pressure on ecological systems, leading to a spiral of degradation as soil resources are depleted and vegetation communities change. A loss of producers' adaptive capacity often occurs as systems become unable to cope with climate and management stressors (Marshall *et al.* 2014). These changes typically take place across multiple scales, involving different stakeholder groups (e.g., land users, technical advisors, administrators and policy makers).

Land degradation may be associated with regime shifts in agro-ecological systems, demanding novel management or land use change. Response strategies may therefore be targeted toward equilibrium (predictable) or non-equilibrium (episodic) management change (Bestelmeyer *et al.* 2015). Climate change can exacerbate and accelerate land degradation. For example, due to accelerated soil erosion, increased evapotranspiration rates, drought, and changes in biodiversity, pests and diseases. Legacy effects of historical land degradation may therefore also influence the magnitude and direction (positive or negative) of the impacts of climate change on agro-ecological systems. Conceptual models of ecosystem resilience (Kelly *et al*. 2015), applied to agriculture as complex adaptive systems, have been effective tools for understanding land degradation impacts on agricultural production and their interconnectedness with social and economic systems (Rist *et al*. 2016). Land degradation is a key factor influencing the vulnerability of agro-ecological systems to climate change.

Exposure, sensitivity, and adaptive capacity of producers determine the vulnerability of agro-ecological systems to climate change, and can each be influenced directly and indirectly by land degradation (Figure 2). Soil quality or soil health, defined by a suite of dynamic soil properties including structure, soil organic carbon, infiltration rates and availability of nutrients (Seybold *et al.* 1999), represents the status of the soil relative to its potential (UNEP-IRP 2016), where better soil health is generally associated with lower sensitivity to climate change. Soil health is impacted by land degradation primarily via erosion, but also soil physical, chemical and biological changes. Declining soil health may occur concurrently with vegetation changes due to land use and management (Bestelmeyer *et al*. 2015), impacting forage and crop production responses to climate change. Through these processes, land degradation can reduce the positive fertilization effects of elevated atmospheric CO_2 on vegetation (Reich and Hobbie 2012).

The impacts of land degradation on agro-ecological systems are also connected to systems' socio-economic vulnerability. Changes to the quantity and quality of ecosystem services as a consequence of climate change will affect livelihoods across value chains (from "farm to fork"). These changes ultimately feed back to affect land management and land degradation. Because of these linkages, land degradation further impacts upon adaptation options. For example, increasing invasive species (e.g. cheatgrass, *Bromus tectorum*) in rangelands of the western United States reduce management options for livestock producers to adapt to increasing drought frequency that impacts forage availability (Briske *et al.* 2015). Accounting for how land degradation impacts adaptation options in such ways will be critical for adaptation planning.

Adaptation planning for agriculture has largely failed to consider the risks associated with ongoing land degradation, or opportunities arising from restoration of degraded land. While some national adaptation plans for agriculture identify the importance of soil conservation (e.g. Walthall *et al.* 2012; Government of Brazil 2016), many still do not address land degradation as an integral part of that planning, for example, Australia (Australian Government 2015) and India (Government of India 2008). For crop and livestock production systems, incremental adaptation options such as changing crop varieties and livestock breeds, and altering the timing and location of management activities, have been an important focus (Howden *et al.* 2007). Yet land degradation can severely reduce the effectiveness of these types of incremental and reactive adaptations. Such adaptations may only have short-term benefits, while long-term and transformational management responses (e.g., land use change) are often required (Kates *et al.* 2012). Autonomous adaptation at local scales will continue to be important for maintaining healthy agro-ecological systems. However, strategies underpinned by forward planning, motivated and empowered land managers, financial resources, and supportive government policy are needed to enable adaptation at broad scales (Chasek *et al*. 2015). Addressing land degradation now, as an anticipatory adaptation strategy, is potentially a highly effective approach to building productive and sustainable agro-ecological systems for the future. Multiple responses are required across local, national and regional scales to build the resilience and reduce the vulnerability of agro-ecological systems to land degradation and climate change.

Future directions for science, management and policy

Science, management and policy opportunities are emerging that will enable land degradation to be addressed as a key element of climate change adaptation planning for agriculture. Politically, there is increasing interest in doing this. The endorsement of SDG target 15.3 (Land Degradation Neutrality (LDN), defined as a world where the amount of healthy and productive land resources necessary to support ecosystem services remains stable or increases; UNCCD 2015) by the United Nations Convention to Combat Desertification (UNCCD) Conference of the Parties increased the visibility of land issues, particularly in relation to the SDGs, and strengthened the focus of the Convention itself on land restoration (UNCCD 2015). Challenges and opportunities associated with LDN are now the focus of international efforts to better characterize areas that are land degradation neutral (e.g., Salvati and Carlucci 2014) and develop pathways to achieving Zero Net Land Degradation (Chasek *et al*. 2015; Stavi and Lal 2015). In 2016, the Intergovernmental Panel on Climate Change (IPCC) agreed to create a special report on desertification, land degradation and climate change that will complement the Sixth Assessment Report (AR6). Coordination is also improving among the UNCCD, UN Framework Convention on Climate Change (UNFCCC) and UN Convention on Biological Diversity (UNCBD) to identify and harness synergies in responses to land degradation and climate change; for example, supporting complementary adaptation strategies within the National Adaptation Programmes of Action under the UNFCCC, and National Action Programmes under the UNCCD (Reed and Stringer 2016). While these important international steps are significant, complementary local, national and regional approaches are required to integrate ways to tackle land degradation within adaptation planning for agriculture. Here we identify and evidence four core multi-level actions that can be taken.

1. Increase understanding of biophysical, biogeochemical and socio-economic interactions

Research is essential to establish how the linkages between land degradation and climate change affect impacts and opportunities, producers' adaptive capacity, and potential response strategies. Two outstanding research requirements are (i) accounting for land degradation in systems approaches for evaluating impacts and adaptation options, and (ii) evaluating the social-biophysical interactions of land degradation and climate change and the implications for adaptive capacity.

Systems approaches to adaptation planning are required to assess the biophysical, biogeochemical, social, and economic interactions between land degradation and climate change (e.g., van Grinkel *et al.* 2013). Integrated Assessment Models (IAMs) are important tools for evaluating climate change impacts on human-environmental systems (Reynolds *et al.* 2011). However, Land Surface Models (LSMs) (e.g., the Community Atmosphere Biosphere Land Exchange (CABLE), Joint UK Land Environment Simulator (JULES), and Noah models) that represent soil-vegetation-atmosphere interactions in IAMs currently do not represent land degradation processes (Best *et al.* 2015). The omission of wind and water erosion, and their biophysical and biogeochemical feedbacks, creates large model uncertainties and severely limits IAM assessments of the linkages between land degradation, climate change and adaptation responses (Chappell *et al.* 2015).

Agricultural systems models that are used to assess farm-level climate impacts and adaptation also omit key land degradation processes and feedbacks. For example, the Agricultural Policy/Environmental eXtender (APEX), and the Agricultural Production Systems sIMulator (APSIM) and Decision Support System for Agrotechnology Transfer (DSSAT) within the Agricultural Model Intercomparison and Improvement Project (AgMIP), incorporate water erosion but either do not represent wind erosion, or omit the combined erosion process feedbacks to soils, nutrients and vegetation (Rosenzweig *et al.* 2013). Exclusion of erosion processes and degradation scenarios from model assessments creates uncertainties in the nature of climate change impacts and the biophysical-to-economic trade-offs for management options

(Panel 1 and Figure 3; Webb *et al.* 2013). Incorporating land degradation processes into systems analyses at all scales is needed to assess agro-ecosystem resilience, the agro-ecological and socio-economic impacts of climate change, and adaptation scenarios. Such improvements are also needed to evaluate the changing effectiveness of adaptation strategies over time and identify tipping points at which adaptations may become maladaptations and negatively impact agro-ecological systems (Magnan *et al*. 2016).

An improved understanding of the linkages between land degradation and human adaptive capacity is also needed to support adaptation planning for agriculture (Stringer *et al.* 2009). How the capacity of land users to adapt to climate change is related to patterns of land degradation has not been established for different agro-ecological systems (e.g., Barbier 2000). A better understanding of the relationship between adaptive capacity and land degradation will facilitate identification of barriers and limits to the adoption of climate-smart and sustainable land management practices (Lipper *et al.* 2014). At national and global scales, understanding the linkages between land degradation and adaptive capacity is important for developing and implementing policies to achieve LDN. Encouraging land users and policymakers to develop their own knowledge about land degradation, informed by scientific understanding, can complement formal knowledge building in support of adaptation planning at all scales.

2. Identify vulnerabilities

Identifying which agro-ecological systems are vulnerable to the interactive effects of land degradation and climate change is vital for prioritising management and policy responses at different scales. In part this is a biophysical and biogeochemical challenge, requiring knowledge of how both inherent land potential (UNEP-IRP 2016) and land degradation processes interact with changes in temperature, precipitation, and atmospheric CO_2 concentrations. Drylands, with limited rainfall and often high temperatures, and areas already experiencing land degradation, are likely most exposed to damaging interactions with climate change (Gisladottir and Stocking 2005). Interactions between land degradation and climate change are also likely to be highly variable in space and time. For example, the impacts of declining rainfall on crop yields and livestock forage availability will vary across degraded and non-degraded lands with different infiltration rates and soil moisture retention (Herrick *et al*. 2013). Application of integrated agro-ecosystems models that incorporate land degradation processes will improve the identification of where these feedbacks are most likely to occur, and which regions are most vulnerable.

Identifying vulnerabilities is also a challenge for social scientists and economists. Key sensitivities and exposure to climate change likely manifest in land use approaches and policy that have resulted in, or are driving, land degradation (Figure 4) (Stringer *et al.* 2009). Historical degradation patterns may provide analogues for identifying vulnerabilities that can be linked to agro-ecological assessments.

Participatory planning approaches that combine biophysical assessments with producer evaluations of adaptation options have revealed vulnerabilities in agricultural systems, e.g. in northern Australia (Webb *et al.* 2013), through comparison of land users' management aspirations with scientific knowledge and the benefits of joint knowledge production. Land degradation concepts can be readily incorporated into such approaches, or other analytical framings of adaptation (Wise *et al.* 2014). Socio-economic vulnerabilities can be as, or more, important than ecological vulnerabilities for climate change adaptation in agriculture (Abson *et al*. 2012). Exploring new approaches that reveal the underpinning factors influencing different system vulnerabilities will therefore be important for identifying successful management and policy responses.

3. Improve knowledge exchange across scales

Improved knowledge exchange among stakeholders such as scientists and land users, technical advisors, administrators, and policy makers across scales is essential to ensure land degradation-climate change linkages are appropriately recognized within management and policy options. Integrating different knowledge systems (e.g., indigenous, traditional, local, scientific), and co-generating new knowledge, often leads to more robust agricultural policy decisions (Raymond *et al.* 2010). Knowledge exchange can also facilitate response options that are more appropriate to the needs of local communities and can protect their livelihoods and wellbeing.

Cross-institutional initiatives and mechanisms for evidence-based policy making may be most effective for knowledge integration and sharing for planning across the land degradation and climate change domains (Akhtar-Schuster *et al.* 2011). At the international level, science-policy interfaces like the IPCC, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and the Science-Policy Interface (SPI) of the UNCCD, as well as assessments like the Millennium Ecosystem Assessment and the IPBES Land Degradation and Restoration Assessment, can all contribute towards multi-stakeholder learning. Developing approaches for successful knowledge exchange (e.g., Chasek *et al*. 2011) across institutional boundaries and among stakeholders (e.g., local land users, researchers, and policy makers) within and outside the UN Conventions will be especially important for increasing adoption of practices and policy that address land degradation and climate change together. Building participatory research and knowledge sharing at national and local scales through coordinated agricultural extension will complement international efforts to support exchange of knowledge and approaches to tackle land degradation within adaptation planning. These participatory approaches will increasingly be able to draw on the growing availability of relevant knowledge and information through the development of web portals, such as the UNCCD's new Knowledge Hub, the US Department of Agriculture's Climate Hubs, and mobile applications such as the Land-Potential Knowledge System (Herrick *et al*. 2016).

4. Develop innovative, multi-win management and policy options

Management and policy options are needed to actively restore agro-ecosystem resilience while minimising negative climate impacts. Some land management strategies will remain spatially and temporally robust, while others may not be sustainable under changing conditions and new management and policy options will be required (Figure 5) (Reynolds *et al.* 2011). 'Multi-win' options that apply innovative sustainable land management (SLM) solutions to reduce land degradation, support restoration, and balance land degradation, climate change adaptation, human well-being and biodiversity outcomes, should be prioritized within the context of existing adaptation approaches such as Climate Smart Agriculture (CSA; Lipper *et al.* 2014). The flexibility of CSA as a proactive option for addressing land degradation and climate change across agro-socio-economic sectors has been recognised for some time (Thomas 2008). However, redoubling efforts to implement these strategies now to enhance existing conservation practices, and within adaptation planning frameworks, will be critical for future food security and the resilience of agro-ecological systems.

Land management and policy options have variable appeal to stakeholders in different situations, agricultural sectors and regions. Adaptation planning must anticipate and overcome, where possible, barriers to management and policy adoption. Planning multi-win responses therefore needs to consider the resilience and restoration potential of the biophysical environment (including under climate change conditions), social needs, institutional needs (to establish incentives and shape behaviours), and evolving needs for knowledge exchange to provide access to relevant information, technology, and agricultural industry engagement. Promoting the use of active adaptive management at all scales (e.g., by land managers, regional climate adaptation planners, industry, and government) can be useful for overcoming barriers to adoption, reducing dis-adoption, enhancing adaptive capacity, and increasing implementation of new management and policy options (Marshall *et al.* 2013). Empowering agricultural land users to take new identities as 'land stewards', for example by increasing the security of land tenure, can increase the range of strategies available to policy makers, the sustained adoption of CSA and SLM by land users, and the likelihood that improvements in land condition will be observed that will reinforce the benefits of combating land degradation to build climate resilience in agriculture.

Conclusions

Combating land degradation is essential for building sustainable agro-ecological systems that are climate resilient, conserve biodiversity, and meet global development goals. Future agro-ecological systems will depend on our ability to develop innovative management and policy options now. At the global scale, increasing coordination among the UNCCD, UNFCCC and UNCBD has sought to build the enabling environment for agro-ecological systems to become land degradation neutral and climate resilient

(Chasek *et al*., 2015; Reed and Stringer, 2016). However, additional new opportunities must be sought for scientists, managers and policymakers to fill critical gaps in assessment capabilities and understanding, and to establish stronger connections with aligned efforts to tackle climate adaptation and biodiversity challenges at local to global scales. To address this need, we have presented four multi-level actions that can be taken to integrate efforts to combat land degradation into climate change adaptation planning.

We argue that research must interrogate the feedbacks between land degradation and climate change, and the linkages between land degradation and the adaptive capacity of land users, taking a holistic systems approach. Integrating land degradation processes and knowledge into agro-ecosystem assessment models will be critical for effectively evaluating interactions between land degradation and climate change, and identifying adaptation strategies in developed and developing countries alike. Agro-ecological systems that are vulnerable to the combined effects of land degradation and climate change must be identified to prioritize actions in these areas and reduce the costs of ongoing land degradation. Lessons learned in regions with resilient agro-ecological systems should be used to support regions with low adaptive capacity (Salvati and Carlucci 2014), while improving knowledge exchange among stakeholders at all scales can support the adoption of strategies to achieve LDN within a changing climate. Responses that provide multi-win outcomes for land degradation, climate change and biodiversity offer the greatest benefits for agro-ecological systems and global food security.

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Panel 1. Australian rangeland degradation increases enterprise vulnerability to climate change

In the Australian rangelands, livestock producers face the challenge of balancing their production goals in a climate with highly variable rainfall while avoiding overgrazing that could result in land degradation. Historical degradation of Australian rangelands significantly impacts forage availability today, and has implications for the economic viability of enterprises under a changing climate. These impacts are illustrated for a beef cattle enterprise near Charters Towers, Queensland (Figure 3; after Webb *et al.* 2013). The data illustrate the effectiveness of land degradation, represented as a decline in soil quality and loss of perennial forage species, on climate impacts averaged across three land types (soil-vegetation complexes) for climate change scenarios of doubled atmospheric CO_2 (from 350 ppm to 700 ppm) with: a hotter and wetter (HW) scenario of +3°C with +17% rainfall, a hotter and drier (HD) scenario of +3°C with -6% rainfall, and a hotter and much drier (HMD) scenario of +3°C with -51% rainfall.

Land degradation affects the magnitude and direction of climate impacts under the baseline (1890-1990) climate, and each climate change scenario, with considerable variability among land type responses. Degraded land is less productive, more susceptible to erosion, and less profitable or not profitable at all. Failure to address declining land condition has increased the vulnerability of enterprises to climate change. Ongoing land degradation may reduce the effectiveness of incremental adaptation strategies, like adjusting stocking rates to suit forage availability, and increase the risk of negative impacts and missed opportunities over the long term. Production on non-degraded lands can benefit more than degraded lands under a climate with improved growing conditions (HW). Production on non-degraded or restored lands could be no worse off, and in fact could be better, under extreme climate stress (HMD) than it is today for land in a degraded condition. Australian investment in policies and practices to mitigate land degradation and restore degraded lands is needed to safeguard enterprise viability and food security under a future climate with poor growing conditions.

List of Figures

Figure 1 – Land degradation can manifest as a decline in ecosystem services associated with ecological change, such as in the rangelands of the Botswana Kalahari. Overgrazing of grasslands (a), especially during drought, may lead to wind erosion and shrub invasion (b). Persistent reduction of grasses and shrub competition may lead to shrub dominance (c). These processes can be exacerbated by climate change. Restoration may require reduced grazing pressure, soil stabilization and mechanical intervention. This may require significant capital input, which may not be available to land users, or create need for land use and livelihood change.

Figure 2 – A framework for conceptualising the linkages between land degradation and vulnerability of agriculture to climate change across ecological and socio-economic domains. These domains overlap where agro-ecological, social and economic processes interact, e.g., in determining the vulnerability of ecological systems via the influence of management strategies on land degradation. Adapted from Marshall *et al*. (2014).

Figure 3 – Climate change impacts on a livestock (beef) enterprise in northern Australia for degraded and non-degraded lands. Impacts are expressed as the mean and standard deviation (error bars) of three simulated land type responses to hotter and wetter (HW), hotter and drier (HD) and hotter and much drier (HMD) climate change scenarios relative to an 1890-1990 baseline (see Panel 1). Adapted from Webb *et al*. (2013).

Figure 4 - Vulnerabilities to the interactive effects of land degradation and climate change likely manifest in land use approaches and policy that drive land degradation. Adaptation options may be limited for some land users, requiring greater government involvement and support across local to national scales to be most effective (Stringer *et al.* 2009).

Figure 5 – Over the last century, regime shifts in desert grasslands (a) of the southwestern US have resulted in the expansion of shrublands dominated by mesquite (*Prosopis glandulosa*) and increased wind erosion (b). The spread of this unpalatable shrub, and associated loss of perennial grasses (e.g., black grama, *Bouteloua eriopoda*), has reduced the carrying capacity for beef cattle and increased the vulnerability of enterprises to drought and climate change. With few options for restoring the shrub-invaded rangelands, novel management strategies with livestock that can utilize available forage (see Anderson *et al*., 2015) are being sought to build resilience in ranching communities.