Land degradation and climate change: building climate resilience in agriculture

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Land degradation and climate change pose enormous risks to global food security. Land degradation increases the vulnerability of agroecological systems to climate change and reduces the effectiveness of adaptation options. Yet these interactions have largely been omitted from climate impact assessments and adaptation planning. We examine how land degradation can influence climate-change impacts and the adaptive capacity of crop and livestock producers across agroecological systems. We then present novel strategies for climate-resilient agriculture that support opportunities to integrate responses to these 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 local to global scales to support strategies for developing the 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.

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Land degradation and climate change are intensifying challenges that have affected global agricultural production and human food security for millennia (Diamond 2005). Tackling these challenges is vital for building sustainable agroecological 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 most likely to interact in different agroecological systems and, critically, how societies must simultaneously adapt to their impacts (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 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 use different definitions, lack comparability, and are 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). Concurrently, 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). Managing accelerating climate-change impacts is an immense and urgent task but in some cases may provide opportunities for restoring land and increasing agricultural production.

In a nutshell:

- The interactive effects of land degradation and climate change on global agriculture and food security are underappreciated
- Land degradation has the potential to influence not only the size and direction of climate impacts but also the effectiveness of management options
- Feedbacks between land degradation, climate change, and the adaptive capacity of land users need to be understood to identify vulnerable systems and prioritize adaptation actions
- Improved knowledge exchange across scales, as well as management and policy responses that focus on "multi-win" options to reduce land degradation while benefiting climate-change adaptation and biodiversity, provides important opportunities for building climate resilience in agriculture

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Combating land degradation is integral to adaptation planning for agriculture, given that land degradation often increases the exposure and sensitivity of agroecological systems to climate impacts, thereby reducing system resilience and influencing the adaptive capacity of land users (Gisladottir and Stocking 2005). Yet the impacts of land degradation and climate change on agriculture have often been masked by the technological advances of the past century (Pingali 2012). For example, in Australia, cereal grain yields have been reduced by soil degradation, resulting in yield plateaus that have been hidden by ongoing areal expansion of croplands (Turner *et al.* 2016). 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, land degradation risks may be even greater. Shrub encroachment and wind erosion in the Botswana Kalahari have 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 else alternative land uses and livelihood options sought, rising temperatures and projected rainfall declines are likely to further limit the ability of southern Botswana communities to reach their development goals. Government policies such as the Tribal Grazing Lands Policy of Botswana (Dougill *et al.* 1999), the European Union's Common Agricultural Policy, and the US farm bill influence land degradation rates across agroecological systems and their resilience to climate change (MA 2005). The potential for land to continue providing ecosystem services under a changing climate is directly affected 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 for biodiversity. These approaches draw on current understanding of the biophysical, social, and economic linkages between land degradation and climate change across areal and temporal scales. They enable identification of key social and biophysical vulnerabilities (eg the inability to cope with reduced forage availability due to declining rainfall, which negatively affects producers' livelihoods), in addition to appropriate adaptation strategies. Adaptation planning for agriculture 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 (Reed and Stringer 2016). Unless these global issues are addressed together in ways that do not negatively affect biodiversity, scientists and resource managers may undermine adaptation efforts, exacerbate food security 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 is likely to interact with climate change and influence the adaptive capacity of agricultural (including livestock) producers, hereafter termed "producers". We then outline four core actions – presented as future science, management, and policy directions – to improve the efficacy of adaptation planning and the resilience of global agroecological systems to climate change.

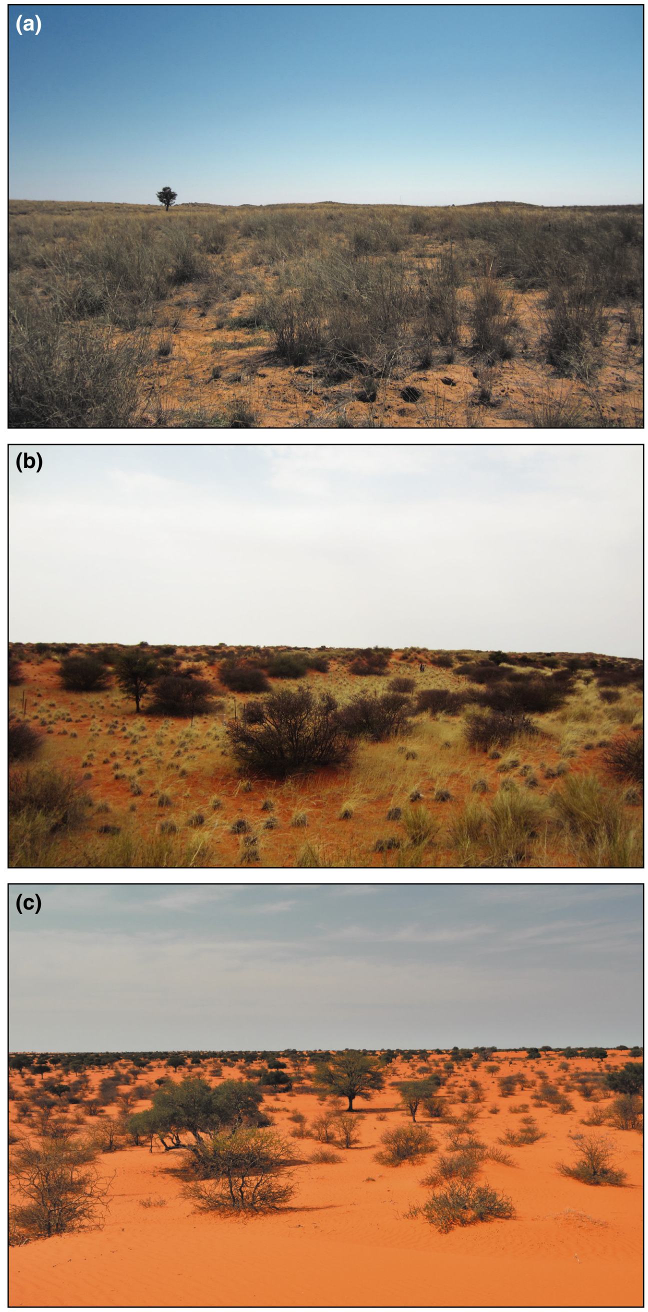

Figure 1. *Land degradation can manifest as a decline in ecosystem services associated with ecological change, such as in the rangelands of the Botswana Kalahari. (a) Overgrazing of grasslands, especially during drought, may lead to (b) wind erosion and shrub invasion. (c) Persistent reduction of grasses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

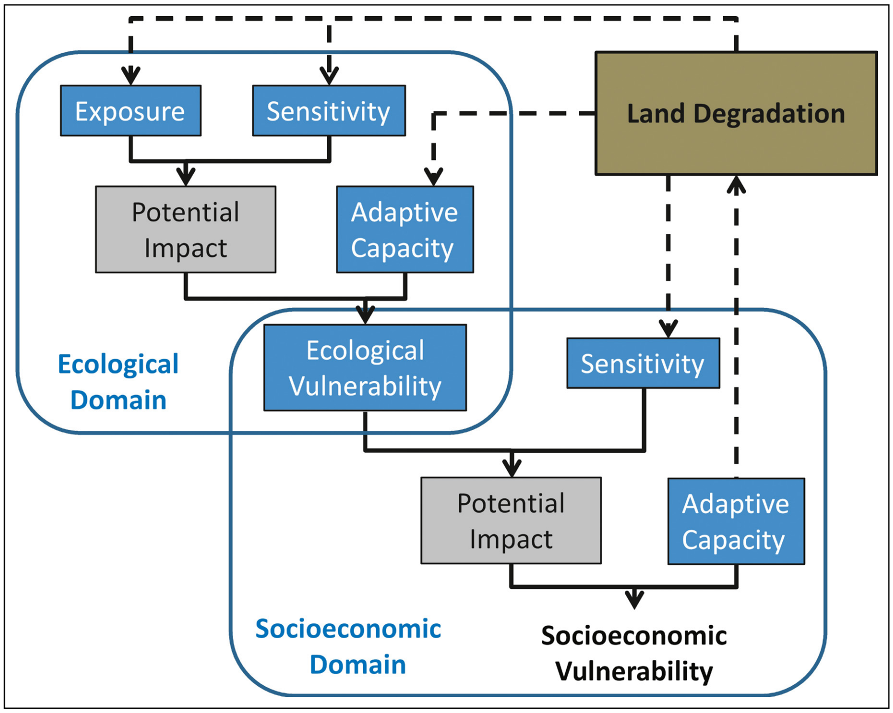

Figure 2. *A framework for conceptualizing the linkages between land degradation and vulnerability of agriculture to climate change across ecological and socioeconomic domains. These domains overlap where agroecological, social, and economic processes interact (eg in determining the vulnerability of ecological systems via the influence of management strategies on land degradation). Solid arrows represent connections between the factors that determine vulnerability, whereas dashed arrows represent potential linkages between vulnerability and land degradation. Adapted from Marshall* et al. *(2014).*

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 agroecological systems as a consequence of land use, or from one or more processes [that] may arise from human activities including: (1) soil erosion by wind and/or water, (2) deterioration of the physical, chemical, and biological or economic properties of soil (eg due to salinization), and (3) long-term loss of natural vegetation" (UNCCD 1994). Land degradation may be exacerbated by land use and land management patterns, and natural phenomena such as drought, heavy rainfall, and fire (MA 2005). These processes may also be influenced by social, economic, and political factors that encourage or impose land-use pressures while failing to balance the supply of ecosystem services with agricultural production demands (D'Odorico *et al.* 2013). Land degradation can therefore manifest in diverse ways across agroecological systems. 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 erosion in croplands (Quinton *et al.* 2010) are all manifestations of land degradation. The impacts may be diffuse across landscapes and regions, or occur as hot spots, and they may exhibit large spatial variability.

Given the connectedness of ecological and social systems, land degradation usually results in a decline in agro-socio-ecosystem resilience, which is defined as 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 processes, leading to a spiral of degradation as soil resources are depleted and vegetation communities change. A loss of adaptive capacity among producers 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 (eg field to landscape), involving different stakeholder groups (eg land users, technical advisors, administrators, and policy makers).

Land degradation may be associated with regime shifts (state changes that occur when a threshold or tipping point is crossed) in agroecological systems, which may require novel management approaches or land-use change. Response strategies may be targeted toward equilibrium (predictable) or non-equilibrium (episodic) ecological change (Bestelmeyer *et al.* 2015). Climate change can exacerbate and accelerate land degradation through various means, including accelerated soil erosion, increased evapotranspiration rates, drought, and changes in biodiversity, pests, and diseases. The legacy of historical land degradation may then further influence the magnitude and direction (positive or negative) of the impacts of climate change on agroecological systems.

Conceptual models describing the resilience of agricultural systems (Kelly *et al.* 2015) have been effective tools for understanding land degradation impacts on agricultural production and the interconnectedness of the impacts with social and economic systems (Rist *et al.* 2014). Models like these suggest that the exposure (degree of climate stress), sensitivity (eg crop responsiveness to climate change), and adaptive capacity of producers determine the vulnerability of agroecological systems to climate change, and each can 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, 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). Improvements in soil health are typically associated with reduced sensitivity to climate change. Soil health is affected by land degradation primarily via erosion, but also by physical, chemical, and biological changes. Changes in vegetation due to land use and management may occur concurrently with declining soil health (Bestelmeyer *et al.* 2015) and may affect forage and crop production responses to climate change. Through these changes, land degradation can limit the increases in plant biomass characteristically associated with elevated atmospheric CO_2 concentrations (CO_2 fertilization) (Reich and Hobbie 2012).

Land degradation also has impacts on the socioeconomic vulnerability of agroecological systems. Changes to the quantity and quality of ecosystem services as a consequence of climate change will affect livelihoods across associated industries (from "farm to fork"). These changes ultimately feed back to affect land management and land degradation. Because of such feedbacks, land degradation further influences adaptation options. For instance, expanding distributions of invasive species (eg cheatgrass, *Bromus tectorum*) throughout rangelands of the western US reduce the management options available to livestock producers to adapt to increasing drought frequency, which reduces forage availability (Briske *et al.* 2015). Accounting for how land degradation affects 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 (eg Walthall *et al.* 2012; Government of Brazil 2016), many still do not address land degradation as an integral part of that planning (eg Australia [Australian Government 2015] and India [Government of India 2008]). For crop and livestock production systems, management 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, which may only have short-term benefits, while long-term and transformational management responses (eg land-use change) are often required (Kates *et al.* 2012). Autonomous adaptation at local scales will continue to be important for maintaining healthy agroecological systems. However, strategies underpinned by forward planning, motivated and empowered land managers, financial resources, and supportive government policies 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 resilient agroecological systems for the future. Multiple responses are required across local, regional, and national scales to build the resilience and reduce the vulnerability of agroecological 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 – 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 (eg Salvati and Carlucci 2014) and develop pathways to achieving LDN (Chasek *et al.* 2015; Stavi and Lal 2015; Akhtar-Schuster *et al.* 2017; Kust *et al.* 2017). In 2016, the Intergovernmental Panel on Climate Change (IPCC) agreed to create a special report on desertification, land degradation, and climate change, which would 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 response 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 international steps are critical, complementary local, regional, and national approaches are required to integrate ways to address land degradation within adaptation planning for agriculture. Here we present four core multi-level actions that can be taken.

Increase understanding of biophysical, biogeochemical, and socioeconomic interactions

Research is essential to establish how the linkages between land degradation and climate change influence impacts and opportunities, producers' adaptive capacity, and potential response strategies. Two outstanding research requirements are (1) accounting for land degradation in systems approaches for evaluating impacts and adaptation options, and (2) 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 in agriculture (eg 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) – including 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 instance, 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 agroecological and socioeconomic impacts of climate change, and scenarios by which agriculture may adapt to climate change. Such improvements are also necessary to evaluate the changing effectiveness of adaptation strategies over time and identify tipping points at which adaptations may become maladaptations and negatively affect agroecological systems (Magnan *et al.* 2016).

An improved understanding of the linkages between land degradation and human adaptive capacity is also required to support adaptation planning for agriculture (Stringer *et al.* 2009). The relationship between land users' capacity to adapt to climate change and patterns of land degradation has not been established for different agroecological systems (eg Barbier 2000). A better understanding of this relationship will facilitate identification of barriers and limits to the adoption of climate-smart agriculture (CSA) and sustainable land management (SLM) 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 policy makers to develop their own knowledge about land degradation can complement scientific knowledge building in support of adaptation planning at all scales.

Identify vulnerabilities

Identifying which agroecological systems are vulnerable to the interactive effects of land degradation and climate change is essential for prioritizing 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 frequent high temperatures, and areas already experiencing land degradation may be most exposed to damaging interactions with climate change (Gisladottir and Stocking 2005). Interactions between land degradation and climate change will also 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 levels of nutrient availability, 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. Land-use approaches and policies that have resulted in land degradation may be responsible for increasing the sensitivity of agroecological systems to climate change (Figure 4) (Stringer *et al.* 2009).Understanding where these interactions might occur will help scientists and managers to identify potential future vulnerabilities, and the biophysical and socioeconomic trade-offs for adaptation options (Webb *et al.* 2013). Socioeconomic vulnerabilities can be as, or more, important than ecological vulnerabilities for climate-change adaptation in agriculture (Abson *et al.* 2012). Using diverse approaches that reveal the socioeconomic factors influencing different agroecological vulnerabilities will therefore be important for identifying successful management and policy responses (Wise *et al.* 2014).

Improve knowledge exchange across scales

Improved knowledge exchange among stakeholders such as scientists and land users, technical advisors, administrators, and policy makers across local to national scales is essential for ensuring that land degradation–climate-change linkages are appropriately recognized

Panel 1. Australian rangeland degradation increases the vulnerability of livestock enterprises to climate change

On Australian rangelands, livestock producers must balance their production goals in a climate with highly variable rainfall while avoiding overgrazing that could result in land degradation. Historical degradation of Australian rangelands substantially affects the current availability of forage, and has implications for the economic viability of livestock 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 effects 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 concentrations (from 350 parts per million [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 under 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, such as 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.

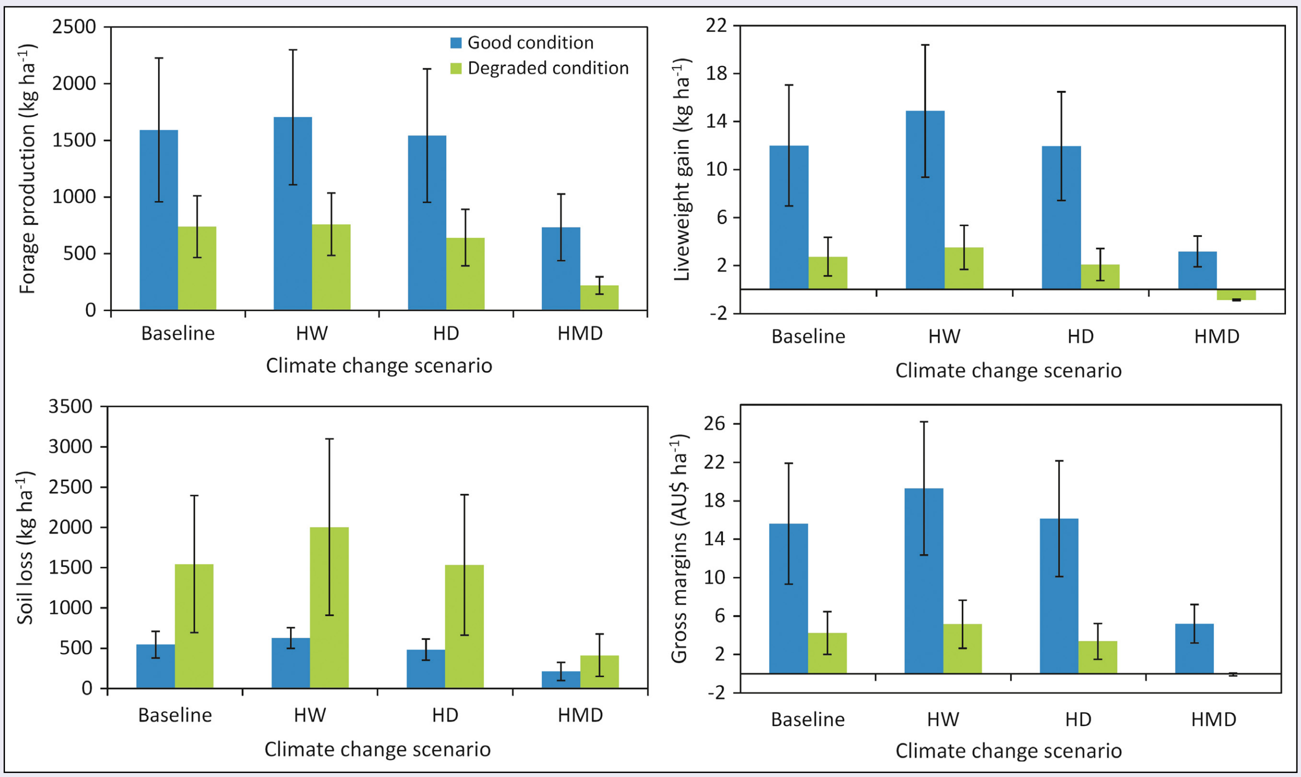

Figure 3. *Climate-change impacts on a livestock (beef) enterprise in northern Australia for degraded and non-degraded lands. Impacts are expressed as the mean and standard deviation (error bars) of three simulated land type responses to hotter and wetter (HW), hotter and drier (HD), and hotter and much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

within management and policy options. Integrating different knowledge systems (eg indigenous, traditional, local, scientific), and co-generating new knowledge, often leads to more robust agricultural policy decisions (Raymond *et al.* 2010; Reed *et al.* 2011). Knowledge exchange can also facilitate responses that are more appropriate to the needs of local communities and can protect their livelihoods and well-being.

Collaborative and evidence-based policy-making initiatives may help to integrate knowledge and facilitate adaptive planning with respect to land degradation and climate change (Akhtar-Schuster *et al.* 2011). At the international level, science–policy interfaces like the IPCC, the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES), and the Science–Policy Interface (SPI) of the

Figure 4. *Management approaches that continue to promote land degradation can make already degraded agroecological systems more vulnerable to climate-change impacts. The impacts may be highly variable across systems: for example, within (a) the Botswana rangelands, (b) salinized croplands of the Central Valley, California, (c) deforested hillslopes of Haiti, and (d) eroded pasturelands in Iceland. Adaptation options may be limited for some land users, requiring greater government involvement and support across local to national scales to be most effective.*

UNCCD, as well as assessments like the Millennium Ecosystem Assessment and the IPBES Land Degradation and Restoration Assessment, can all contribute toward multi-stakeholder learning. Developing approaches for successful knowledge exchange (eg Chasek *et al.* 2011) across institutional boundaries and among stakeholders (eg local land users, researchers, and policy makers) within and outside the UN Conventions will be especially important for adopting practices and policies that address land degradation and climate change together. Promoting participatory research and knowledge sharing at national and local scales through coordinated agricultural extension services will complement analogous efforts at the international level to incorporate land degradation into adaptation planning. These participatory approaches will increasingly be able to use relevant information made available through 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).

Develop innovative, multi-win management and policy options

Management and policy options are needed to actively restore agro-ecosystem resilience while minimizing negative climate impacts. Some land management strategies will remain robust, while others may not be sustainable under changing conditions, in which case new management and policy options will be required (Figure 5) (Reynolds *et al.* 2011). Multi-win options – specifically those that apply innovative SLM solutions to (1) reduce land degradation, (2) support restoration of degraded lands, and (3) balance land degradation, climate-change adaptation, human well-being, and biodiversity outcomes – should be prioritized within the context of existing adaptation

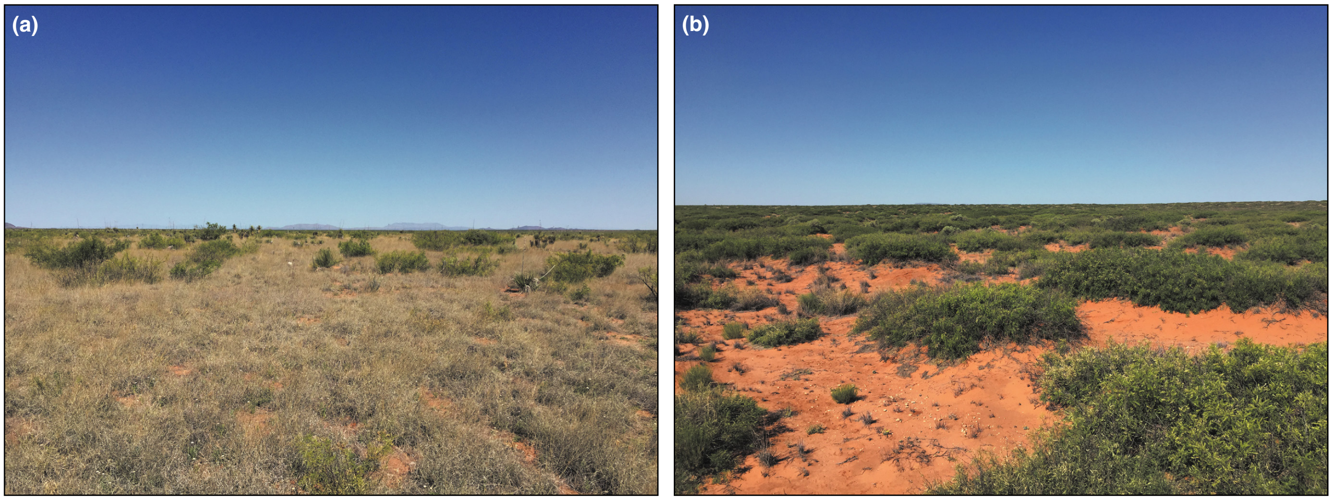

Figure 5. *Over the past century, (a) regime shifts in desert grasslands of the southwestern US have resulted in (b) the expansion of shrublands dominated by mesquite (*Prosopis glandulosa*) and increased wind erosion. The spread of this unpalatable shrub, and the associated loss of perennial grasses (eg black grama,* Bouteloua eriopoda*), has reduced the carrying capacity for beef cattle and increased the vulnerability of livestock 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.*

approaches such as 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 long been recognized (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 agroecological systems.

Land management and policy options for adapting to climate change 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. In doing so, planners should consider the resilience and restoration potential of landscapes and how these may alter as a result of climate change. Approaches should be developed that allow for exchanging knowledge and technologies, and for establishing incentives to adapt and shape management behaviors, and these must reflect the needs of different agroecological systems. Promoting the use of active adaptive management at all scales (eg by land managers, regional climate adaptation planners, industry, and government) can be useful for overcoming barriers to adoption and may prevent managers from reverting back to unsustainable farming practices (Marshall *et al.* 2013). Empowering agricultural land users to assume new identities as "land stewards" (eg by strengthening producers' rights to use farmland) can increase the range of strategies available to policy makers, the sustained adoption of CSA and SLM by land users, and the likelihood that land degradation is effectively addressed to build climate resilience in agriculture.

Conclusions

Addressing land degradation is essential for building sustainable agroecological systems that are climate resilient, conserve biodiversity, and meet global development goals. Future agroecological systems will depend on the present-day development of innovative management and policy options. There are increasing opportunities for coordination among the UNCCD, UNFCCC, and UNCBD – despite their different foci – to enable agroecological systems to become land degradation neutral and resilient to climate change (Akhtar-Schuster *et al.* 2017). However, scientists, managers, and policy makers must not only fill critical gaps in the current understanding of land degradation–climate-change interactions, but must also strengthen collaborations to address adaptation-related challenges at local to global scales. Here, we have presented four multi-level actions that can help to integrate land degradation countermeasures into climate-change adaptation planning.

We argue that research must critically assess 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 key to effectively evaluating interactions between land degradation and climate change, and to identifying adaptation strategies in both developed and developing countries. Agroecological systems that are most vulnerable to the combined effects of land degradation and climate change must receive priority attention. Lessons learned about successful adaptation in regions with resilient agroecological systems should be applied to support regions with low adaptive capacity (Salvati and Carlucci 2014); at the same time, greater exchange of knowledge between various stakeholders will help to promote strategies to achieve LDN within a changing climate. Responses that provide multi-win outcomes for land degradation, climate change, and biodiversity offer the greatest potential benefits for agroecological systems and global food security.

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References

Abson DJ, Dougill AJ, and Stringer LC. 2012. Using Principal Components Analysis for information-rich socio-ecological vulnerability mapping in Southern Africa. *Appl Geogr* **35**: 515–24.

Akhtar-Schuster M, Stringer LC, Erlewein E, *et al.* 2017. Unpacking the concept of Land Degradation Neutrality and addressing its operation through the Rio Conventions. *J Environ Manage* **195**: 4–15.

Akhtar-Schuster M, Thomas RJ, Stringer LC, *et al.* 2011. Improving the enabling environment to combat land degradation: institutional, financial, legal and science–policy challenges and solutions. *Land Degrad Dev* **22**: 299–312.

Anderson DM, Estell RE, Gonzalez A, *et al.* 2015. Criollo cattle: heritage genetics for arid landscapes. *Rangelands* **37**: 62–67.

Australian Government. 2015. Commonwealth of Australia, National Climate Resilience and Adaptation Strategy. Canberra, Australia: Department of the Environment.

Barbier EB. 2000. The economic linkages between rural poverty and land degradation: some evidence from Africa. *Agr Ecosyst Environ* **82**: 355–70.

Best MJ, Abramowitz G, Johnson HR, *et al.* 2015. The plumbing of Land Surface Models: benchmarking model performance. *J Hydrometeorol* **16**: 1425–42.

Bestelmeyer BT, Okin GS, Duniway MC, *et al.* 2015. Desertification, land use, and the transformation of global drylands. *Front Ecol Environ* **13**: 28–36.

Briske DD, Joyce LA, Polley HW, *et al.* 2015. Climate-change adaptation on rangelands: linking regional exposure with diverse adaptive capacity. *Front Ecol Environ* **13**: 249–56.

Chappell A, Baldock J, and Sanderman J. 2015. The global significance of omitting soil erosion from soil organic carbon cycling schemes. *Nature Climate Change* **6**: 187–91.

Chasek P, Essahli W, Akhtar-Schuster M, *et al.* 2011. Integrated land degradation monitoring and assessment: horizontal knowledge management at the national and international levels. *Land Degrad Dev* **22**: 272–84.

Chasek P, Safriel U, Shikongo S, *et al.* 2015. Operationalizing Zero Net Land Degradation: the next stage in international efforts to combat desertification? *J Arid Environ* **112**: 5–13.

CSIRO and BOM (Commonwealth Scientific and Industrial Research Organisation and the Australian Bureau of Meteorology). 2015. Climate change in Australia: projections for Australia's NRM regions. Technical report. http://bit.ly/2tubd3H. Viewed 20 Jul 2017.

Diamond JM. 2005. Collapse: how societies choose to fail or succeed. New York, NY: Viking Press.

D'Odorico P, Bhattachan A, Davis KF, *et al.* 2013. Global desertification: drivers and feedbacks. *Adv Water Resour* **51**: 326–44.

Dougill AJ, Fraser EDG, and Reed MS. 2010. Anticipating vulnerability to climate change in dryland pastoral systems: using dynamic systems models for the Kalahari. *Ecol Soc* **15**: 17.

Dougill AJ, Thomas DSG, and Heathwaite AL. 1999. Environmental change in the Kalahari: integrated land degradation studies for nonequilibrium dryland environments. *Ann Assoc Am Geogr* **89**: 420–42.

Drenge HE and Chou NT. 1994. Global desertification dimensions and costs. In: Drenge HE (Ed). Degradation and restoration of arid lands. Lubbock, TX: Texas Technical University.

ELD Initiative (Economics of Land Degradation Initiative). 2015. The value of land: prosperous lands and positive rewards through sustainable land management. http://bit.ly/2gQrF87. Viewed 20 Jul 2017.

Gisladottir G and Stocking M. 2005. Land degradation control and its global environmental benefits. *Land Degrad Dev* **16**: 99–112.

Government of Brazil. 2016. National Adaptation Plan to Climate Change, Strategy for Agriculture. http://bit.ly/2vsMBFt. Viewed 20 Jul 2017.

Government of India. 2008. India's National Action Plan on Climate Change. www.moef.nic.in/sites/default/files/Pg01-52_2.pdf.

Herrick JE, Beh A, Barrios E, *et al.* 2016. The Land-Potential Knowledge System (LandPKS): mobile apps and collaboration for optimizing climate change investments. *Ecosyst Health Sustain* **2**: e01209.

Herrick JE, Sala OE, and Karl JW. 2013. Land degradation and climate change: a sin of omission? *Front Ecol Environ* **11**: 283.

Howden SM, Soussana J-F, Tubiello FN, *et al.* 2007. Adapting agriculture to climate change. *P Natl Acad Sci USA* **104**: 19691–96.

Huang J, Yu H, Guan X, *et al.* 2015. Accelerated dryland expansion under climate change. *Nat Clim Change* **6**: 166–71.

IPCC (Intergovernmental Panel on Climate Change). 2014. Summary for policymakers. In: Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC.

Karamesouti M, Detsis V, Kounalaki A, *et al.* 2015. Land-use and land degradation processes affecting soil resources: evidence from a traditional Mediterranean cropland (Greece). *Catena* **132**: 45–55.

Kates RW, Travis WR, and Wilbanks TJ. 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. *P Natl Acad Sci USA* **109**: 7156–61.

Kelly C, Ferrara A, Wilson GA, *et al.* 2015. Community resilience and land degradation in forest and shrubland socio-ecological systems: evidence from Gorgoglione, Basilicata, Italy. *Land Use Policy* **46**: 11–20.

Kust G, Andreeva O, and Cowie A. 2017. Land Degradation Neutrality: concept development, practical applications and assessment. *J Environ Manage* **195**: 16–24.

Lepers E, Lambin EF, Janetos AC, *et al.* 2005. A synthesis of information on rapid land-cover change for the period 1981–2000. *BioScience* **55**: 115–24.

Lipper L, Thornton P, Campbell BM, *et al.* 2014. Climate-smart agriculture for food security. *Nature Climate Change* **4**: 1068–72.

MA (Millennium Ecosystem Assessment). 2005. Ecosystems and human well-being: desertification synthesis. Washington, DC: World Resources Institute.

Magnan AK, Schipper ELF, Burkett M, *et al.* 2016. Addressing the risk of maladaptation to climate change. *WIREs Clim Change* **7**: 646–65.

Marshall NA, Park S, Howden SM, *et al.* 2013. Climate change awareness is associated with enhanced adaptive capacity. *Agr Syst* **117**: 30–34.

Marshall NA, Stokes CJ, Webb NP, *et al.* 2014. Social vulnerability to climate change in primary producers: a typology approach. *Agr Ecosyst Environ* **186**: 86–93.

Miettinen J, Stibig H-J, and Achard F. 2014. Remote sensing of forest degradation in Southeast Asia – aiming for a regional view through 5–30 m satellite data. *Global Ecol Conserv* **2**: 24–36.

Oldeman LR. 1994. The global extent of soil degradation. In: Greenland DJ and Szabolcs I (Eds). Land resilience and sustainable land use. Wallingford, UK: CABI.

Pingali PL. 2012. Green revolution: impacts, limits, and the path ahead. *P Natl Acad Sci USA* **109**: 12302–08.

Qadir M, Quillérou E, Nangia V, *et al.* 2014. Economics of salt-induced land degradation and restoration. *Nat Resour Forum* **38**: 282–95.

Quinton JN, Govers G, Van Oost K, and Bardgett RD. 2010. The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geosci* **3**: 311–14.

Raymond CM, Fazey I, Reed MS, *et al.* 2010. Integrating local and scientific knowledge for environmental management. *J Environ Manage* **91**: 1766–77.

Reed MS and Stringer LC. 2016. Land degradation, desertification and climate change: anticipating, assessing and adapting to future change. New York, NY: Routledge.

Reed MS, Buenemann M, Atlhopheng J, *et al.* 2011. Cross-scale monitoring and assessment of land degradation and sustainable land management: a methodological framework for knowledge management. *Land Degrad Dev* **22**: 261–71.

Reich PB and Hobbie SE. 2012. Decade-long soil nitrogen constraint on the CO_2 fertilization of plant biomass. *Nat Clim Change* **3**: 278–82.

Reynolds JF, Grainger A, Stafford Smith DM, *et al.* 2011. Scientific concepts for an integrated analysis of desertification. *Land Degrad Dev* **22**: 166–83.

Rist L, Felton A, Nyström M, *et al.* 2014. Applying resilience thinking to production systems. *Ecosphere* **5**: 73.

Rosenzweig C, Jones JW, Hatfield JL, *et al.* 2013. The Agricultural Model Intercomparison and Improvement Project (AgMIP): protocols and pilot studies. *Agr Forest Meteorol* **170**: 166–82.

Salvati L and Carlucci M. 2014. Zero Net Land Degradation in Italy: the role of socioeconomic and agro-forest factors. *J Environ Manage* **145**: 299–306.

Seybold CA, Herrick JE, and Brejda JJ. 1999. Soil resilience: a fundamental component of soil quality. *Soil Sci* **164**: 224–34.

Stavi I and Lal R. 2015. Achieving Zero Net Land Degradation: challenges and opportunities. *J Arid Environ* **112**: 44–51.

Stringer LC, Dyer JC, Reed MS, *et al.* 2009. Adaptations to climate change, drought and desertification: local insights to enhance policy in southern Africa. *Environ Sci Policy* **12**: 748–65.

Thomas RJ. 2008. 10th anniversary review: addressing land degradation and climate change in dryland agroecosystems through sustainable land management. *J Environ Monitor* **10**: 595–603.

Turner GM, Dunlop M, and Candy S. 2016. The impacts of expansion and degradation on Australian cropping yields – an integrated historical perspective. *Agr Syst* **143**: 22–37.

UNCCD (United Nations Convention to Combat Desertification). 1994. United Nations Convention to Combat Desertification in those countries experiencing serious drought and/or desertification particularly in Africa: text with annexes. Nairobi, Kenya: UNEP.

UNCCD (United Nations Convention to Combat Desertification). 2015. Land Degradation Neutrality: resilience at local, national and regional levels. http://bit.ly/2vJ0ZJm. Viewed 25 Oct 2016.

UNEP-IRP (United Nations Environment Programme–International Resource Panel). 2016. Unlocking the sustainable potential of land resources: evaluation systems, strategies and tools. A report of the Working Group on Land and Soils of the International Resource Panel. http://bit.ly/2txdJ9i. Viewed 20 Jul 2017.

United Nations. 2015. United Nations General Assembly, Seventeenth Session. Transforming our World: the 2030 Agenda for Sustainable Development. http://bit.ly/1OTd4Sr. Viewed 25 Oct 2016.

van Grinkel M, Sayer J, Sinclair F, *et al.* 2013. An integrated agro-ecosystem and livelihood systems approach for the poor and vulnerable in dry areas. *Food Secur* **5**: 751–67.

Walthall CL, Hatfield J, Backlund P, *et al.* 2012. Climate change and agriculture in the United States: effects and adaptation. USDA Technical Bulletin 1935. Washington, DC: USDA.

Webb NP, Stokes CJ, and Marshall NA. 2013. Integrating biophysical and socio-economic evaluations to improve the efficacy of adaptation assessments for agriculture. *Global Environ Change* **23**: 1164–77.

Wise RM, Fazey I, Stafford Smith DM, *et al.* 2014. Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environ Change* **28**: 325–36.

