Chapter 1
Land Degradation in Drylands: An Ecogeomorphological Approach

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Abstract Land degradation is particularly pernicious and pervasive in dryland regions. The dependency of local livelihoods on the services provided by ecosystems is greater in drylands than in any other ecosystems, rendering their inhabitants exceptionally vulnerable to land degradation. Current approaches to managing drylands to mitigate land degradation often fail to produce significant improvements because local knowledge is often undervalued and the complexity of underlying processes leading to land degradation is still not well understood. There remains a need to uncover the underlying dynamics and characteristic responses to environmental drivers and human-induced disturbances. The physical processes associated with land degradation in drylands fall at the interface of ecology and geomorphology. Regrettably, the disciplines of ecology and geomorphology have largely performed research in isolation of each other. The disciplines, in common with most, have a centrifugal perspective, looking outwards from themselves towards cognate disciplines. To address multidisciplinary scientific questions – such as land degradation in drylands – a centripetal approach is required in which the problem is the focus towards which the disciplines direct their attention. The purpose of this

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book is to take such a centripetal approach towards the understanding of the process linkages between ecogeomorphological dryland processes and patterns to better our understanding of land degradation, and to overcome the lack of interdisciplinarity in current dryland research.

1.1 Land Degradation in Drylands

The United Nations Convention to Combat Desertification (UNCCD) defines land degradation as “a persistent reduction in biological and economic productivity” (UNCCD 1994). Land degradation is a global-scale, ongoing, and relentless problem that poses a major long-term challenge to humans in terms of its adverse impact on biomass productivity, food security, biodiversity and environmental sustainability. Land degradation is particularly pernicious and pervasive in dryland regions, which cover more than 41 % of the Earth’s terrestrial surface (Millennium Ecosystem Assessment 2005). Drylands, which are sub-divided into arid, hyper-arid, semi-arid and dry sub-humid areas (Fig. 1.1) are characterized by extremely low primary productivity, nutrient-poor soils and sparse and patchy vegetation, yet have particularly high population-growth rates (MEA 2005), and are now home to over two billion people.

Land degradation in drylands is a multi-faceted problem. Recent efforts to understand land degradation have focused on the biophysical and socio-economic drivers of land degradation, human vulnerability to land degradation in terms of social, economic and political exposure to potentially harmful perturbations, poverty alleviation, and community-driven development to enhance the role of communities the sustainable management of drylands (Reynolds et al. 2007). For the most part,

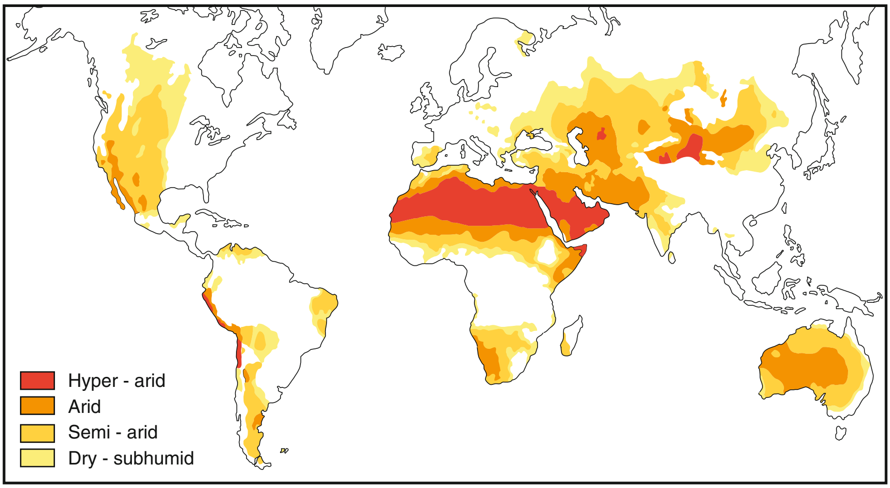

Fig. 1.1 World distribution of drylands (Adapted from Parsons and Abrahams 2009)

people living in drylands lag behind others in terms of human well being and development indicators, and more people in drylands than in any other ecosystem depend on ecosystem services for their basic needs (MEA 2005). Significant ecosystem services, such as agriculture and livestock farming, are dependent upon primary productivity. A reduction in primary production in drylands which is one of the primary characteristics of degradation, reduces the capacity of these systems to provide essential ecosystem services, and ultimately affects the resilience of these systems to future environmental pressures, thus increasing the vulnerability of people living in drylands. *In extremis*, land degradation in drylands can lead to desertification and the effective productive loss of entire landscapes. Estimates of the extent of dryland degradation vary greatly. Lepers (2003) puts it as low as 10 % of the total global dryland extent, whereas Middleton and Thomas (1997) and Dregne and Chou (1992) estimated it in the 1990s at between 20 and 70 %, respectively. At present, there are multiple initiatives seeking to understand different components of land degradation including the Land Degradation Assessment in Drylands project (LADA 2011) and the United Nations Convention to Combat Desertification (UNCCD 1994).

Diverse views are held on the complex relationship between climatic and anthropic drivers of land degradation and how these drivers affect land-degradation processes. Despite this diversity, a relatively broad consensus is presented by the MEA (2005) (Fig. 1.2). Important land-degradation processes in which include soil erosion by wind and water, depletion of soil fertility, soil salinization and changes in soil structure. Changes in soil structure can lead to crusting and compaction, enhancing desertification and anaerobism. Significant chemical processes associated with land degradation include acidification, leaching, salinization and nutrient depletion. Biological processes include alterations in the amount or diversity of natural vegetation or plant cover resulting in a decrease of biodiversity. The net effect of these physical, chemical and biological processes is an increase in the vulnerability of these systems to environmental perturbations, and a reduction in the ecosystem services that these systems can provide.

Land degradation in drylands is a problem that extends beyond the geographical boundaries of drylands. Because of the interconnectedness of many of Earth's processes (illustrated in Fig. 1.2), changes in processes operating in drylands regarding vegetation and soil structure can affect processes at broader spatial scales. For example, dust storms which occur commonly in degraded regions, have negative health implications, and cause broader-scale climate and hydrological feedbacks (Painter et al. 2010). Likewise, soil erosion in drylands mobilizes stored carbon and reduces carbon-sequestration capacity (Lal 2001), thus potentially affecting the global-scale climatic feedbacks (IPCC 2001; Meehl et al. 2007).

Land degradation is driven by a set of interlocking, socio-economic drivers, including industrial and transgenic farming, a globalized economy and capital, speculation in commodities, migration, pollution, falling environmental standards and the capture of arable land for fuel production. Population increase to around nine billion by 2050 (UN 2008) is likely to cause an increase in the extent and intensity of land degradation over the coming decades, as the magnitude and extent of these

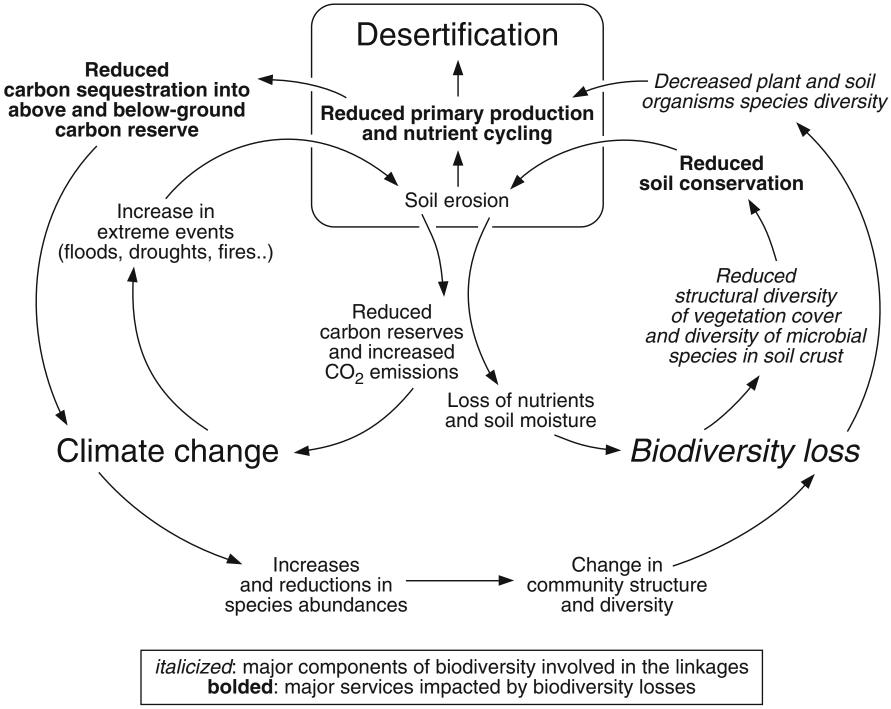

Fig. 1.2 The major components of land degradation that affect the prevision of essential ecosystem services and may ultimately lead to desertification. The *inner loops* connect biodiversity loss and climate change through soil erosion, while the *outer loop* interrelates biodiversity loss and climate change (Modified from Millennium Ecosystem Assessment 2005 and reproduced by permission of World Resources Institute)

drivers increases. For example, the transformation of rangelands to croplands will continue. Depending on the type of cultivation and irrigation methods practised on agricultural land, increases in the severity and extent of soil salinization and erosion will occur. Increases in livestock densities on rangeland will reduce vegetation cover further, exposing the soil to more erosion. Sustainable land management in drylands will play a key role in minimizing land degradation. However, current approaches to manage drylands to mitigate land degradation often fail to produce significant improvements because local knowledge is often undervalued and not included in land-management approaches, and furthermore, the complexity of underlying processes leading to land degradation is still not well understood.

Historically, empirical studies that have dominated the investigation of land degradation have focussed on physical, biological and chemical factors, at a limited range of spatial and temporal scales. The advent of remote sensing and modelling approaches over recent decades has allowed for empirical studies across multiple spatial and temporal scales, allowing greater insights into system behaviour. More recently, modelling-based studies have also played a valuable role in investigating different components of land degradation. The progression of discipline-specific empirical and modelling-based analyses by both ecologists and geomorphologists has inevitably led to specialized approaches and research agenda through which the vital interactions and feedback dynamics between the biotic and abiotic components of the dryland system cannot be explored. While there have been several attempts to overcome disciplinary boundaries in dryland research in the last decades (primary examples include the work by Thornes 1990; Schlesinger et al. 1990; Ludwig et al. 2005; Wainwright et al. 2002; and D'Odorico and Porporato 2006), research efforts considering linkages between social dimensions of land degradation, ecological, hydrological and geomorphological processes, and the structure and function of the system remains limited, and is at best, a compilation of case studies. The ongoing failure to incorporate these biophysical interactions in environmental studies limits our ability to predict the response of drylands to climate change and human-induced disturbances (Reinhardt et al. 2010) and to make sustainable land-management decisions accordingly.

1.2 Nonlinear Dynamics, Self-organization and Connectivity

In disciplines concerned with land degradation, there has been much discussion about *driving processes* and *emerging patterns*. Patterns and processes are mutually causal, but there are still many unknowns as to how these processes and patterns are connected. For a better understanding of dryland systems and land degradation, there is a need to uncover the underlying dynamics and characteristic responses to environmental drivers and human-induced disturbances.

Changes in system state arising from land degradation have been widely demonstrated to exhibit nonlinear, threshold dynamics (e.g. Laycock 1991). Because of hysteresis – a characteristic often associated with such dynamics – a system that has transitioned to a degraded stable state may not return to its former state following the removal of the driving forces of degradation. Another underlying property of drylands is self-organization (Barbier et al. 2006; Deblauwe et al. 2011), which is when larger-scale properties such as vegetation patterning emerge as a response to local-scale interactions.

Previously, there has been a focus on identifying thresholds at which sudden changes in system state occur, under the premise that if it is known when a threshold will be reached, it can be avoided. However, given the underlying complexity of dryland systems in terms of their self-organizing characteristics and system feedbacks, approaches that simply identify environmental thresholds in different types of systems are limited in their capacity to aid our understanding of land degradation. In light of this complexity, it has been recognized that to understand land degradation in drylands, attention needs to be paid to the dynamics of system state change in terms of changes in processes, self-organizing characteristics and biotic-abiotic feedbacks rather than focussing on trying to identify thresholds (Turnbull et al. 2008). It has been hypothesized that land degradation can be represented by a cusp-catastrophe model (ibid., see also Chap. 3), whereby changes in ecosystem states or dynamic régimes can be reinforced by positive stabilizing feedbacks between plants and their environment that ultimately creates high ecosystem resilience.

One key aspect of understanding changes in processes, self-organizing characteristics and biotic-abiotic feedbacks in drylands, is the extent to which system components are connected, both structurally and functionally. This concept of "connectivity" has already been the subject of considerable research (Taylor et al. 1993; Bracken and Croke 2007; Turnbull et al. 2008; Okin et al. 2009; Wainwright et al. 2011). This body of research indicates that both patterns and processes in drylands are controlled by the interaction of advective and diffusive flows of resources such as soil, water, nitrogen and propagules. Spatial heterogeneities in soil and vegetation properties are the result of these fluxes that, in turn, promote the emergence of connected pathways that modify further the advective and diffusive fluxes. The connectivity of these patterns and processes leading to system feedbacks are especially pronounced in drylands due to the high rates of processes in the abiotic régime (Turnbull et al. 2012).

There is a variety of approaches available to study the nonlinear nature of land degradation in drylands. However, all of the concepts introduced above are normally applied by separated disciplines to analyse only one (biotic or abiotic) constituent of a dryland system. That is identified here as the key problem of past and current dryland research: a lack of an integrated analysis of ecogeomorphic systems.

1.3 Ecogeomorphology in Drylands: The Purpose and Content of the Book

Processes and patterns associated with land degradation in drylands fall at the interface of ecology and geomorphology. Over recent years there has been increasing recognition of ecogeomorphology – a term we use to refer to the coupled ecological-geomorphological system in which feedbacks between biotic and abiotic components occur (Wainwright 2009; Wainwright and Parsons 2010).

Vegetation in drylands is characteristically patchy and is sometimes patterned. The multi-scale, dynamic distribution of vegetation in drylands is an emergent property that depends on complex, poorly understood nonlinear relationships and feedback dynamics between plants, soils and transport processes and human impacts. Regrettably, the disciplines of ecology and geomorphology have largely performed research in isolation of each other, "selectively picking and choosing snippets of information and theory from the other discipline when needed" (Renschler et al. 2007, p. 4). The disciplines are not alone in this behaviour. Figure 1.3 characterizes separate disciplines as having a centrifugal perspective, looking outwards from themselves towards their individual aspects. To address multidisciplinary scientific questions – such as land degradation in drylands – a centripetal approach is required in which the problem is the focus towards which the disciplines direct their attention (cf. Fig. 15.1).

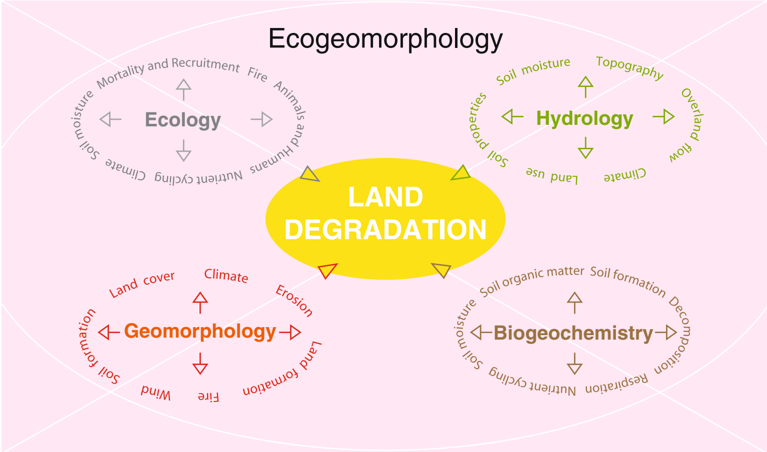

Fig. 1.3 Centrifugal approach of individual disciplines and centripetal approach of ecogeomorphic, multi-disciplinary land-degradation research

The purpose of this book is to take such a centripetal approach towards the understanding of the process linkages between ecogeomorphological dryland processes and patterns to better our understanding of land degradation, and to overcome the lack of interdisciplinarity in current dryland research. To gain a truly interdisciplinary perspective all chapters are multi-authored, drawing together the expertise of ecologists, hydrologists, geomorphologists, mathematicians, biologists, agronomists and remote sensing experts.

The first section of this book, entitled "Theory: linking process to pattern" deals with the establishment of an integrated view of current concepts of pattern formation and self-organization, abiotic and biotic interactions over a continuum of spatial and temporal scales, and process integration from both ecological and geomorphological perspectives. In the second section of this book, entitled "Methods for confronting models with data", we bring together hitherto divergent methodological approaches to provide a fully dynamic view of the dryland system. We explore innovative ways of modelling ecogeomorphic feedback mechanisms and patterns, and uncertainty assessments are discussed. In the third section, we present four case studies from Europe, Africa, Australia and North America that present the state of the art on understanding ecogeomorphology in different dryland settings. The concluding chapter sets forth a new ecogeomorphological research agenda for land-degradation studies in drylands, which necessitates the further penetration of empirical and disciplinary boundaries and requires the focussing of research efforts between ecologists and geomorphologists and development of common research goals and research approaches.

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References

Barbier N, Couteron P, Lejoly J, Deblauwe V, Lejeune O (2006) Self-organised vegetation patterning as fingerprint of climate and human impact on semiarid ecosystems. J Ecol 94: 537–547

Bracken LJ, Croke J (2007) The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. Hydrol Process 21:1749–1763. doi:10D1002/hyp.6313

D'Odorico P, Porporato A (2006) Ecohydrology of arid and semiarid ecosystems: an introduction. In: D'Odorico P, Porporato A (eds) Dryland ecohydrology. Springer, Berlin, pp 1–10

Deblauwe V, Couteron P, Lejeune O, Bogaert J, Barbier N (2011) Environmental modulation of self-organized periodic vegetation patterns in Sudan. Ecography 34:990–1001

Dregne HE, Chou N (1992) Global desertification and costs. In: Dregne HE (ed) Degradation and restoration of arid lands. Texas Tech University, Lubbock, pp 249–282

IPCC (Intergovernmental Panel on Climate Change) (2001) Climate change 2001: Working Group I: the scientific basis, summary for policymakers. Cambridge University Press, Cambridge

LADA Land Degradation Assessment in Drylands project (2011) FAO Food and Agriculture Organisation of the United Nations. http://www.fao.org/nr/lada/. Accessed 8 Aug 2012

Lal R (2001) Potential of desertification control to sequester carbon and mitigate the greenhouse effect. Clim Chang 51:35–72

Laycock WA (1991) Stable states and thresholds of range condition on North American rangelands: a viewpoint. J Range Manage 44:427–433

Lepers E (2003) Synthesis of the main areas of land-cover and land-use change. Millennium Ecosystem Assessment, Final Report. http://www.geo.ucl.ac.be/LUCC/lucc.html. Accessed 8 Aug 2012

Ludwig JA, Wilcox BP, Breshears DD, Tongway DJ, Imeson AC (2005) Vegetation patches and runoff-erosion as interacting ecohdydrological processes in semiarid landscapes. Ecology 86:288–297

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao ZC (2007) Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on climate change. Cambridge University Press, Cambridge

Middleton N, Thomas D (1997) World atlas of desertification. Arnold, London

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

Okin GS, Parsons AJ, Wainwright J, Herrick JE, Bestelmeyer BT, Peters DC, Fredrickson EL (2009) Do changes in connectivity explain desertification? Bioscience 59:237–244

Painter TH, Deems JS, Belnap J, Hamlet AF, Landry CC, Udall B (2010) Response of Colorado River runoff to dust radiative forcing in snow. Proc Natl Acad Sci U S A 107:17125–17130

Parsons AJ, Abrahams AD (eds) (2009) Geomorphology of desert environments, 2nd edn. Springer, Dordrecht

Reinhardt L, Jerolmack D, Cardinale BJ, Vanacker V, Wright J (2010) Dynamic interactions of life and its landscape: feedbacks at the interface of geomorphology and ecology. Earth Surf Process Landf 35:78–101

Renschler C, Doyle MW, Thoms M (2007) Geomorphology and ecosystems: challenges and keys for success in bridging disciplines. Geomorphology 89:1–8

Reynolds JF, Stafford Smith DM, Lambin EF, Turner BL, Mortimore M, Batterbury SPJ, Thomas E, Downing TE, Dowlatabadi H, Fernández RJ, Herrick JE, Huber-Sannwald E, Jiang H, Leemans R, Lynam T, Maestre FT, Ayarza M, Walker B (2007) Global desertification: building a science for dryland development. Science 316:847–851. doi:10.1126/science.1131634

Schlesinger WH, Reynolds JF, Cunningham GL, Huenneke LF, Jarrell WM, Virginia RA, Whitford WG (1990) Biological feedbacks in global desertification. Science 247:1043–1048

Taylor PD, Fahrig L, Henein K, Merriam G (1993) Connectivity is a vital element of landscape structure. Oikos 68:571–573

Thornes JB (ed) (1990) Vegetation and erosion: processes and environments. Wiley, Chichester

Turnbull L, Wainwright J, Brazier RE (2008) A conceptual framework for understanding semi-arid land degradation: ecohydrological interactions across multiple-space and time scales. Ecohydrology 1(1):23–34

Turnbull L, Wilcox BP, Belnap J, Ravi S, D'Odorico P, Childers D, Gwenzi W, Okin G, Wainwright J, Caylor KK, Sankey T (2012) Understanding the role of ecohydrological feedbacks in ecosystem state change in drylands. Ecohydrology 5:174–183

UNCCD (1994) United Nations Convention to Combat Desertification (UNCCD). United Nations, New York

United Nations (2008) World population prospects. The 2008 revision. United Nations, New York

Wainwright J (2009) Desert ecogeomorphology. In: Parsons AJ, Abrahams AD (eds) Geomorphology of desert environments, 2nd ed. Springer, Dordrecht, pp 21–66

Wainwright J, Parsons AJ (2010) Classics in physical geography revisited. Thornes, J.B. 1985: The ecology of erosion. Geography 70:222–235. Prog Phys Geogr 34(3):399–408

Wainwright J, Parsons AJ, Schlesinger WH, Abrahams AD (2002) Hydrology-vegetation interactions in areas of discontinuous flow on a semi-arid bajada, Southern New Mexico. J Arid Environ 51:319–338

Wainwright J, Turnbull L, Ibrahim TG, Lexartza-Artza I, Thornton SF, Brazier RE (2011) Linking environmental regimes, space and time: interpretations of structural and functional connectivity. Geomorphology 126(3–4):387–404