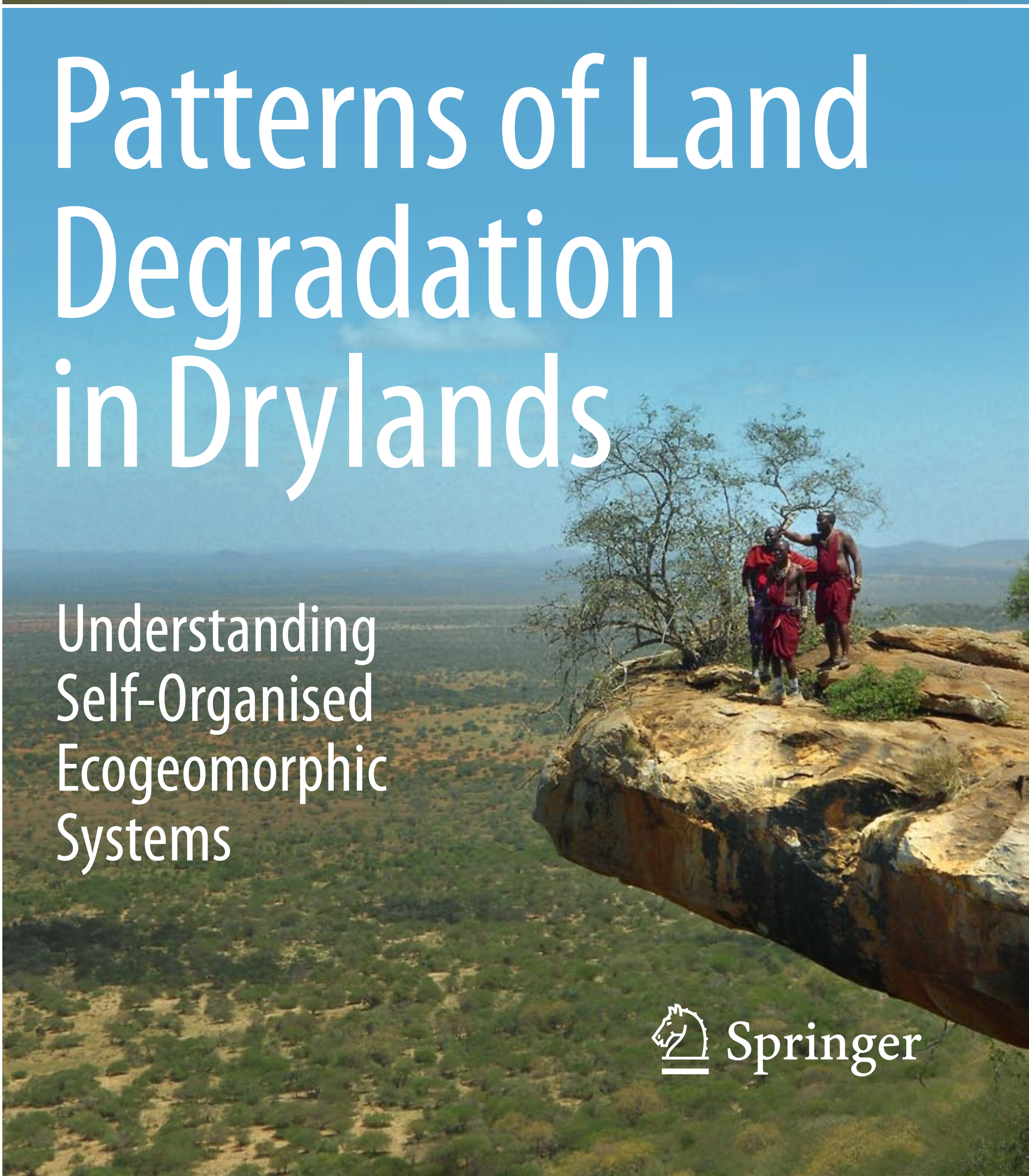
Eva Nora Mueller · John Wainwright
Anthony J. Parsons · Laura Turnbull
Editors

Patterns of Land Degradation in Drylands

Understanding Self-Organised Ecogeomorphic Systems



Springer

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Preface

This book was initiated through an interdisciplinary ESF Exploratory Workshop – 'Self-organized ecogeomorphic systems: confronting models with data for land degradation in drylands' – which was held in Potsdam, Germany, on 7–10 June 2010. The workshop brought together for the first time European scientists working in drylands from multiple communities covering the fields of ecology and landscape ecology, geomorphology, hydrology, agronomy, Earth observation and mathematics to discuss their definitions of land degradation, empirical approaches, questions of corresponding spatial and temporal scales, the importance of self-organization and the application of existing modelling approaches.

During the meeting it became clear that there was a fundamental lack of common ground regarding concepts and methodological approaches between the disciplines. To address this deficiency in understanding land degradation and to provide a basis for future interdisciplinary research on ecogeomorphic systems, we harnessed the expertise of this interdisciplinary group to create this keystone manual.

Individual chapters are multi-authored, integrating research and perspectives from the workshop's participants and several invited experts. As opposed to the usual approach to producing an edited book, we took an editorial decision to select themes that emerged from the workshop and subsequent discussions and invite authors to make short contributions on those themes. We then individually and together integrated the materials produced in order to ensure the consistency and coherence of the chapters. The ordering of the authors names is according to the size of their contribution to the chapters. We would like to thank all the contributors for their full co-operation on the less than usual approach in pulling together this volume in the format we decided on.

The editors would like to thank the European Science Foundation funding scheme for fully supporting the exploratory workshop (Grant reference number EW09-011).

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Chapter 1
Land Degradation in Drylands: An Ecogeomorphological Approach

Eva Nora Mueller, John Wainwright, Anthony J. Parsons, and Laura Turnbull

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,

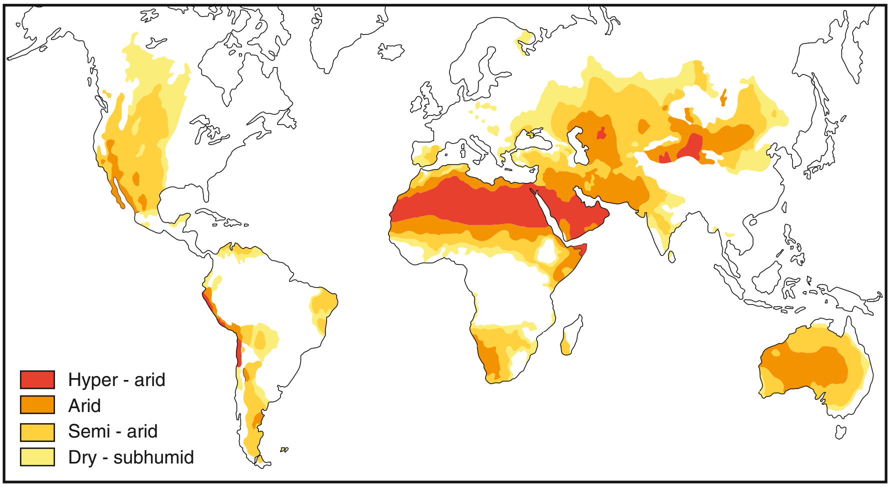

Fig. 1.1 World distribution of drylands (Adapted from Parsons and Abrahams 2009)

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

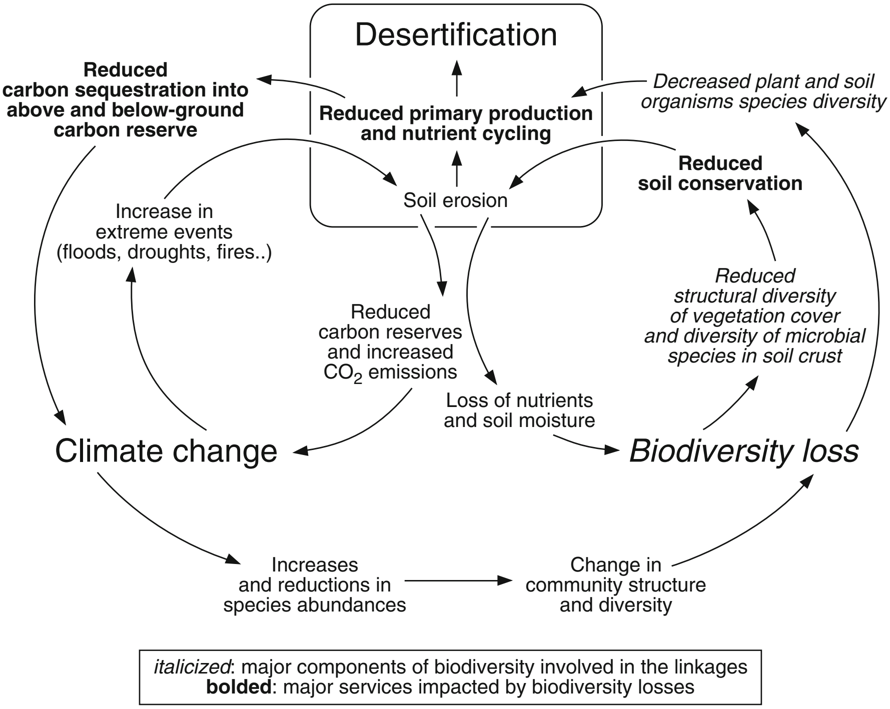

Fig. 1.2 The major components of land degradation that affect the prevision of essential ecosystem services and may ultimately lead to desertification. The *inner loops* connect biodiversity loss and climate change through soil erosion, while the *outer loop* interrelates biodiversity loss and climate 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).

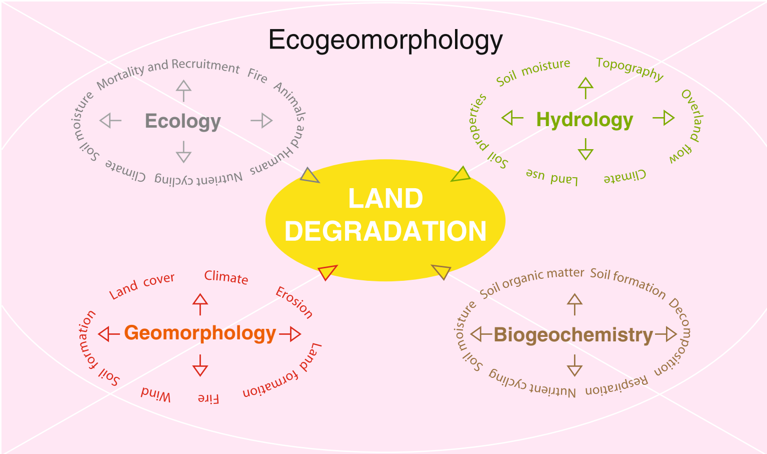

Fig. 1.3 Centrifugal approach of individual disciplines and centripetal approach of ecogeomorphic, multi-disciplinary land-degradation research

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.

Acknowledgments This chapter is a contribution to the book *Patterns of Land Degradation in Drylands: Understanding Self-Organised Ecogeomorphic Systems*, which is the outcome of an ESF-funded Exploratory Workshop – "Self-organized ecogeomorphic systems: confronting models with data for land degradation in drylands" – which was held in Potsdam, Germany, 7–10 June 2010.

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Part I
Theory: Linking Process to Pattern

Chapter 2
The Study of Land Degradation in Drylands: State of the Art

Tamara Hochstrasser, James D.A. Millington, Vasilios P. Papanastasis, Anthony J. Parsons, Pier Paolo Roggero, Richard E. Brazier, Joan Estrany, Almo Farina, and Alan Puttock

Abstract Land degradation is difficult to define because land can only be considered degraded with respect to some use to which it may be put. However, physical and biological properties of the landscape are typically measured to characterize degradation rather than its inherent or potential utility. One approach to characterizing land degradation is by assessing the provisioning of ecosystem services. Most provisioning ecosystem services depend on water, and water management is crucial to maintaining and increasing ecosystem services in arid lands. In contrast, vegetation change has been most commonly employed as an indicator of land degradation. Nevertheless, the close relationship that exists between vegetation and other biophysical processes of the environment means that any change in vegetation will result in a concomitant change to these other processes also. Of particular importance is a change in vegetation distribution since the spatial distribution of associated biophysical parameters controls landscape fluxes, and

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E.N. Mueller et al. (eds.), *Patterns of Land Degradation in Drylands: Understanding Self-Organised Ecogeomorphic Systems*, DOI 10.1007/978-94-007-5727-1_2,

hence degradation, by controlling landscape connectivity. From a management perspective, an understanding of the degree of connectivity in a landscape can aid in triage of remediation efforts. Areas that are dominated by long connected pathways will not respond to localized, small-scale manipulations because those pathways present inertia that a small-scale manipulation cannot overcome. Two important ecosystem services provided by drylands are grazing land and agricultural land. Both land uses can be drivers of degradation. The role of grazing in land degradation depends on several factors which can be grouped into three categories: number of animals, kind of animal species and grazing system. For agriculture, systematic crop residue removal without fertilisation, poor cultivation practices and extensive soil salinization are examples of mismanagement that may lead to land degradation. Aside from the immediate provisioning of food, drylands provide ecosystem services at a broader scale. Drylands are highly significant to the global carbon cycle. Land degradation in drylands has implications for the effectiveness of carbon sequestration as well as for storage (through soil erosion). Because many dryland soils have been degraded they are currently far from saturated with carbon and as a result their potential to sequester carbon may be highly significant. To understand land degradation better, efforts have been made to develop integrated human-environment research that overcomes the perceived deficiencies of reductionist, discipline-based research. However, much integrated environmental research to-date has resulted in a 'hierarchical relationship' between the human and physical components. Three approaches have been advocated to improve human-environment understanding: (a) systems science that emphasises feedbacks between integrated human and natural systems; (b) computer-simulation modelling that explicitly represents the interaction of individual human decisions

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and physical processes; and (c) participatory research that emphasises engagement with the actors in the region being studied. However, many questions remain open, and advancing beyond narrow scientific disciplinary specialization is vital if the hierarchical relationship in understanding physical and social causes of land degradation is to be broken.

2.1 Introduction: What Is Land Degradation?

Land degradation is difficult to define. At the ESF workshop on which this book is based, the participants were each asked to write down their understanding of the term. The result is presented in Fig. 2.1 as a mind map. What is evident from this mind map is that, in common with previous work (in particular the Millennium Ecosystem Assessment 2005), most associations with land degradation address issues of the use to which land may be put, especially the relationship of land to its utility for humans.

At the heart of the notion of land degradation lays a fundamental contradiction. "Degradation" is a value judgement; land can only be considered degraded with respect to some use to which it may be put, either in the past or potentially in the future (so-called, ecosystem services – see Sect. 2.2). However, in order to characterize how degraded land is, it is the physical and biological properties of the landscape that are typically measured rather than the inherent or potential utility. At best, in the case of current ecosystem services, the link between those physical and biological properties and the chosen land use is not wholly clear. In the case of a potential, but unknown future use there is no apparent link between current biophysical properties and a future assessment of ecosystem services. Inherently, biophysical measures of degradation can only apply to the current value of the land, and is incommensurate with the broader concept of ecosystem services. However, this problem is widely ignored in the discussion about land degradation and ecosystem services (Sect. 2.2).

In this chapter, first we examine the notion of land degradation in relation to ecosystem services. Next, we review indicators that are used to assess land degradation, and consider how these diverse indicators have been integrated through concepts of connectivity, before moving on to investigate, the roles of agriculture and pastoralism in causing land degradation in drylands. Finally, we take a broader perspective. The issues surrounding the links between specific ecosystem services and biophysical measures of land degradation are only part of the story. Land degradation has wider ramifications, and these ramifications justify the focus on describing land degradation in terms of biophysical properties of the land rather than the narrower utilitarian perspective. We consider such wider ramifications through the example of the specific issue of carbon dynamics. The chapter closes with two considerations of wider perspectives on the nature of biophysical and social processes in land degradation.

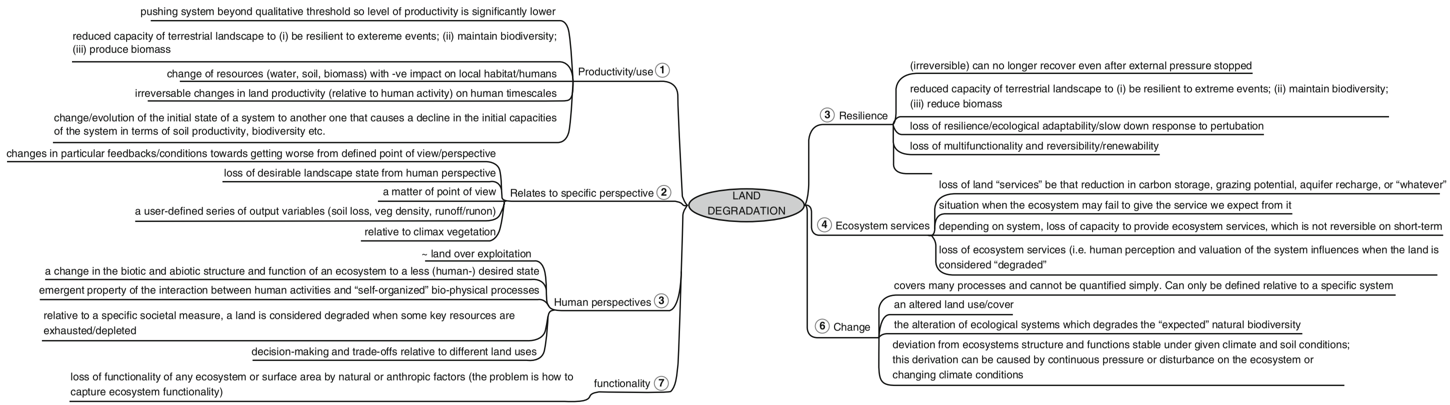

Fig. 2.1 Mind map of the concept of land degradation

2.2 Ecosystem Services and Land Degradation

Ecosystem services are commonly considered to be functions of or processes in ecosystems valued by humans – '"things that ecosystems provide that matter to people"' (Millennium Ecosystem Assessment 2005, p. 5). In drylands, the main provisioning ecosystem services (i.e. the production of forage, crops, fibre, fuelwood, and biochemicals) are dependent on biological productivity and water availability, which in turn are dependent on supporting services, such as soil development, primary productivity and nutrient cycling (Millennium Ecosystem Assessment 2005, p. 5; Havstad et al. 2007). Ecosystem services are considered to be diminished by land degradation. It is one view that land degradation is synonymous with loss of ecosystem services. The Millennium Ecosystem Assessment (2005, p. 5) defines land degradation as "a persistent reduction of biological and economic productivity" – thus the reduction of ecosystem services. The very reason for calling land 'degraded' is that it does not deliver ecosystem services to a level expected by the human beneficiaries of the ecosystem services. Therefore, 'land degradation' is influenced by the human expectations regarding ecosystem performance, and perceptions of the state of any ecosystem in terms of degradation can differ between groups with different experience and knowledge of the system (Davis 2005; Roba and Oba 2009). Thus, any discussion on degradation should involve a discussion on desirable ecosystem services and the parts of the ecosystem expected to deliver those them (Riginos and Herrick 2010).

To benefit from ecosystem services in arid lands, humans have to learn to cope with the special dynamics of ecosystems with scarce water resources variability and low predictability (Reynolds et al. 2007a, b). Societies that depend on the use of ecosystem services have usually developed strategies to deal with these characteristics of arid systems that resemble those of desert plants (for a brief review of these comparisons see e.g. Schwinning and Sala 2004), for example, by developing sophisticated storage mechanisms, by spatial and temporal flexibility as to what activities are carried out when and where (often associated with complex mechanisms to build and use expert [elders'] knowledge). One example of such an adaptation is pastoralism, a word that has many meanings, but can be defined as a 'finely-honed … relationship between local ecology, domesticated livestock and people in rangelands, particularly in resource-scarce and ecologically variable regions, often at the threshold of human survival' (Nori et al. 2005, p. 5). Although there is considerable debate on the sustainability of pastoralism under current environmental and social pressures, there is no doubt that the intricate system of using variable natural resources for livestock production developed by pastoralists could be used as part of a wider strategy to reach development goals in arid lands (Davis 2005; Hagmann and Ifejika Speranza 2010). Other examples are sophisticated irrigation strategies and communal water sharing plans developed by traditional societies, such as the North American Hohokam or the Medieval Muslim society on the Iberian peninsula (San José 2005; Nelson et al. 2010).

Water management is crucial to maintaining and increasing ecosystem services in arid lands. Effective science-based water management implies three aspects: (1) strengthening the knowledge base of when, where, and how much water will be received in the form of precipitation, (2) optimizing the partitioning of this water between infiltration, runoff, evaporation and transpiration, and (3) storing water for dry periods. Considerable spatial and temporal variation in those three aspects exists between landscape units because of their differences in geologic substrate, vegetation, soil, topography and past land use (Bestelmeyer et al. 2009). Suboptimal partitioning of water due to mismanagement can lead to enhanced soil erosion and degradation of provisioning services (Huber-Sannwald et al. 2006). Early recognition of the fundamental change caused by different partitioning of water in different vegetation types led to the proposition to classify arid lands based on how plants partition water (Le Houérou 1984). While a Western scientific approach is not the only approach to optimal management of arid lands (Bryant and Wilson 1998), it is a challenge to scientific research in arid lands to provide populations in these areas with the necessary information to optimize prediction, partitioning and storage of water. For prediction, both climatic forecasts and close observation of the state of vegetation and soil in arid lands is necessary. Land managers themselves should be strongly involved in the assessment and monitoring of their land to enable them to forecast changes in ecosystem (Bestelmeyer et al. 2009). Some indicators have been identified that can at least assist with this task (Roba and Oba 2009; Riginos and Herrick 2010). For partitioning it is important to understand the hydrology of arid lands and all factors influencing it. Great progress on this has been made and is reported in this book. For storage, long-term planning and landscape landscape-level thinking is necessary.

Water management in arid lands is designed to meet different societal needs and often conflicts arise between different social groups regarding their priorities for water use and water-dependent ecosystem services (Warner et al. 2006; Havstad et al. 2007). For example, the use of water and the ploughing of low-lying areas for crops can negatively impact livestock or fish production in a given region (Hagmann and Ifejika Speranza 2010). Not only can conflicts arise between different provisioning services such as crop and livestock production, but also because regulating services such as carbon sequestration, dust control, flood prevention, sanitation, amenity, and climate regulation in urban environments are gaining in importance in arid lands and may compete for water and land resources (Havstad et al. 2007). As a matter of fact, because of the increase in human populations in arid lands, projects to alleviate poverty in these marginal areas often include the development of such alternative ecosystem services for economic gain of the local population. Such projects further enhance the need for optimizing water and land allocation to meet the needs of all groups involved (i.e. the need for better local governance), but they also highlight the need for further scientific and (appropriate) technological advances to enhance ecosystem services (Warner et al. 2006).

While ecosystem management is dependent on societal factors, in order to reach the societally defined best outcome of ecosystem management, all elements of ecosystems have to be considered when optimizing ecosystem services (e.g. infrastructure (houses, roads), livestock and other animals, vegetation) and their interactions can be crucial to explaining outcomes of ecosystem management (Bestelmeyer et al. 2009). Land management influences the provision of ecosystem services through its interaction with biophysical processes (Huber-Sannwald et al. 2006). For example, movement of livestock can significantly contribute to seed dispersal and thus influence vegetation pattern, which in turn can influence water dynamics. Research has demonstrated the link between ecosystem dynamics and provision of ecosystem services and highlighted feedbacks in the system (e.g. Schlesinger et al. 1990; Lawrence et al. 2007). The latter are important because it has been recognized that dryland ecosystems can exhibit threshold dynamics that can severely degrade the ability of the ecosystem to provide expected services (Bestelmeyer et al. 2009). Such threshold dynamics can occur due to positive feedbacks at the patch scale (Schlesinger et al. 1990), but they can also occur due to interactions across scales (Peters et al. 2007). In order to make predictions for ecosystem-service delivery, the scale at which dynamics are investigated should comprise all parts of the ecosystem that are dynamically linked. Because of cross-scale linkages there is a great danger of erroneous conclusions based on investigations of ecosystem dynamics in only a subset of the ecosystem (Peters et al. 2006; Brauman et al. 2007; Bestelmeyer et al. 2009). Indeed, even global-scale processes may sometimes have to be considered to fully understand ecosystem dynamics (Loik et al. 2004, see also Chaps. 3 and 6).

Aggravation of poverty in arid lands is expected if ecosystem services cannot be enhanced or maintained in these areas and their degradation be halted. Ecosystem services in drylands are clearly under major threat from a combined range of pressures including climate change, privatization of natural resources (in particular land and water), and population growth. In addition to these factors, challenges in managing ecosystem services in drylands arise from the great variability of ecosystem dynamics in these areas, with many processes linked to pulse events (Schwinning and Sala 2004; Reynolds et al. 2007a, b). It is important in order to attain sustainability in ecosystem services to prepare for such events and increase resilience of the socio-ecological system (Gunderson 2000). Resilience (see Sect. 3.2) of dryland ecosystems is not only dependent on the biophysical environment, but also on the economic and societal development of the human populations dependent on arid land ecosystem services (Lawrence et al. 2007; Reynolds et al. 2007a, b). It is a challenge for both environmental and sociological research to put in place the necessary support system to build resilience in these systems that are often already in a state of stress and/or degradation (Bestelmeyer et al. 2009). Addressing this challenge requires not only increased understanding of complex socio-ecological systems, but also effective communication between stakeholders (Reynolds et al. 2007a, b; Roba and Oba 2009).

2.3 Indicators of Land Degradation: Physical, Chemical and Biological Parameters

Notwithstanding the crucial social context of land degradation, attempts to quantify it have been made in terms of the physical, chemical and biological parameters of the landscape. Not surprisingly, therefore, in a world of varied social contexts and different requirements for ecosystem services, such indicators of land degradation cannot have universal application. A range of indicators has been used to identify land degradation in drylands, but of these it is probably vegetation that has been most commonly employed. Two reasons may be advanced as to why this is so. First, vegetation change is the most easily observable change in the landscape. Even without quantification, cover and species change can be readily identified. Secondly, the dominant land use of the majority of drylands is grazing for domesticated animals. A reduction in vegetation cover or of palatable species results in a reduction in related ecosystem services. One of the most common vegetation changes in land degradation that has been identified in many areas of the world is a transition from grassland to shrubland, and has been documented in areas such as the Mediterranean (Martinez-Mena et al. 1999; Bochet et al. 1999; Maestre and Cortina 2002), the American southwest (Buffington and Herbel 1965; Gibbens et al. 2005) and in many parts in Africa (Kraaij and Milton 2006; Dean et al. 1995; Hoffman et al. 1999). However, even in terms of grazing, it cannot always be assumed that shrublands represent poorer ecosystem services than grasslands. In the Upper Karoo of South Africa, for example, there are instances of unpalatable grasses replacing palatable shrubs.

Because of the close relationship that exists between vegetation and other biophysical processes of the environment, any change in vegetation will result in a concomitant change to these processes also. However, a simple cause-effect relationship whereby vegetation change causes changes to other biophysical processes is to be eschewed (Thornes 1985; Wainwright and Parsons 2010). Although climate change or overgrazing are often regarded as drivers of vegetation change, in reality there are feedbacks between vegetation and other environmental processes. These feedbacks are often positive, so that the triggering of land degradation may be as much to do with autogenic drivers as with allogenic ones. Land degradation is, therefore, characterized by many changes other than easily recognised vegetation change. One way or another, such changes are manifest through changes to spatial distributions.

One of the key concepts in characterising the change in spatial distributions of biophysical parameters accompanying vegetation change is that of Islands of Fertility (Charley and West 1975; Goldberg and Turner 1986; Schlesinger and Pilmanis 1998). The significance of the development of such Islands of Fertility for runoff and erosion is depicted in Fig. 2.2. This figure illustrates two of the significant changes that accompany vegetation change: increases in both runoff and erosion. In a series of experiments on large plots, Parsons et al. (1996a) demonstrated a