Chapter 18

UNDERSTANDING GLOBAL DESERTIFICATION: BIOPHYSICAL AND SOCIOECONOMIC DIMENSIONS OF HYDROLOGY

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1. Introduction

Drylands are regions of the globe where the index of aridity (IA)—defined as the ratio of mean annual precipitation (P) to mean annual potential evapotranspiration (PET)—is less than 0.65 (see Chapters 1 and 8). If we restrict IA to the range of 0.05 to 0.65, drylands consist of *arid*, *semiarid*, and *dry sub-humid* regions, which together cover approximately 5.2 billion hectares or 40% of the land area of the world (Table 1). This definition *excludes* hyper-arid regions of the globe where IA < 0.05, such as the Atacama, Arabian, and Sahara deserts (ca. 0.98 billion hectares or 7.5% of global land area). Based on human land use, ca. 88% of drylands are classified as rangeland, with the remaining 12% used in agricultural production (3% irrigated cropland, 9% rainfed; Table 1). Combined, Asia and Africa contain 64% of all global drylands, dwarfing the amount of dryland area on other continents. In terms of importance, however, these numbers can be somewhat misleading. While Europe contains only ca. 5% of the world's drylands, this represents over 32% of its landmass and is home to 25% of its population. Similarly, Australia contains about 10% of the world's drylands but they cover over 75% of the continent and are home to 25% of its population.

Some of the highest densities of the world's human populations are located in the drylands of India, China, and Europe (White et al., 2003). In addition, drylands contain the fastest growing human populations on Earth; thus, it is not surprising that these areas are facing enormous environmental problems and challenges (Clarke et al., 2002). Among them, land degradation—commonly referred to as desertification—is perhaps the most important environmental issue (Le Houérou, 1996; Darkoh, 1998; Dregne, 1996; Kassas, 1995; Reynolds, 2001). Nevertheless, in spite of its importance, desertification remains a controversial topic: scientists and policy-makers from diverse disciplines and perspectives are engaged in ongoing debates ranging from defining land degradation to estimating the amount of total land affected (Reynolds, 2001; Thomas, 1997; Reynolds and Stafford Smith, 2002a).

In this chapter we review some of the key concerns and challenges associated with desertification in drylands, emphasizing the role of hydrological processes. First, we briefly review the extent, causes and consequences of desertification, elucidating some of the underlying issues on this topic that make research and exchange of dialogue so challenging. Second, we discuss the importance of ecohydrological feedbacks and linkages in desertification, focusing on both biophysical and socioeconomic aspects. Hydrological processes lie at the heart of desertification in drylands (Sharma, 1998), and thus are key to understanding both the causes and consequences of land degradation. Importantly, these processes must be viewed in the context of "shared water" between society and nature in order to avoid future human water shortages and undesirable environmental impacts, particularly in developing countries dealing with desertification. Third, we present an overview of the Dahlem Desertification Paradigm (DDP), a new approach to desertification designed to facilitate directed research effort and progress, and briefly describe an international network designed to facilitate debate and solicit input to refine and improve the DDP. Lastly, we introduce a stepwise model of grazing-induced land degradation, which highlights interactions between hydrological, ecological, and socioeconomic processes with management and restoration options, and briefly discuss future research needs.

Table 1. *Amounts and distribution of drylands of the world, and global totals of drylands considered to be degraded, subdivided into three dominant types of human land-use categories: irrigated agricultural cropland, rainfed agricultural cropland, and rangelands. Compiled from UNEP (1992) and Grainger (1992). T = total amount of dryland area (millions of hectares), and D = total amount of degraded dryland area (millions of hectares).*

	IRRIGATED CROPLAND			RAINFED CROPLAND			RANGELANDS			TOTALS		
Continent	**T**	*D*	*(%)*	**T**	*D*	*(%)*	**T**	*D*	*(%)*	**T**	*D*	*(%)*
Africa	**10.4**	*1.9*	*18*	**79.8**	*48.9*	*61*	**1,342.4**	*995.1*	*74*	**1,432.6**	*1,045.9*	*73*
Asia	**92**	*31.81*	*35*	**218.2**	*122.3*	*56*	**1,571.2**	*1,187.6*	*76*	**1,881.4**	*1,341.7*	*71*
Australia	**1.9**	*0.25*	*13*	**42.2**	*14.3*	*34*	**657.2**	*361.4*	*55*	**701.3**	*375.9*	*54*
Europe	**11.9**	*1.91*	*16*	**22.1**	*11.9*	*54*	**111.6**	*80.5*	*72*	**145.6**	*94.31*	*65*
N. America	**20.9**	*5.86*	*28*	**74.2**	*11.6*	*16*	**483.1**	*411.2*	*85*	**578.2**	*428.7*	*74*
S. America	**8.4**	*1.42*	*17*	**21.4**	*6.6*	*31*	**390.9**	*297.8*	*76*	**420.7**	*305.82*	*73*
TOTALS	**145.5**	*43.15*	*30*	**457.7**	*215.6*	*47*	**4,556.4**	*3,333.5*	*73*	**5,159.6**	*3,592.2*	*70*

2.   Desertification: a global concern

2.1. BACKGROUND

Many definitions of desertification have been proposed (see review in Reynolds, 2001). We favor the definition stemming from the United Nations Convention to Combat Desertification (CCD) (UNCCD, 1994): "land degradation in arid, semi-arid and dry subhumid areas resulting from various factors, including climatic variations and human activities". This definition makes it clear that desertification is about biophysical and socioeconomic linkages and how they affect human welfare. It also emphasizes that land degradation is not equated to soil degradation per se. Hence, it is essential in any elaboration of what constitutes land degradation, to make it clear that whilst *biophysical* components of ecosystems and their properties are involved (e.g., soil erosion and the loss of vegetation), the interpretation of change as 'loss' is dependent upon the integration of these components within the context of the *socio-economic* activities of human beings (often via a generic use of the term 'productivity'). We further propose a model for understanding and predicting conditions of arid land degradation in the context of the balance between natural and social systems (Figure 1).
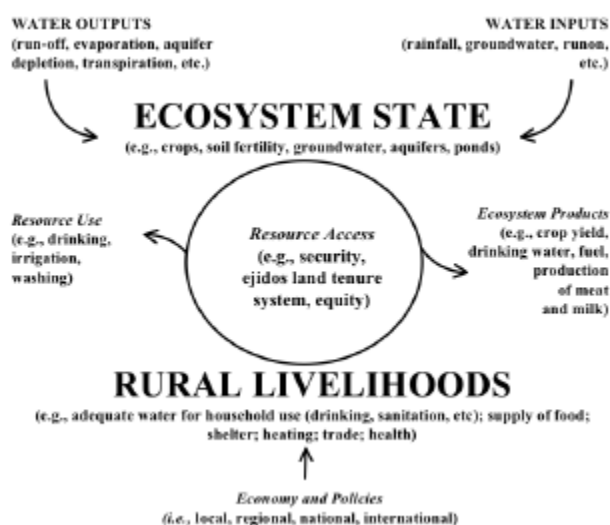
WATER OUTPUTS
(run-off, evaporation, aquifer
depletion, transpiration, etc.)

WATER INPUTS
(rainfall, groundwater, runon,
etc.)

ECOSYSTEM STATE
(e.g., crops, soil fertility, groundwater, aquifers, ponds)

Resource Use
(e.g., drinking,
irrigation,
washing)

Resource Access
(e.g., security,
ejidos land tenure
system, equity)

Ecosystem Products
(e.g., crop yield,
drinking water, fuel,
production
of meat
and milk)

RURAL LIVELIHOODS
(e.g., adequate water for household use (drinking, sanitation, etc); supply of food;
shelter; heating; trade; health)

Economy and Policies
(i.e., local, regional, national, international)

Figure 1. Illustration of social and biophysical factors in a rural community in a developing country. The cores of the biophysical and socioeconomic systems are shown as the 'state of the ecosystem' and 'rural livelihood', respectively, whereas hydrological processes are highlighted to show how the biophysical-socioeconomic systems are closely linked and constantly changing. From Huber-Sannwald et al. (2005).

Desertification is caused by a relatively large number of factors, which vary from region to region, and that often act in concert with one another in varying degrees. In a worldwide review of the causes of desertification, Geist and Lambin (2004) identified four major categories of proximal causal agents: 1) increased aridity; 2) agricultural impacts, including livestock production and crop production; 3) wood extraction, and other economic plant removal; and 4) infrastructure extension, which could be separated into irrigation, roads, settlements, and extractive industry (e.g., mining, oil, gas). Their study showed that: i) only about 10% of the case studies were driven by a single cause (with about 5% due to increased aridity and 5% to agricultural impacts); ii) about 30% of the case studies were attributable (primarily) to increased aridity and agricultural impacts; and iii) the remaining cases were combinations of three or all of the proximal causal factors. These results clearly highlight the complexity of desertification, and the need for integrative approaches that consider both its biophysical and socio-economic dimensions, which we discuss in more detail below.

2.2. EXTENT OF DESERTIFICATION

The extent of global desertification is routinely reported by international agencies to be as high as 70% of all drylands (UNCCD, 2000). However, such estimates must be considered with caution. Obtaining accurate, logical estimates on the amount of drylands that have been "desertified" is not a trivial task, especially given the lack of agreement as to the meaning of land degradation (Reynolds and Stafford Smith, 2002a). Thus, the multitude of global estimates of the extent of desertification are a product of subjective opinions, qualitative assessments, and data of varying authenticity and consistency (Verstraete, 1986; Hellden, 1991; Mainguet, 1991; Thomas and Middleton, 1994; Nicholson et al., 1998).

The CCD definition of desertification (see Section 2.1) is not amenable to easy quantification as a single number or as a synthetic index. Another confounding problem is how

changes that occur over short-term temporal scales (e.g., decrease in plant cover) are often cited as evidence of desertification, ignoring the fact that drylands are highly variable over time and that a temporary loss of vegetation cover due to a short-term drought is not necessarily related to a permanent loss indicative of desertification (Tucker et al., 1998; Tucker and Nicholson, 1998; Nicholson et al., 1998; Reynolds, 2001). For a detail discussion of these topics, see Thomas (1997) and Reynolds (2001).

2.3. IMPORTANCE OF MULTIPLE CAUSAL AGENTS

A crucial, but often overlooked, fact is that desertification is usually promoted by two or more causal agents (see Geist and Lambin, 2004). However, most estimates of desertification are derived from either *biophysical* factors (e.g. soil erosion, plant cover) or *socioeconomic* factors (e.g., low production, economic stress, poverty, emigration), but rarely both (Stafford Smith and Reynolds, 2002). This complicates quantitative estimates of the process since most studies focus only on single variables, or on a set of related variables, either biophysical *or* socioeconomic. When assessments are made without good knowledge of the underlying causes, it brings into question the validity of the variables or sets of variables being used in the assessment.

In recent years there has been a concerted effort to categorize and map various forms of land degradation, but these efforts failed to include a detailed identification of the critical biophysical *and* socioeconomic variables that cause the observed dynamics (Stafford Smith and Reynolds, 2002). This problem lies at the base of the confusion about how much 'desertification' there really is (see Batterbury et al., 2002). Much of this confusion could be eliminated by focusing on a small number of critical variables that contribute to an understanding of the *cause*, rather than *effect*, of desertification (Stafford Smith and Reynolds, 2002). Of course, this is all the more problematic when we try to account for the differences in causal factors driving desertification in different regions of the world and at different times: approaches developed to estimate desertification in one region may not be effective in others. The failure to recognize these issues has led to the disparities of estimates of desertification in the literature and is responsible for many of the disagreements alluded to above (Stafford Smith and Pickup, 1993; Stafford Smith and Reynolds, 2002).

2.4. CONSEQUENCES

Regardless of the specific amount of area affected, desertification has serious biophysical and socioeconomic consequences. The list of socioeconomic consequences is large, and includes, for example, loss of social capital, an increase in household debt, loss of local customs and traditional environmental knowledge, emigration, and so forth (Zaman, 1997; Fredickson et al., 1998; Latchininsky and Gapparov, 1996; Pamo, 1998; Bollig and Schulte, 1999; Stafford Smith and Reynolds, 2003). From the biophysical point of view the list is equally large, and includes, for example, factors such as the loss of soil and plant cover, a decrease in soil fertility and in biodiversity, a reduction of infiltration in rainfall, and the modification of local climate (Schlesinger et al., 1999; Sharma, 1998; Maestre and Cortina, 2004; Whitford, 1993; Von Handenberger et al., 2001; Reynolds, 2001; Rosenfeld et al., 2001).

However, care must be taken when applying general statements regarding the consequences of desertification to specific situations. For instance, while there is an established view that biodiversity decreases with desertification, a number of recent studies have shown that shrub encroachment into former grasslands in the southwestern United States, a form of desertification (Schlesinger et al., 1990), results in an *increase* in the species richness of birds (Pidgeon et al., 2001), mammals (Whitford, 1997) and ants (Bestelmeyer, 2005). In another example, based on the preliminary results of relatively simple models used over 30 years ago, it has long been conjectured that desertification is responsible for alteration of regional climates. Recent studies

challenge this view: while land degradation is accompanied by changes in land-surface properties, which have the potential to influence energy and water balances, Xue and Fennessy (2002) argue that atmosphere–biosphere interactions are much more complex than the situations considered by these simple models, and that other key processes, including interactions between soil moisture, soil texture and structure, albedo and evaporation, are also involved in the alteration of regional climate (see Chapter 6). Improvements in surface models and more realistic changes in land-surface conditions will help improve our understanding of the mechanisms of land–atmosphere interaction and the role of desertification in climate feedbacks (Xue and Fennessy, 2002 Asner and Heidebrecht, 2005).

3.   Hydrology and desertification: importance and feedbacks

By definition, drylands are areas where precipitation is so scarce that water is the main factor controlling biological processes (Whitford, 2002). A sound understanding of hydrology is thus essential in order to develop robust management strategies that address both the causes and consequences of land degradation in drylands. In this section, we briefly review some of the unique attributes and processes of drylands and their effects on hydrological functioning and visa versa.

3.1. BIOPHYSICAL LINKS

Rainfall size and frequency—and antecedent soil moisture—is a key driver of plant performance in arid and semi-arid areas (Reynolds et al., 2004). Once rainfall reaches the soil surface, its redistribution is influenced by topography (Puigdefábregas et al., 1999; see also Chapter 7), characteristics of bare soil surfaces (Eldridge et al., 2000; Maestre et al., 2002; see also Chapter 3), and by ecosystem structural attributes such as the number, width and spatial pattern of discrete plant patches (Ludwig and Tongway, 1995). With regard to the latter, in many dryland regions of the world vegetation occurs as a two-phase mosaic, consisting of vegetated patches within a matrix of bare soil (Valentin et al., 1999). The maintenance of these vegetated patches and thus, the overall functioning of the ecosystem, is dependent upon inputs of rainfall and the redistribution of water, sediments and nutrients from bare soil to these discrete patches (Noy-Meir, 1973; Aguiar and Sala, 1999;Reynolds et al., 1997). Such dynamics in two-phase mosaics have been aptly characterized as a series of "sources" (areas of loss) and "sinks" (areas of accumulation), reflecting a myriad of complex interactions between climate, topography, vegetation and soil surface properties.

     Because drylands are highly sensitive, any type of disturbance—ranging from *natural* (e.g., reduction in total precipitation, shifts in rainfall seasonality) to *anthropogenic* (roads, plowing, overgrazing, etc.)—that negatively impact key structural components (e.g. plant cover) may initiate a 'cascading' effect on other components and processes, leading to a progressive deterioration of the ecological structure and functioning, and thus promoting desertification processes (Aguiar and Sala, 1999; Von Handerberg et al., 2001; Seguieri and Galle, 1998; Puigdefábregas et al., 1999; Reynolds et al., 1997; Reynolds and Stafford Smith, 2002b).

3.2. SOCIOECONOMIC LINKS

From a socioeconomic point of view, hydrology in drylands is also of paramount importance considering that local and regional water availability affects all aspects of economic prosperity and sustainable development. Hydrology is a major determinant of plant and livestock yield, and thus human impacts—intentional and otherwise—on basic hydrological processes such as infiltration and runoff carry significant implications (Li et al., 2000; Abu-Awwad and Kharabsheh,

2000; Droppelman and Berliner, 2003). This is an especially acute concern in developing countries where the welfare of people is more directly dependent upon the hydrological functioning of local agro-ecosystems (Sharma, 1998). Any disruption in these hydrological processes, which leads to a reduction in water availability, will reduce the capacity of the land to support plant growth and animal production. During early stages of desertification such losses are compensated by the social resilience of the local human populations, especially in developing countries, or by economical inputs from government (Vogel and Smith, 2002). However, when certain thresholds are crossed, social resilience or government subsidies may not be enough to compensate for the loss of productivity. This in turn fuels a multitude of socioeconomic changes, ranging from modifications in trade promoted by lower agricultural production to the migration of large populations of human beings (Fernández et al., 2002).

Many countries are facing increasingly severe reductions in water availability (United Nations, 2003). Whereas drought is a contributing factor, the key long-term drivers are increasing human population growth, extensive land cover change, and rural development. While developed countries are not immune, these drivers are largely characteristic of developing countries, which often fall below sustainable levels of water availability for *both* human populations and natural ecosystems (United Nations, 1997). Although most countries and international programs are logically focused on the human problems of alleviating hunger and poverty associated with limited water, there is a recent, growing concern for the impacts of human appropriation of water on natural ecosystems (Wallace et al., 2003).

Understanding the balance and the complex of feedbacks of "shared water" between society and nature is required to avoid future human water shortages and undesirable environmental impacts (Wallace et al., 2003). This is particularly relevant for developing countries dealing with desertification. In Figure 1, Huber-Sannwald et al. (2005) present an illustration of the numerous connections (direct and indirect) between the *biophysical* (shown as the 'state of the ecosystem') and *socioeconomic* (represented as 'rural livelihoods') dimensions in a typical rural dryland systems. Within this framework several hydrological functions are depicted, which are crucial elements of both the natural ecosystem (e.g., rainfall, run-off , evaporation) and socioeconomic system (e.g., drinking water, profit from crop yield, water for sanitation). When portrayed in the context of the many feedbacks, linkages, and causal pathways between the biophysical and socioeconomic dimensions, it is evident that hydrology is a fundamental component of the social structure of rural communities.

3.3. FEEDBACK LOOPS

Links between desertification and hydrological processes in drylands are often self-reinforced through complex feedback loops. For instance, Rosenfeld et al. (2001) reported a feedback loop between rainfall and desert dust. Using aircraft and satellite observations, they have shown that small droplets dominate clouds derived from desert dust, and that this leads to a reduced rainfall due to little coalescence of these droplets (see Chapters 8 and 9). The reduction of rainfall promoted by the formation of these desert dust-clouds reduces soil water availability, which in turn raises more dust, thus providing a possible positive feedback to further decrease precipitation and foster desertification in drylands. This feedback loop is initiated by human activities (see Chapter 9), such as overgrazing and cultivation, which tend to expose and disrupt the topsoil, enhancing dust emission from the soil surface (Tegen and Fung, 1995).

Another example of a possible desertification loop is provided by studies evaluating the spatial pattern of the tussock grass *Stipa tenacissima* in semiarid Mediterranean steppes (Figure 2). The two-phase mosaic patterns of vegetation in these areas resemble those of the "tiger bush" vegetation typical of arid and semiarid areas worldwide (Valentin et al., 1999), and are determined by topography and the associated water fluxes (Puigdefábregas and Sánchez, 1996). On moderate slopes, *S. tenacissima* tussocks tend to be aligned parallel to the contours; this

maximizes their ability to trap and store water and sediment and gives the appearance of a regular pattern (Puigdefábregas et al., 1999; Webster and Maestre, 2004). As the gradient steepens, the amount of water, nutrients and sediments transported during runoff events increases up to levels that may exceed the ability of existing tussocks to retain them. Under these circumstances, vegetated patches tend to become broken, and stripes develop downslope (Puigdefábregas et al., 1999). As a consequence of this change in the spatial configuration of vegetation, a greater proportion of resources are exported from the system, the quality of the soil in places once occupied by patches drops, and the overall resilience of the system against further runoff events is reduced, fostering erosion and degradation processes (Ludwig and Tongway, 1995). Degradation processes that destroy or modify the number and width of *S. tenacissima* tussocks, such as grazing and fiber cropping, often result in an increased distance between remaining tussocks (Maestre and Cortina, 2004). Such increased distance is negatively related to infiltration at the plot scale (Figure 3), and thus favors the generation of runoff and soil loss. The increase of runoff in the bare ground areas prevent their re-colonization by the tussocks, thus providing a possible feedback to further increase water and sediment loss, and thus desertification.

These examples illustrate how the study of feedbacks between hydrological, ecological and human processes is an essential focus in the integrative discipline of ecohydrology (Eagleson, 2002). This is especially important for studying desertification processes in drylands. Disturbances to the hydrological cycle that result in detrimental changes in ecosystem processes can potentially have severe consequences. For example, a disturbance that triggers gully formation and sediment transport has the potential to self-propagate at remarkably large spatial scales, the result of which is to reshape vast landscapes in semiarid and arid regions (Huber-Sannwald et al., 2005).

4.   The Dahlem Desertification Paradigm (DDP): A new look at desertification

4.1. BACKGROUND

Traditional approaches to study desertification in drylands have focused on either the human or the natural dimensions of the problem. Yet, as noted above, desertification encompasses both biophysical and socioeconomic issues and partial approaches are not comprehensive enough to provide an adequate framing of the relevant questions (Reynolds and Stafford Smith, 2002b). In fact, partial approaches have been identified as a major obstacle to improve our abilities to understand and model this complex phenomenon, and to provide land managers and stakeholders with appropriate tools to mitigate their negative effects (Reynolds and Stafford Smith, 2002a). While many useful conceptual, methodological and technological advances have been developed in recent years to improve the assessment and understanding of desertification processes (e.g., Tongway, 1995; de Soyza et al., 1998; Prince et al., 1998; Puigdefábregas and Mendizábal, 1998; Oxley and Lemon, 2003), a comprehensive conceptual framework that embraced both the natural and human dimensions of desertification was lacking.

To fill this gap, an initiative involving the Global Change and Terrestrial Ecosystems (GCTE) and Land Use and Cover Change (LUCC) programs of the International Geosphere-Biosphere Programme (IGBP) was formulated. The intent of this initiative was to bring together researchers from the various global change programs, representing both natural and human-influenced systems, with the objective of stimulating, developing, and refining new ideas to bear on desertification as an important global change concern. Over the course of multiple meetings, conferences and brain-storming sessions, the Dahlem Desertification Paradigm (DDP) evolved from this activity (Reynolds and Stafford Smith, 2002b). In general, many of the constituent ideas contained within the DDP are not necessarily new, but rather, the DDP brings together much of

the previous work on this difficult topic in a way that reveals new insights and ultimately may serve as a framework to identify the causes, consequences and extent of desertification.
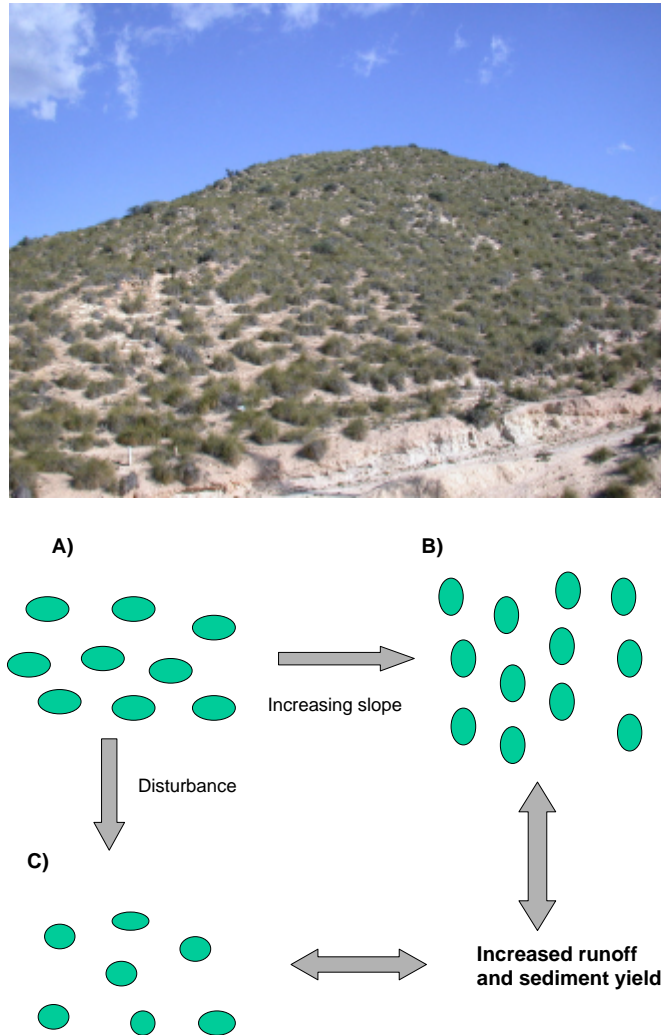

Figure 2. A possible desertification feedback between changes in plant spatial patterns and increased erosion in semiarid Mediterranean steppes dominated by the perennial tussock grass Stipa tenacissima *(upper graph). On moderate slopes,* S. tenacissima *tussocks tend to be aligned parallel to the contours (A). As the gradient steepens, the amount of water, nutrients and sediments transported during runoff events increases up to levels that may exceed the ability of existing tussocks to retain them, and stripes develop downslope (B). Degradation processes that destroy or modify the number and width of* S. tenacissima *tussocks, such as grazing and fiber cropping, may result in an increased distance between remaining tussocks (C). In both cases, the increase of runoff in the bare ground areas prevent their re-colonization by the tussocks, thus providing a possible feedback to further increase water and sediment loss, and thus desertification. Based on Puigdefábregas and Sánchez (1996) and Maestre and Cortina (2004).*
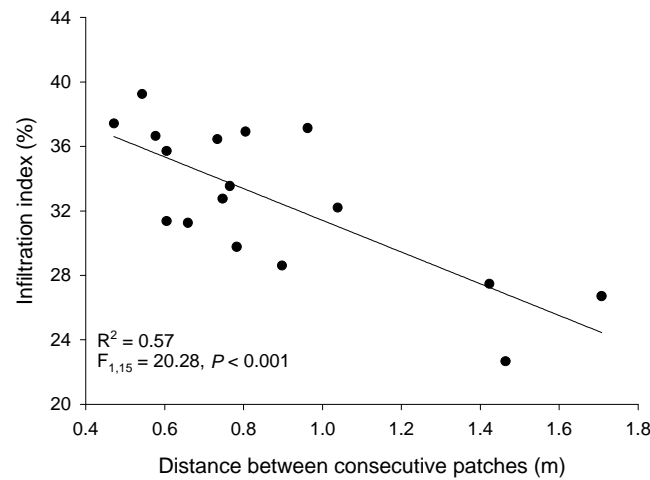
Figure 3. *Relationship between the distance between consecutive perennial plant patches and the infiltration index (a surrogate of infiltration rate) in sixteen* Stipa tenacissima *steppes located along a degradation gradient in SE Spain. From data reported in Maestre and Cortina (2004).*

4.2. THE DDP

The DDP, presented in detail in Reynolds and Stafford-Smith (2002b), is unique in two ways: i) it attempts to capture the multitude of interrelationships within human-environment systems that cause desertification, within a *single*, synthetic framework; and ii) it is testable, which ensures that it can be revised and improved upon as a *dynamic* framework. The DDP consists on nine assertions (Table 2), which embrace a hierarchical view of desertification in drylands and highlight key linkages between socioeconomic and biophysical systems at different temporal and spatial scales. In general, the DDP can be summarized as follows:

- that an integrated approach to desertification, which simultaneously considers both biophysical and socioeconomic attributes in dryland systems, is essential (assertions #1, #7);
- that the biophysical and socioeconomic attributes that govern or cause land degradation in any particular dryland region are invariably '*slow*' (e.g., soil nutrients) relative to those that are of immediate concern to human welfare (e.g., crop yields, the '*fast*' variables). It is necessary to distinguish these in order to identify the *causes* of land degradation from its *effects* (assertion #2);
- that socio-ecological systems in drylands of the world are *not static* (assertions #3, #6);
- that while change is inevitable, there does exist a *constrained set of ways* in which these socio-ecological systems function, thereby allowing us to understand and manage them (assertion #9);
- that restoring degraded socio-ecological systems to a sustainable state requires outside intervention (assertion #4);
- that socio-ecological systems in drylands of the world are hierarchical (assertion #8). Hence, scale-related concerns abound and desertification itself is a regionally-emergent property of localized degradation (assertion #5).

Table 2. *The nine assertions of the Dahlem Desertification Paradigm, and some of their implications. From Stafford Smith and Reynolds (2002).*

Assertions	Implications
Assertion 1. Desertification Always Involves Human and Environmental Drivers	Always expect to include both socioeconomic and biophysical variables in any monitoring or intervention scheme
Assertion 2. 'Slow' Variables are Critical Determinants of System Dynamics	Identify and manage for the small set of 'slow' variables that drive the 'fast' ecological goods and services that matter at any given scale
Assertion 3. Thresholds are Crucial, and May Change Over Time	Identify thresholds in the change variables at which there are significant increases in the costs of recovery, and quantify these costs, seeking ways to manage the thresholds to increase resilience
Assertion 4. The Costs of Intervention Rises Non-linearly with Increasing Degradation	Intervene early where possible, and invest to reduce the transaction costs of increasing scales of intervention
Assertion 5. Desertification is a Regionally Emergent Property of Local Degradation	Take care to define precisely the spatial and temporal extent of and processes resulting in any given measure of local degradation. But don't try to probe desertification beyond a measure of generalized impact at higher scales
Assertion 6. Coupled Human-Environment Systems Change over Time	Understand and manage the circumstances in which the human and environmental sub-systems become 'de-coupled'
Assertion 7. The Development of Appropriate Local Environmental Knowledge (LEK) must be Accelerated	Create better partnerships between LEK development and conventional scientific research, employing good experimental design, effective adaptive feedback and monitoring
Assertion 8. Systems are Hierarchically Nested (Manage the Hierarchy!)	Recognize and manage the fact that changes at one level affect others; create flexible but linked institutions across the hierarchical levels, and ensure processes are managed through scale-matched institutions
Assertion 9. A Limited Suite of Processes and Variables at Any Scale Makes the Problem Tractable	Analyze the types of syndromes at different scales, and seek the investment levers which will best control their effects – awareness and regulation where the drivers are natural, changed policy and institutions where the drivers are social

4.3. ARID*NET* RESEARCH NETWORK

The joint GCTE-LUCC initiative on desertification that gave birth to the DDP is embodied within the ARID*net* (Assessment, Research, and Integration of Desertification) research network (http://www.biology.duke.edu/aridnet/). The general objective of this network is to foster the exchange of ideas by facilitating practical, field-level interactions between researchers and stakeholders. ARID*net* is organized into three geographical nodes (Figure 4) and is pursuing four specific tasks:

1) Paradigm-building: By conducting workshops and symposia in different parts of the world, the goal of ARID*net* is to facilitate the development and refinement of the contents of the DDP via the joint participation of the international community of desertification researchers, stakeholders, and policy-makers;

2) Case studies: Working Groups (WG) are being formed to develop case studies based on existing data and specific stakeholders. The WGs are designed to represent a wide range of biophysical-socioeconomic land degradation issues throughout the world. Recently, the first case study was completed in La Amapola, a small rural community located in the surroundings of San Luis Potosí, in the Central Plateau of Mexico (Huber-Sannwald et al. 2005). New studies will be evaluated in forthcoming months;

3) Synthesis. The case studies will be synthesized into a quantitative assessment of what really matters in desertification. This synthesis will especially focus on those interactions between key biophysical and socioeconomic variables; and

4) Network-building. An important goal of ARID*net* is to recruit, and foster the participation, of a diversity of researchers from different fields and countries in the activities of the network.
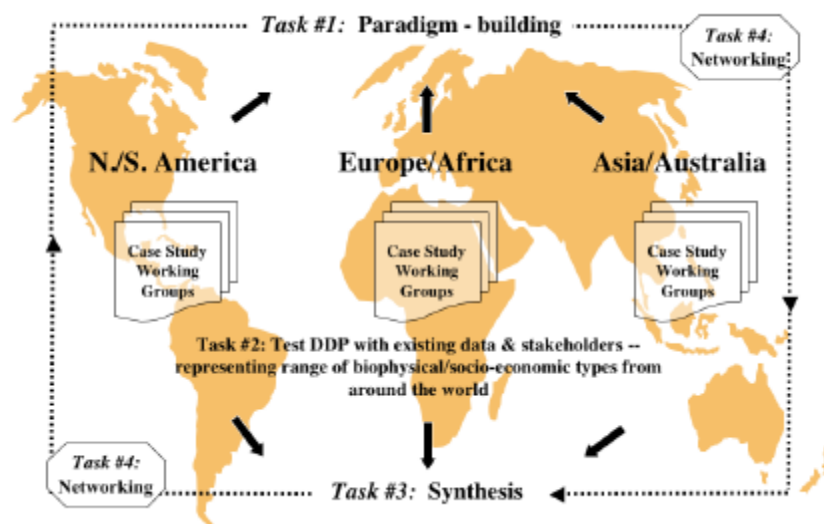
Figure 4. ARIDnet *is organized into three nodes, with four tasks. The development and maintenance of the* ARIDnet *website (http://www.biology.duke.edu/aridnet/) is currently underway to support these tasks.*

5. Concluding remarks

5.1. STEPWISE MODEL OF LAND DEGRADATION INCORPORATING HYDROLOGY

The DDP (Table 2) suggests that the process of chronic land degradation is directional, i.e. that it increases in severity, surpassing numerous thresholds along the way involving both biophysical (e.g., ecology, hydrology) and socioeconomic (income, hunger, customs, etc) variables, eventually reaching an irreversible (potentially) set of conditions. In this section we present a final example (modified from Reynolds 2001) that includes the ideas underlying the DDP and that focuses on a hypothetical instance of land degradation of rangelands in which grazing-induced desertification is a stepwise phenomena, and the potential for recovery *at any given step* is related to the function of the affected component. Some of the key processes and variables involved in this conceptual

model are summarized in Table 3. The human dimensions component emphasizes management options and that part of the ecosystem specifically targeted for management.

Table 3. *Proposed stepwise degradation of landscape, driven mainly by overgrazing, illustrating key biophysical and socioeconomic factors involved. Symptoms characterize the state of plant and animal assemblages; management options refer to actions to improve the condition of the landscape; and management "target" refers to where management could be focused. A system threshold (see Assertion #3, Table 2) may be somewhere between steps 2-4. Based on conceptual model for stepwise degradation of arid and semiarid rangelands by Milton et al. (1994) as modified by Reynolds (2001).*

Step	Biophysical Factors		Socioeconomic Factors	
No.	Ecological	Hydrological	Management Options	Management Targets
0	Biomass and composition of vegetation varies with weather; Adequate drinking water	Hydrologically functional landscape; High infiltration, low runoff	Adaptive management Education/Out-reach Education at household level is crucial	Household Community
1	Herbivory reduces palatable plants and modifies plant demography; Increase in exotic or undesirable species	The proportion of bare soil increases	Strict grazing controls (rotation schemes, intensity, type of animals, etc.)	Secondary producers
2	Plant species that fail to recruit are lost, as are their specialized predators and symbionts reduced primary and secondary productivity	Formation of erosion cells	Manage vegetation (e.g., seeding, plant removal); removal of livestock; culling abundant herbivores	Primary and secondary producers
3	Biomass and productivity of vegetation fluctuates as ephemerals benefit from lost of perennial cover; Perennial biomass reduced (short-lived plants and instability increase), resident birds decrease; dominant vegetation: annual weeds, exotic perennials	Signs of hydrologic dysfunctionality; Changes in surface albedo and soil moisture; Formation of erosion gullies	Manage soil cover (e.g., mulching, erosion barriers, roughen soil surface)	Physical environment
4	Denudation of all vegetation cover; changes in ecosystem structure and function; Inadequate drinking water	Hydrologically dysfunctional landscape; lots of bare soil; Accelerated wind erosion; Aridification; Soil salinization, large gullies, low infiltration	Only large amounts of external funding could have any impact (Assertion #4, Table 2)	Physical environment

At step zero, the landscape is hydrologically functional, that is, it is characterized by high infiltration rates, low runoff, no erosion, high vegetative cover and so forth. As Reid et al. (1999) note, a fully functional landscape is one in which only very small part of the water and nutrients that enter the system are subsequently lost. Runoff is redistributed within the system but not lost. In contrast, a significant portion of water and other resources are lost in a dysfunctional landscape because the patches of vegetation are too spotty or low in number to trap surface runoff (see Section 3.1). The type of management that might be used at this step is mostly linked to educational activities. Annual changes in biomass and composition of vegetation vary as a function of natural climatic cycles and stochastic events (e.g, fire, drought, diseases). An understanding of the relationships between these processes can be used effectively as a management tool and thus we believe education is a crucial factor at this stage since the farmer or rancher is able to exert formable control over the landscape *prior* to it becoming highly

degraded. For example, a rancher can change livestock densities (secondary producers) depending upon range conditions (see Vogel and Smith, 2002 for a number of examples of how management at this level can be highly effective, requiring no outside intervention).

The first step of ecological degradation concerns a decline in the native plant populations since those species are the ones most frequently defoliated by grazers, whereas toxic or distasteful plants (generally unaffected by grazers) are able to establish. The type of management that might be used at this step (shifting or varying the grazing season, stocking intensity, animal type) is a function of the type of objective (e.g., game viewing, meat production) and vegetation type (annual or perennial grassland, shrubland, savanna). The second step in land degradation involves a decrease in plant and animal productivity and signs of telling signs of changing hydrology. The challenge for resource managers is to identify threshold conditions in the local area with high potential to lead to formation of phenomena as erosion cells, rapid deep drainage losses, excessive lateral-flow, and so forth. For example, Pickup (1985) describes how erosion cells initially form once the vegetation in a particular area is denuded: high impact of rainfall tends to scour the soil surface, leading to the movement of water and sediment out of the bare area, and into adjacent ones. One started, such changes led to conditions that tend to facilitate further changes. Reversal of degradation at this stage is usually not cost-effective, particularly in regions where it might involve removal of domestic livestock, culling of other abundant herbivores, and manipulating the vegetation (reseeding, herbicide treatments, bush-cutting, etc.).

The third step involves processes associated with the reduction of perennial plant vegetation cover and an increase in ephemeral and weedy species. This includes accelerated wind and water erosion and various land surface impacts, such as increased albedo, surface temperatures, reduced soil moisture storage, and cloudiness. Once a rangeland reaches this condition, conditions are not suitable for the rancher to make profits and restoration necessarily must focus on the physical environment, e.g., reducing erosion, increasing water infiltration, protecting the soil surface from sun and frost, and creating microsites suitable for the establishment of perennial seedlings. This is costly, and requires outside intervention. Whisenant (1999) describe a number of examples of restoration approaches (ranging from low- to high-tech) that address this level of degradation. Their probability of success is highly variable and strongly coupled to abiotic conditions (Maestre et al., 2003). However, it can be improved by incorporating recent advances in our knowledge of dryland ecosystem structure, functioning and dynamics into restoration actions (Tongway and Ludwig, 1996; Ludwig and Tongway, 1996; Maestre et al., 2001; Maestre and Cortina, 2004).

The final step in the degradation process is characterized by a complete loss of vegetation cover, accelerated erosion, and soil salinization: a true 'human-made' desert that is hydrologically dysfunctional. Such rangelands are usually abandoned due to the high costs of—and low probably of successful—restoration and rehabilitation.

Whereas viewing land degradation as a directional process is an oversimplification, it is useful for showing how different factors are involved at different stages of degradation and how the various assertions of the Dahlem Desertification Paradigm (DDP) can be linked to real-world examples. Furthermore, this example also points out that rational decision-making based on an integrated view of the problem is necessary.

5.2. RESEARCH NEEDS

In this chapter we have emphasized that both biophysical components and the socioeconomic activities of human beings are necessarily involved in desertification processes, both as causal agents and as actors suffering its consequences. For example, in Figure 1 we identify some key components of hydrology in dryland systems that depicts some of the key interrelationships between the biophysical and socioeconomic dimensions in rural dryland communities. The simplified, stepwise model of land degradation (as depicted in Figure 5) highlights the enormous degree of complexity and importance of desertification (Puigdefábregas, 1998; Reynolds and

Stafford Smith, 2002b; Geist and Lambin, 2004). As a coupled biophysical and socioeconomic process, researchers and policy-makers are increasingly sensitive to the necessity of examining both dimensions *simultaneously*. To do so requires multi-scaled, multidisciplinary approaches. Although it is an enormous challenge—involving the building the bridges to improve communication among scientists across disciplines and establishing multidisciplinary collaborations—the potential rewards are equally large: this will undoubtedly advance our understanding of this complex, problematic phenomenon.
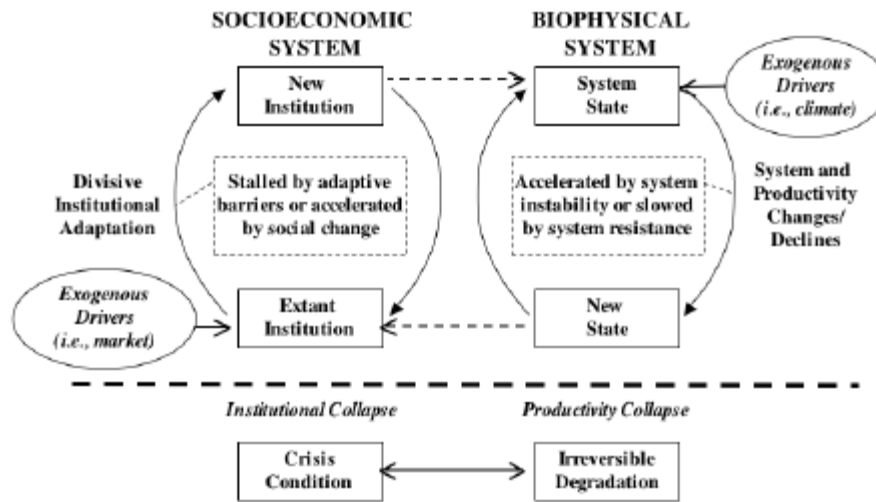
Figure 5. Balance between natural and social systems is key to understanding land degradation in drylands. We suggest that the systems are not static and that, even under conditions of dramatic change and uncertainty, sustainable land use is possible when environmental change and institutional adaptation are synchronous, that is, when the rate of change and spatial overlap in the human and environmental systems are matched. Accelerated environmental change and decelerated and uncoordinated community adaptation can together lead to social crisis and irreversible environmental degradation (Modified from Robbins et al. 2002).

There is an enormous body of empirical evidence and case studies on the drivers and consequences of desertification. However, not surprisingly the overwhelming majority of these focus on either the natural or social sciences. In the long-term, we are confident that this will change. For example, the new Global Land Project (GLP; Details at: http://www.nrel.colostate.edu/projects/glp.colostate.edu/), a joint research project for land systems of the IGBP and the International Human Dimensions Programme, emphasizes the study of coupled human-environment systems. The aforementioned ARID*net* project (Section 4.3) is an excellent example of such interdisciplinary collaboration. While surprisingly few quantitative syntheses of desertification data (e.g., Geist, 2004; Geist and Lambin, 2004) have been previously conducted, these new programs (and others) will undoubtedly stimulate future syntheses to identify the causal drivers of desertification, to evaluate the effectiveness of the different actions taken to combat it, and to identify areas in need of further research.

Our brief overview outlining the role of hydrological processes on desertification suggests that future studies should pay particular attention to the feedbacks between hydrological processes and both ecosystem structure and human activities, especially in those cases when feedbacks are amplifying those processes leading to desertification. Understanding these feedbacks is of crucial

importance in order to establish appropriate management measures to reverse them, and thus should be a core topic for future research in the area.

5.3. FUTURE DIRECTIONS

In this chapter we have described the Dahlem Desertification Paradigm (DDP) as a tool to aid in developing a synthetic framework for tackling the enormous problem of dryland degradation (Section 4.2). Undoubtedly, we must recognize the simultaneous roles of—and complex feedbacks between—the meteorological, ecological, and human dimensions of land degradation and recognize that in the past, a failure to do so slowed progress.

There is an immediate need at all levels (local, regional, national, international) for policy decisions on how to identify, prevent and/or adapt to desertification and land degradation in general. It is essential to move beyond isolated studies of various parts of the desertification problem and to work through the causal links of dryland land degradation, from climate dynamics to ecological impacts to policy response strategies, and to span a wide range of temporal and spatial scales, from small geographical units to larger regions. The DDP is able to incorporate our state-of-the-art knowledge about the detection, prevention and consequences of desertification and is flexible enough to embrace specific concerns—such as hydrology in this chapter—enabling us to better understand linkages and interactions between biophysical and socioeconomic issues. Through rigorous testing and refinement (Section 4.3), it is our hope that the DDP framework will continue to evolve by incorporating new ideas and approaches in order to explore the full suite of quantitative as well as qualitative interactions between the various elements of the problem.

Although the DDP is new, an international network (Section 4.3; Figure 4) is facilitating research to refine and test its core principles via multiple case studies throughout the world. These case studies will be selected from a wide range of biophysical and socioeconomic conditions and, in time, will help advance our understanding of desertification. It will be particularly useful to bring new ideas to the long-standing debate and controversies surrounding desertification (e.g., Section 2.2). Ultimately, it is the job of researchers to assist policy-makers and land managers to develop useful and straightforward—but at the same time, powerful and robust—tools that can be readily employed to deal with the complex topic of desertification in drylands.

6. Acknowledgements

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