HYDROLOGICAL PROCESSES
Hydrol. Process. **20**, 3395–3411 (2006)
DOI: 10.1002/hyp.6337

Ecohydrological feedbacks and linkages associated with land degradation: a case study from Mexico

Elisabeth Huber-Sannwald,[1] Fernando T. Maestre,[2,3] Jeffrey E. Herrick[4]
and James F. Reynolds[2,5]*

[1] *División de Ingeniería Ambiental y Manejo de Recursos Naturales, Instituto Potosino de Investigación Científica y Tecnológica (IPICYT), Apdo. Postal 3-74 Tangamanga 78231, San Luis Potosí, SLP, MÉXICO*
[2] *Department of Biology, Phytotron Bldg., Box 90340, Duke University Durham NC 27708-90340, USA*
[3] *Permanent address: Unidad de Biodiversidad y Conservación, E.S.C.E.T., Universidad Rey Juan Carlos, C/Tulipán s/n, 28933 Móstoles, Spain*
[4] *USDA-ARS Jornada Experimental Range MSC 3JER, Box 30003 NMSU Las Cruces NM 88003-8003, USA*
[5] *Division of Environmental Science and Policy, Nicholas School of the Environment and Earth Science, Duke University, Durham NC 27708-90340, USA*

Abstract:

Land degradation and desertification are major environmental problems of human societies in drylands of North and South America. Mexico is one of the most severely affected countries. An assessment of how both biophysical and socio-economic processes simultaneously affect, and are affected by, land degradation is recognized as one of the most important and challenging topics in the research on global change. Towards meeting this challenge, in June 2004 an interdisciplinary mix of scientists assembled in Mexico to participate in a workshop convened by the ARID*net* network. The focus of the workshop was to apply a new conceptual framework—the Dahlem Desertification Paradigm (DDP)—to La Amapola, a small rural community located in the Central Plateau of Mexico. The DDP aims to advance understanding of global desertification issues by focusing on the interrelationships within coupled human-environment systems that cause desertification. In this paper we summarize the conclusions of the La Amapola workshop. First, we present a brief review of some of the broader issues and concerns of global desertification, which led to the formation of ARID*net* and to the DDP. Second, we provide an overview of land degradation issues in La Amapola, highlighting examples of hydrological linkages between biophysical and socio-economic factors. Third, we summarize our findings in a conceptual model, which highlights linkages between biophysical and socio-economic factors in La Amapola, and the role of hydrology in desertification. Lastly, we discuss the results derived from the application of the major assertions of the DDP to La Amapola. The numerous feedbacks, linkages, and causal pathways between the biophysical and human dimensions suggest that hydrology is the fundamental component of the livelihoods of rural communities in this region of Mexico, and thus it is of central importance when evaluating desertification. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS ARID*net* case study; coupled human-environment system; Dahlem Desertification Paradigm; ecohydrological indices; Mexican drylands

Received 15 July 2005; Accepted 12 December 2005

INTRODUCTION

Land degradation and desertification are major environmental problems of human societies in global drylands. The United Nations (UN) contends that desertification threatens the livelihoods of a billion people in over 100 countries distributed over one-quarter of the earth's land surface (UNEP, 1992). It established the Convention to Combat Desertification (CCD) to 'target poverty, drought, and food insecurity in dryland countries

---

* Correspondence to: James F. Reynolds, Department of Biology, Phytotron Bldg, Box 90340, Duke University, Durham NC 27708-90340, USA. E-mail: james.f.reynolds@duke.edu

experiencing desertification . . . and to facilitate the role of national governments in enacting policies to combat land degradation' (United Nations, 1994). In the context of the CCD, the UN defines *land degradation* as 'the reduction or loss of the biological and economic productivity and complexity of terrestrial ecosystems, including soils, vegetation, other biota, and the ecological, biogeochemical, and hydrological processes that operate therein' (United Nations, 1994) and *desertification* as 'land degradation in arid, semiarid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities' (UNCCD, 1994). As noted by Stafford Smith and Reynolds (2002), these definitions suggest that whether or not land degradations (for example, soil erosion) are 'losses' is dependent on the socio-economic activities of the human beings who are directly affected.

According to the World Atlas of Desertification (Middleton and Thomas, 1997), most drylands in North and South America suffer from some degree of desertification. In the southwestern United States, this is best exemplified by widespread woody plant encroachment in grassland and savanna ecosystems (Schlesinger *et al.*, 1990; Bahre, 1991), whereas in Latin America, the majority of degraded lands are found in the highland pastures and grasslands of Argentina, Bolivia, Peru, Ecuador, Colombia, the central basin of Chile, in the coastal forest and dry uplands of the planalto region of northeastern Brazil, and the central plateau of Mexico (Gutiérrez, 1993; Lopez-Ocaña, 1996; Busso, 1997).

Mexico is one of the most severely affected countries (Natural Heritage Institute, 1997). Most of the terrestrial land mass of Mexico has suffered (or is currently undergoing) some form of degradation (Schwartz and Notini, 1994), especially in the northern region of the country where rain-fed agriculture and livestock production are key economic drivers (i.e. over-cultivation and overgrazing, respectively, Manzano *et al.*, 2000). While quantitative assessments of the total land area impacted vary (see below), it is estimated that approximately 2250 km^2 of potentially productive farmlands are abandoned or taken out of production annually (Schwartz and Notini, 1994; Natural Heritage Institute, 1997; SEMARNAT, 2003). An in-depth study by the Natural Heritage Institute (1997) concluded that agricultural-related activities, especially deforestation and overgrazing, are the main drivers (75%) of soil erosion and other forms of desertification in Mexico. In a more recent assessment, SEMARNAT (2003) listed agriculture (39%) and overgrazing (39%) as the principal causes of land degradation, followed by deforestation (16%) and urbanization (3·5%).

The crisis of land degradation is intimately linked to water shortages (Duda, 2003; Ripl, 2003), which is a growing concern throughout Latin America (United Nations, 2003; World Water Assessment Programme, 2005). By definition, drylands, which include arid, semiarid and dry sub-humid areas, are areas where precipitation is scarce (Middleton and Thomas, 1997) and, as a result, they are commonly associated with harsh environmental and social conditions, and the human populations that inhabit these regions are often considered to be the most ecologically and politically marginalized populations on earth (Thomas, 1997; Khagram *et al.*, 2003). Throughout Mexico, degradation of agricultural and pastoral lands has led to acute shortages of water, both for agriculture and human consumption (Schwartz and Notini, 1994; SEMARNAT, 2003; United Nations, 2003). The key long-term drivers of land degradation involve complex interactions among economic, demographic, and ecological factors (Aide and Grau, 2004), which, in Mexico, include excessive clearing and cultivation of land unsuitable for agriculture, exploitation of forests for fuel and conversion into pastureland, inefficient irrigation practices, unregulated mining practices, and urban expansion (Natural Heritage Institute, 1997; Villers-Ruíz and Trejo-Vázquez, 1998; Manzano *et al.*, 2000; SEMARNAT, 2003; Aide and Grau, 2004). Although most government and international programs are logically focused on alleviating hunger and poverty associated with declining water resources, there is a growing concern for the impacts of human appropriation of water on natural ecosystems (Jackson *et al.*, 2001; Wallace *et al.*, 2003; Aide and Grau, 2004; World Water Assessment Programme, 2005).

Although both biophysical and socio-economic factors drive land degradation, research is often focused on either the hydrological, ecological, meteorological or socio-economic aspects of desertification, rarely their interactions (Reynolds and Stafford Smith, 2002b). The assessment of how both biophysical and socio-economic processes simultaneously affect, and are affected by, land degradation has been recognized as one of the most important and challenging topics for further research (Reynolds, 2001). In an attempt to address this challenge, a new conceptual framework—the Dahlem Desertification Paradigm (DDP) (Reynolds and Stafford Smith, 2002b; Stafford Smith and Reynolds, 2002)—was recently launched. The DDP aims to advance understanding of global desertification issues by focusing on the interrelationships within coupled human-environment systems that cause desertification.

In June 2004, an interdisciplinary mix of 30 social and natural scientists assembled in San Luis Potosí (Mexico) to participate in a workshop convened by the ARID*net* network (Assessment, Research, and Integration of Desertification network. ARID*net* (funded by the Collaborative Research Network program of the National Science Foundation) is a consortium of researchers from various global change programs on natural and human-influenced systems. The goals of ARID*net* are (i) to foster international cooperation, discussion, and exchange of ideas about global desertification, (ii) to conduct case studies in a range of biophysical and socio-economic land degradation types around the world, and (iii) to facilitate communication between researchers and stakeholders to facilitate new ideas for practical, field-level sustainable land management (see http://www.biology.duke.edu/aridnet/) (Reynolds *et al*., 2003; Reynolds *et al*., 2005). The focus of the workshop was to apply the DDP to La Amapola, a small rural community located in the Central Plateau of Mexico. In this paper we summarize the conclusions of the workshop, and present a conceptual model of ecohydrological feedbacks and linkages associated with land degradation, based on the concept of 'shared water' between human societies and natural ecosystems (Falkenmark, 2003; Wallace *et al*., 2003). First, we present a brief review of some of the broader issues and concerns of global desertification, which led to the formation of ARID*net* and to the DDP. Second, we provide an overview of land degradation issues in La Amapola, highlighting examples of hydrological linkages between biophysical and socio-economic factors. Third, we summarize our findings in a conceptual model that highlights the links between biophysical and socio-economic factors in La Amapola, and the role of hydrology in desertification. Lastly, we discuss the results derived from the application of the major assertions of the DDP to La Amapola.

THE DDP: A NEW PARADIGM

Land degradation and desertification are composite phenomena that have no single, readily identifiable attributes. Perhaps this is why there are so many conflicting and confusing definitions (see reviews by Thomas, 1997; Reynolds, 2001). To many, land degradation only involves either biophysical (e.g. soil erosion, loss of plant cover, change in albedo) or socio-economic factors (decreased economic production, population migration, poverty, etc.). However, the UN definitions of land degradation and desertification used here (see Introduction) make it clear that land degradation and desertification concern both biophysical and socio-economic linkages and how they affect human welfare. As such, they do not lend themselves to easy quantification (as discussed by Reynolds and Stafford Smith, 2002a). This complicates the use of quantitative estimators, since desertification assessments made without knowledge of the underlying causes bring into question the validity of the variables or sets of variables being used (Geist and Lambin, 2004).

The aforementioned criticisms and concerns about desertification stimulated a joint initiative by the Global Change and Terrestrial Ecosystems (GCTE) and Land-Use and Land-Cover Change (LUCC) programs of the International Geosphere–Biosphere Programme (http://www.igbp.kva.se/). The intent of this initiative was to bring together researchers from the various global change programs, representing both natural and human-influenced systems, to stimulate new thinking on desertificacion. The first activity was a Dahlem Conference (http://www.fu-berlin.de/dahlem/) entitled 'The Meteorological, Ecological, and Human Dimensions of Global Desertification,' which led to two key products: the development of a new synthetic framework for global desertification, which is referred to as the DDP, and the formation of ARID*net*.

The DDP, presented in detail in Stafford Smith and Reynolds (2002), is a conceptual framework that is unique in two ways: (i) it captures 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, evolving framework. The DDP embraces a hierarchical view of land

DOI: 10.1002/hyp

Table I. Nine assertions of the DDP and their implications. From Stafford Smith and Reynolds (2002)

Assertion	Brief description	Implications
1	Desertification always involves human and environmental drivers	Always expect to include both socio-economic and biophysical variables in any monitoring or intervention scheme
2	'Slow' variables are critical determinants of system dynamics	Identify and manage the small set of 'slow' variables that drive the 'fast' ecological goods and services that matter at any given scale
3	Thresholds are crucial, and may change over time	Identify thresholds in the change variables at which there is a significant increase in the costs of recovery, and quantify these costs, seeking ways to manage the thresholds to increase resilience
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
5	Desertification is a regionally emergent property of local degradation	Take care to define precisely the spatial and temporal extent and process represented in any given measure of local degradation (but do not try to probe desertification beyond a measure of generalized impact at higher scales)
6	Coupled human-environment systems change over time	Understand and manage the circumstances in which the human and environmental sub-systems become 'de-coupled'
7	The development of appropriate local environmental knowledge (LEK) must be accelerated	Create a better partnership between LEK development and conventional scientific research, involving good experimental design, effective adaptive feedback and monitoring
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
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 that will best control their effects—awareness and regulation where the drivers are natural, changed policy and institutions where the drivers are social

degradation, and highlights key linkages between socio-economic and biophysical systems at multiple scales of concern. The strength of the DDP as a theoretical framework lies in its cross-scale conceptual holism, as it embraces the wide range of concerns involved in this complex phenomenon. The DDP consists of nine assertions, which are presented in Table I.

LA AMAPOLA: CASE STUDY

Ejido system of rural agriculture

Mexico's rural agriculture is uniquely characterized by a communal or *ejido* system. Ejidos are communal land holdings where individual households have access to natural resources of the community commons. The agrarian land reforms in 1917 led to shifts in land tenure, when large areas of the country were returned to rural and peasant communities forming ejidos (Sanderson, 1984). Currently, 3 million households are found in over 30 000 ejidos in Mexico, which cover about 60% of Mexico's total land area encompassing 70% of Mexico's croplands and 50% of its irrigated lands (Schwartz and Notini, 1994; Deininger and Bresciani, 2001; Alcorn and Toledo, 2002). Most ejido land throughout Mexico is marginal at best because of dry climate, poor soils, and/or severely degraded conditions (LaBaume and Dahl, 1986; Escurra and Montaña, 1990). While ejido land may be used by individual households for cultivation and/or grazing, most of the land remains common property (McCarty *et al*., 1998), although recent changes in national policy permits individual ejido households to sell or rent their land (Schwartz and Notini, 1994; Deininger and Bresciani, 2001; Alcorn and Toledo, 2002).

Scales of concern

One of the first tasks of the workshop was to identify key biophysical and socio-economic processes and to group them accordingly, that is, according to either patch or landscape scales (for biophysical processes) and to either household or community scales (for socio-economic processes). While arbitrary, these scales (Table II) are useful for representing different spatial and temporal considerations and, importantly, are helpful to highlight potentially important cross- and within-scale interactions. Furthermore, the causal factors involved in land degradation may have different levels of influence, depending on the specific location or region of the world and/or the specific time of their occurrence (see Stafford Smith and Reynolds, 2003). In the following sections, we provide a brief overview of some of these key socio-economic and biophysical processes. The miscellaneous socio-economic data presented are based on information provided by INEGI (2000), interviews with Amapola elders and the former and current *comisariados* (legal representative of an *ejido*) of the *ejido* Escalerillas and several individual households. The interviews were conducted by participants during the workshop and by EHS over a period of several months prior to the workshop (March 2004), during the workshop, and numerous times afterwards (September 2004 to fall 2005).

Biophysical and socio-economic overview

La Amapola, which was founded in 1924, is a small, remote community of the large ejido Escalerillas, located on the southeast side of the Sierra San Miguelito, approximately 35 km SW of San Luis Potosi (latitude 21°56′60″ N; longitude 101°10′0″ W; altitude 2105 m). La Amapola is situated in the foothills of a narrow, open valley with gentle slopes and sediment rich alluvial fans. Following the natural features of the region, we identified three landscape units: rocky hills, alluvial fans, and valley floor (Figures 1, 2).

Each landscape unit is composed of patch types, defined as being relatively different in respect to vegetation composition/cover and land-use (both quantitatively and qualitatively) from their immediate surroundings (Reynolds and Wu, 1999). For La Amapola, four patch types were identified: (i) forests: the forests occur at the upper elevations (Figure 1(c), (d)), and are composed of various species of pine (*Pinus cembroides, P. johannis*) and oak (*Quercus potosina*); (ii) rangeland: the northeast and southwest facing slopes are covered by open rangelands dominated by small unpalatable shrubs (*Isocoma veneta, Brickelia veronicifolia*) and native perennial grasses (*Aristida* spp. *Bouteloua hirsuta, B. scorpioides, Lycurus phleoides, Muhlenbergia* spp.) (Figure 1(a), (d)), (iii) cropland: the main crops planted each year, using a rotational or mixed planting approach, include corn, bean, squash, and barley. The individual fields are dispersed throughout the landscape, from terraced fields along the alluvial fan to scattered fields on the valley floor (Figure 1(b), (d)), and (iv) miscellaneous: dispersed throughout the landscape—extending from the valley bottom up to small terraces on the southwest facing slopes of the rocky slopes—are water collection tanks, bare land, water reservoirs, individual households, home gardens (e.g. small peach orchards), livestock corrals, a small chicken farm, a small one-room school, a health clinic, a church, and the central supply of drinking water. Dirt roads connect individual households, along with narrow walking paths between crop fields lined by dense *Opuntia* sp. and *Agave* sp. fences and erosion gullies (Figure 1(c)).The spatiotemporal distribution of patches across the landscape is dictated by the natural geomorphology, ecological factors (e.g. seed dispersal, soil depth, disturbance history), socio-economic factors (e.g. availability of labor, servicing a debt by cutting wood, construction), and meteorological variables (e.g. rainfall, microtemperature inversions). Interviews, historical records, and repeat aerial photography all indicate that the aforementioned patch types for La Amapola have been relatively stable over the past 40 years.

As a characteristic of the ejidos, the population of La Amapola has fluctuated greatly in size over the years. During the past 3–4 decades, however, the community has stabilized to *ca.* 12 households and 48 inhabitants. Emigration has been driven by rapidly changing job opportunities, such as the local stone quarry industry

Table II. Potential *socio-economic* and *biophysical* issues of concern in La Amapola, highlighting different spatiotemporal scales. Note that potential interactions exist across and within rows and columns. Based on Reynolds and Stafford Smith (2002b)

Scale	**Socio-Economic Issues**	**Scale**	**Biophysical Issues**	*Relevant temporal and spatial scales of concern*	
				Temporal	Spatial
FARM/ HOUSEHOLD	Household size Labor needs Food security Access to drinking water Access to irrigation water Crop storage (to avoid mice; infestation with grain and bean weevil; etc.) Education Access to government aid programs Selling/renting land	**PATCH**	Soil fertility Soil stability Seed viability (local cultivars) Size of livestock herd Composition and dominance of plant functional groups Shrub encroachment in grass-dominated patches Irrigation water	days weeks months seasonal	small (m^2)
COMMUNITY/ VILLAGE	Land tenure and ownership bylaws Conflict resolution Population size Local land planning (location and installation of earthen dams to facilitate livestock access to water) Local and regional livestock market Over-exploitation of resources may lead to need to migrate and hence loss of LEK	**LANDSCAPE**	Gully formation Encroachment of shrubs in pasture Soil erosion Overland flow Maintenance of patch structure (such as patch–patch connectivity)	year decade ↓	large (km^2) ↓

in nearby communities and neighbouring ejidos. Since the inhabitants of La Amapola live at the subsistence level, they depend almost exclusively on agriculture and on occasional food packages provided by social programs via the municipality of San Luis Potosí. In La Amapola, common land corresponds to the rangeland and forest, whereas land used for growing crops is divided between households, with each household assigned specific fields (Figures 1, 2). Nevertheless, while each household of an ejido has the right to access and exploit the natural resources as needed to sustain their livelihoods, they must operate within well-defined community limits. Consequently, all land-use and management decisions are made at the individual household level but with restrictions imposed at the community level (Alcorn and Toledo, 2002). These units correspond to the household and community scales shown in Table II.

Water for general household use (cooking, drinking, sanitation) comes from four local springs. While the springs provide sufficient water for the entire community from May until January, springflow is highly variable depending upon annual rainfall. In addition, drinking water is delivered monthly or bimonthly to the community from groundwater wells by the city of San Luis Potosí.

Livestock production changes substantially from year-to-year and even within a year. In 2004, La Amapola's collective herd consisted of 250 goats, 100 sheep, 80 cattle and 30 horses and donkeys. Recently (spring 2005), the goat herd has increased to 450 animals. The rangelands are grazed by goats and sheep, while during summer months the cattle are moved to the remote pine forests in the same ejido.

Figure 1. Views of La Amapola, Mexico, showing rocky hills, alluvial fan, valley floor landscape units. Key features to note: (a) earthen dam and waterhole; (b) alluvial fan; (c) erosion gully; and (d) free-ranging livestock and crops on valley floor

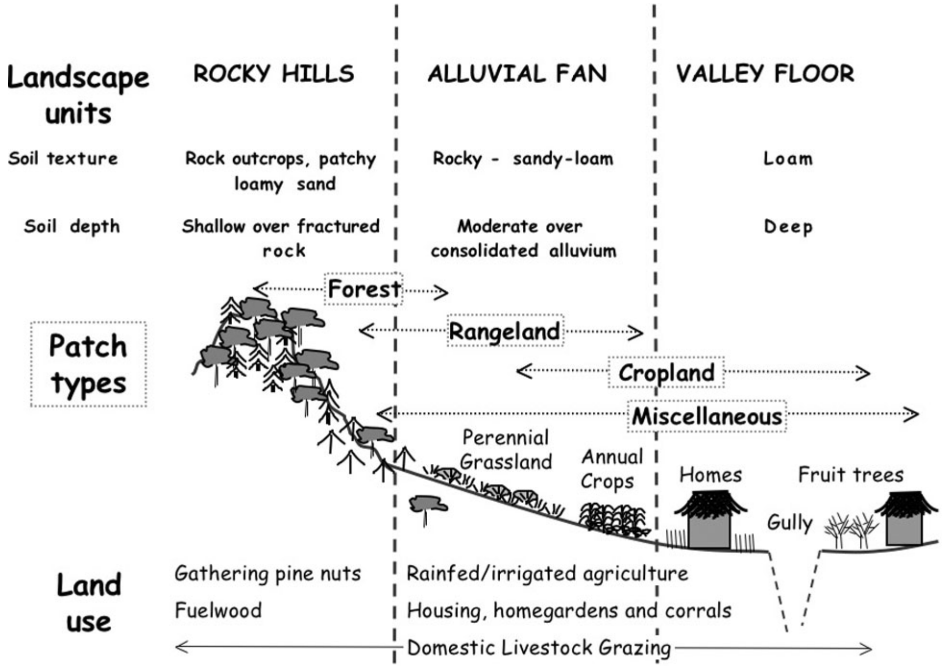

Figure 2. Schematic representation of landscape units (from Figure 1), the vegetative patch types found in each of them, and the general land-use categories

ECOHYDROLOGICAL INDICES OF DESERTIFICATION: A CONCEPTUAL MODEL

During our field visit to La Amapola, we used qualitative indicators (e.g. rills, water flow patterns, pedestals and terracettes, bare ground, gullies, litter movement, soil erodibility, soil surface loss and degradation, plant community composition and distribution, and compaction) included in the *Interpreting Indicators of Rangeland Health* protocol (Pyke *et al*., 2002) to conduct a preliminary, rapid description of several areas across the landscape (Figures 1, 2). All indicators suggested significant degradation at one or more locations in the landscape and, thus, we concluded that hydrologic function is significantly degraded relative to its potential, and that the landscape may have reached a 'hydrologically dysfunctional' state (as defined by Thurow, 1991). This conclusion was reinforced by an examination of several of the dirt tanks (Figure 1), which showed signs of rapid sedimentation reflecting the high rates of soil erosion and which has serious implications for the community. Inferred and observed positive biophysical feedbacks between reduced infiltration, reduced plant production, degraded soil structure, and increased soil erosion are likely to exacerbate these problems in the future, even in the absence of socio-economic drivers.

In Figure 3, we present a conceptual model that highlights key ecohydrological indices of desertification for La Amapola. This model depicts hydrological connections (direct and indirect) between biophysical dimensions (depicted here as the 'state of the ecosystem') and socio-economic dimensions (the 'rural livelihoods') of La Amapola as well as key hydrological processes and functions that are crucial elements of both the natural ecosystem (e.g. rainfall, runoff, evapotranspiration) and the socio-economic system (e.g. drinking water, profit from crop yield, water for sanitation). This conceptual model combines basic tenets of the DDP (Table I) with the concept of 'sharing of water' between natural ecosystems and societal needs (Falkenmark, 2003; Wallace *et al*., 2003). This conceptual model reflects the fundamental importance of hydrology for both the social structure and economic productivity of rural communities like La Amapola. As water quality and quantity decline, human nutrition and health suffer. A less healthy population has less energy available to develop creative conservation strategies, resulting in a direct feedback between

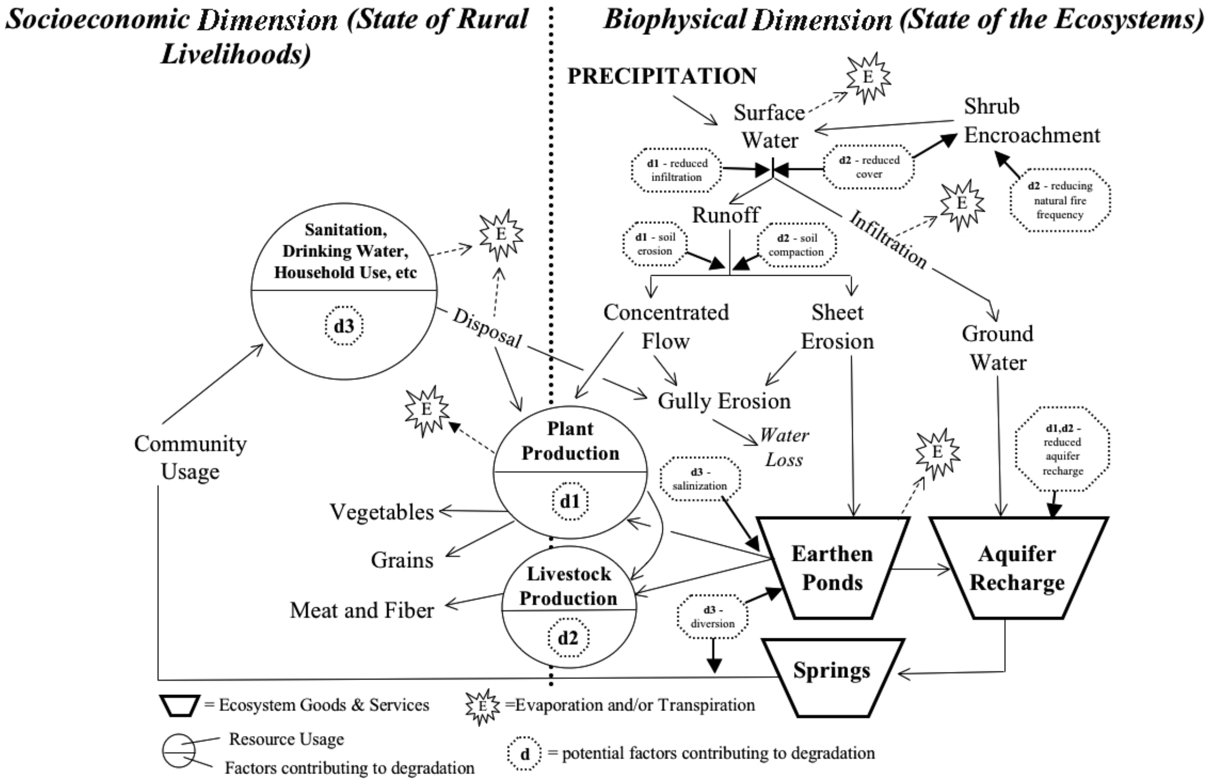

Figure 3. Conceptual model illustrating ecohydrological indices of desertification for La Amapola. On the basis of concepts of 'shared water' between society and nature (i.e. water is highlighted as the important 'ecosystem goods and services') and basic tenets of the DDP (Table I). We show plant (crop and grass biomass) and livestock production as 'shared' between the two dimensions because they are fundamentally biophysical processes that are controlled by human activities. Hydrological processes are highlighted to depict how biophysical–socio-economic systems are closely linked and constantly changing, and how land degradation has numerous ecohydrological implications

the two dimensions. Hence, understanding the balance and complexity of the various feedbacks of 'shared water' between society and nature is an important first step to avoid water shortages and undesirable environmental effects, especially given the cumulative impacts of those societal processes that lead to land degradation.

Though an oversimplification, the land uses associated with hydrologic degradation in La Amapola are shown as circles in Figure 3, which include plant production, livestock production, and various usages for human livelihood (e.g. drinking water, sanitation). Each of these land usages contribute to the hydrologically dysfunctional state of the landscape via a variety of processes associated with soil degradation (e.g. tillaging) (**d1**), overgrazing (e.g. removing biomass, soil compaction) (**d2**), and diverting water for other human uses (e.g. for drinking water, irrigation) (**d3**). Degradation of soil structure by repeated tillage and overgrazing by livestock is perhaps the most obvious, with numerous hydrologic implications, including the reduction of plant cover, soil compaction, reduced infiltration and increased runoff, soil erosion, and reduced aquifer recharge (Thurow, 1991) (Figure 3). Overgrazing may also contribute to shrub and tree encroachment by reducing natural fire frequency. In this environment, shrub and tree encroachment generally increases both runoff (Neave and Abrahams, 2002) and soil moisture heterogeneity (Breshears and Barnes, 1999); furthermore, in this precipitation zone, it may also reduce spring production and streamflow (Wilcox, 2002).

Of the changes in soil hydrology associated with soil structure degradation and soil cover reduction in La Amapola, soil erosion is perhaps the most significant. This is prominently illustrated by several large erosion gullies (Figure 1(c)), rills, and the loss of the soil surface horizon. Current soil erosion suggests continuing losses of organic matter, soil fertility, and soil water holding capacity. These effects are further exacerbated by increased soil erodibility associated with soil structure degradation through tillage, and reduced soil organic matter inputs associated with the removal of perennial plant cover and annual crop residues.

In La Amapola, large earthen dams are used to create several floodwater storage catchments, which collect runoff during rain events (Figure 1(b)). These 'water ponds', which are now accumulating sediment, are used for irrigating crops (during the rainy season, July–October) as well as for drinking water for animals. Irrigation at the scale practiced in La Amapola has potentially positive and negative effects. By increasing plant production, irrigation may reduce soil erosion and improve soil structure during the rainy season; however, some of the water is diverted from natural streams, with potentially negative effects and, characteristic of dryland regions, salinization is a potential concern (Wichelns, 1999). Overall, in La Amapola, there is relatively little irrigated land, so the impacts are likely to be minimal.

APPLYING THE DDP TO LA AMAPOLA

La Amapola serves as an excellent 'case study' to apply the DDP, as it is an area in which the biophysical limitations are characterized by significant changes in ecohydrology. It is located within a highly degraded landscape, both socio-economic and biophysical drivers are currently in force, water is crucial to agrarian livelihoods, and it is similar to many rural communities facing similar land degradation concerns worldwide. To apply the DDP, we examined the assertions (Table I) in the context of 'sharing of water' between local ecosystems and La Amapola's societal needs (sensu Falkenmark, 2003; Wallace *et al.*, 2003). However, some of the assertions, while conceptually robust and appealing, were especially difficult to evaluate for La Amapola because of a lack of quantitative data. Hence, much of what we present here is somewhat qualitative (and occasionally subjective), a reflection of the short time (5 days) available for the workshop and the paucity of scientific data for this isolated region of Mexico. Owing to limitations of space, the bulk of our discussion here is limited to assertions 1–4 of the DDP.

Coupled biophysical-socio-economic systems

Assertion #1 of the DDP embraces the definition of desertification used by the UNCCD (1994), which goes a step further by making it explicitly clear that while biophysical components of ecosystems and their properties are involved, 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. For La Amapola, we evaluated 'loss' in terms of the availability and utilization of water resources. The management of this landscape by the La Amapola community, which is accomplished by following established traditions that are mixed with various administrative mandates from local authorities (and national government programs), is a simple example of socio-economic dynamics. At the household level, individuals raise cattle, sheep, and goats primarily for supplemental income, while using a few for household consumption. For example, a herd of 80 goats corresponds to approximately 30 000 Mexican pesos (over 2700 US$, based on 30-kg-sized animals @ 14 pesos/kg). Given the poor range conditions, livestock are allowed to graze freely over large areas of the landscape (Figure 1), thus contributing to the redistribution of organic matter, plant propagules and nutrients (via grazing and dung deposition) between the various patch types (Figure 2). The direction and strength of such reciprocal interactions (at all scales shown in Table II) are directly controlled by both biophysical (e.g. rainfall) and socio-economic (e.g. individual households and/or the community may decide to exclude highly vulnerable areas from grazing) factors, reinforcing the overwhelming significance of assertion #1.

'Slow' and 'Fast' variables

The critical determinants of coupled human-environmental systems may consist of a relatively small number of 'slow' variables that are not sensitive to short-term events (Carpenter and Turner, 2000). Assertion #2 embraces the notion that identifying these slow variables, while extremely difficult, is important when studying land degradation in drylands. For example, the capacity of the landscape of La Amapola to maintain its biotic integrity and to produce different ecosystem services is strongly dependent upon a suite of 'slow' biophysical variables, including soil stability and depth, soil texture, soil fertility, plant species composition, and the structure and spatial pattern of the different patch types (Table III).

In contrast, 'fast' variables, such as grain yield, livestock production, and the water content of the soil, are variables that change too rapidly to be useful indicators of long-term trends or patterns. Nevertheless, as Stafford Smith and Reynolds (2002) argue, many efforts to respond to degradation are often distracted by the immediate effects of such short-term or 'fast' phenomena, especially drought, shortages in household income, and deaths of livestock, which often simply mirror the weather-driven noise. For example, crop production per La Amapola household is highly variable from year to year owing to fluctuations in annual precipitation. Bean production can change from essentially zero to three tons of grain per household per year, depending on the amount and seasonal distribution of rainfall. Not surprisingly, during years with high precipitation (and thus increased grass and forage production) farmers tend to increase the stocking rates of goats in order to secure immediate, short-term profits, but at the expense of long-term sustainability of the landscape.

Fernández *et al*. (2002) discuss various management scenarios that could potentially enable La Amapola households to balance 'slow' biophysical variables with 'fast'-changing economic variables. For example, during several years of above-average rainfall, a household with adequate resources (food, expendable cash to meet needs, equity, etc.) can limit the size of its herd and thus permit the perennial grass cover to expand; in contrast, another household in dire need of resources may be compelled to 'take advantage' of these favorable conditions and will add additional livestock so as to increase their short-term profit (as has been the case in La Amapola community between 2004 and 2005), but at the expense of long-term sustainability of the land. As acknowledged, identifying these slow variables is very difficult and, given the short time we spent in La Amapola, we are left to speculate as to what crucial, slow variables are governing the long-term dynamics of this system. It behooves us to mention that although an individual farmer in La Amapola is unlikely to think of these ecosystems in terms of 'slow' and 'fast' variables, the existence of LEK (assertion #7) undoubtedly suggests that certain elders likely possess deep understanding of their landscapes, and what to expect from year to year.

Thresholds

The Resilience Alliance and SFI (Santa Fe Institute) (2004) recently established an online database for documenting thresholds and regime shifts in linked social-ecological systems. This attests to the potential importance of thresholds, yet it also signifies the relative scarcity of supporting data and how difficult it is to quantify thresholds. The idea is that when a threshold is surpassed, the internal dynamics change (interactions, synergies, feedbacks, etc.) and the system moves into a new state or condition. As a heuristically powerful concept, biophysical and socio-economic thresholds are fundamental to the DDP (assertion #3). Obviously, in instances where thresholds may be important, a sound understanding of the structure and dynamics of a particular system is helpful. Since we presently lack such knowledge for the coupled social-ecological systems of La Amapola, our approach is to seek analogies from similar dryland regions. Once a set of plausible biophysical and socio-economic thresholds are identified, this can serve as the basis for further research.

For example, in the aforementioned online database, Meyers (2004) published a dataset characterizing thresholds and 'slow' biophysical variables for a rangeland site in northern Patagonia, which (as for La Amapola) consists of perennial grasses and shrubs. The list of slow variables include soil depth, soil fertility (in the areas that are not intensively cultivated), and seed bank, which play an important role in the balance between perennial grass cover, annual rainfall, and grazing by domestic livestock. The balance is upset if a certain threshold of grazing intensity is exceeded, which leads to destructive feedbacks involving reductions in grass cover, increase in bare soil, decrease in infiltration, increase in soil erosion, further reductions in grass

DOI: 10.1002/hyp

Table III. Examples of ‘fast’ and ‘slow’ variables affecting the ejido community of La Amapola. Based on Stafford Smith and Reynolds (2002) and references cited therein

	Variables	Fast	Slower	Slowest
Socio-economic Dimensions	Productivity of La Amapola household farm	Grain production	Livestock value	Genetic makeup of herd
	Community of Amapola	Number and distribution of households; size of communal herds	Government programs (installation of chicken farm, construction of earthen dams)	Organization of effective political organization
	Economy of household farm in La Amapola	Net disposable income	Interest rates	Capital wealth
	Socio-cultural elements within community	Emigration of families or younger generation	Social interactions beyond households, sharing of knowledge and decision making (e.g. recognition of and adaptation to negative changes)	Traditions, customs, LEK
	Economy of Mexico	Interest rates, national programs (PROCAMPO), economic opportunities	Export efficiency, NAFTA and importation policies	Market globalization
Biophysical Dimensions	Rangeland-pest dynamics	Insects	Foliage	Shrubs
	Rangeland soils and hydrology	Moisture content	Infiltration capacity	Water holding capacity
	Savannas	Annual grasses and forbs	Perennial grasses	Shrubs
	Rangeland-fire dynamics	Fuel moisture content	Fuel mass and structure	Shrub-grass balance

cover, and so forth. Since no specific value for threshold grazing intensity is given, we compare this to a case study of a semiarid grass-tree savanna in northeastern Australia, where grazing intensity must be closely managed to maintain a ground cover of perennial grasses at 60% or higher (Fernández *et al*., 2002). If the grass cover drops below this value, a key biophysical threshold is surpassed with potentially dire consequences, e.g. a complex of destructive feedbacks as described above. Whereas the Meyers (2004) dataset does not include socio-economic variables, the Fernández *et al.* (2002) study also provides an analysis of socio-economic slow variables and thresholds. Briefly, when equity ratios (an index that considers both debts and capital resources of a household) of households in this region of Australia drop below the threshold of about 80%, debts are difficult to service.

Restoration of the La Amapola landscape

The United States Commission on Immigration Reform (CIR) was created to study the effects of the Immigration Act of 1990, especially with regard to migration from Mexico to the United States. In an effort to elucidate the root causes of migration, the CIR commissioned several studies, all of which focused on land degradation in arid regions of Mexico (for details, see Schwartz and Notini, 1994; Natural Heritage Institute, 1997). Surveys of Mexican migrants working on U.S. farms revealed that many of them explicitly identified land degradation as a factor in their decision to migrate to the United States. Furthermore, many also expressed an interest in returning to their homeland if conditions could be improved. In view of this, is it possible to restore the degraded La Amapola landscape to a hydrologically functional condition? Of course, not only will the cost of intervention likely be very high, especially where degradation is as severe as in La Amapola, but also critical decisions will have to be made as to whether the system can, in fact, be 'recovered.' The complexity encompassed by such a challenge necessarily leads to the realization that coupled human-environment systems like the La Amapola case study are hierarchical (assertion #8) and highly dynamic (assertion #6), both of which are extremely important characteristics in attempting to understand linkages, feedbacks, and controls.

Its current condition suggests that numerous thresholds (biophysical and socio-economic, see Section Thresholds) have been surpassed. Are these thresholds reversible? A theoretical modelling study of desertification of a semiarid ecosystem by Reynolds *et al.* (1997) suggests that they are not. Using a biophysical landscape model, they found that when a certain threshold (the ratio of bare soil : grass : shrub cover) was surpassed, a series of destructive feedbacks ensued; that is, the loss of grass led to further losses, which immediately changed the spatial patterning of vegetation across the landscape, thereby impacting localized hydrology and thus increases in soil erosion and further losses of grass cover, and so forth. Once the threshold was surpassed, the overall trajectory of the ecosystem was irreversibly headed towards further degradation. Once soil is lost from the system, restoration becomes increasingly difficult and, in many cases, impractical (assertion #4). Of course, whether or not this applies to La Amapola is uncertain, but, superficially, many similarities exist.

A series of thresholds of differing magnitude (or importance) are considered key to the recovery of ecosystem functioning following disturbance (Archer, 1989; Whisenant *et al*., 1995; Hobbs and Norton, 1996; Reynolds *et al*., 1997; Fernández *et al*., 2002; Walker and Meyers, 2004). For example, from a biophysical perspective we rank the loss of topsoil in La Amapola as more significant than a switch from overland water flow to gully erosion; from a socio-economic perspective, we would rank a loss of social capital among neighbouring ejido communities as more significant than a reduction in a family's equity. While all of these are seminal events, the main point here is that some of these are easier to overcome than others, which leads to the next topic, the relationship between the state of the system and the cost of intervention (assertion #4).

Though there is extensive literature on restoration, relevant to this issue, we limit our discussion to the general framework of the DDP. In general, in La Amapola, as for most rural communities, as the degree of land degradation increases, the cost of intervention to 'recover' the system increases. Consequently, thresholds are key to assertion #4, representing a set of obstacles of increasing difficulty that prevent the system from returning to a less-degraded state without external inputs (Whisenant *et al*., 1995; Fernández *et al*., 2002). Some land degradation issues can be tackled with resources readily available at the household level, for example, by easing grazing pressure on certain pastures (as discussed above), by altering crop rotation practices, by consolidating loans (thereby reducing pressure to maximize land-use), and so forth. Some land degradation issues may require outside intervention at higher scales, e.g. neighbouring ejido communities, provincial or state intervention. An excellent example of this in the case of La Amapola is the construction of earthen dams (Figure 1). The decisions on dam location are made at the community level (Table II), yet without consultation or consideration of soil and land management issues because the prime purpose of the dams is livestock and crop production. In the case of La Amapola, building greater social capital among neighbouring communities can potentially reduce the transaction costs when one community must call on another for help. Although many traditional communities have such arrangements in place, these can be lost as a result of capitalization and emigration, and the cost of regenerating such relationships can be high, especially in sparsely populated areas. For the La Amapola landscape, outside intervention will be necessary, the costs are likely to be high, and only certain components of the system can be restored to a functional condition.

SUMMARY AND CONCLUSIONS

In this paper, we report on the findings from a workshop convened by the ARID*net* network on land degradation in La Amapola, a small rural community in the Central Plateau of Mexico. We focus on the intimate links that exist between desertification and the hydrological cycle. The variety of human activities that lead to land degradation in drylands also affect hydrology, which can negatively impact water resources and lead to crises in water availability. Although this is commonplace in the arid and semiarid regions of the globe, including the Americas, these problems are especially acute in Mexico.

Using the village of La Amapola as a case study, we present a simple conceptual model (Figure 3) that illustrates key ecohydrological indices of desertification. This model highlights the numerous connections (direct and indirect) between the biophysical 'state of the ecosystem' and the 'rural livelihoods' of individuals living there. Furthermore, since this conceptual model is based on (i) a partitioning of 'shared water' between society and nature (Wallace *et al*., 2003) and (ii) the (DDP, Table I), we consider this to be an essential component of an integrated analysis of desertification in this region of Mexico. Although specific details of the model will necessarily vary from location to location, the basic structure and model development process described can be generalized to other sites.

From our preliminary results we have developed several long-term goals, centered initially on assertions 1–3 of the DDP. These assertions stress that desertification always involves both human and environmental drivers, and that each household is involved in a complex interplay between multiple variables, bounded by biophysical and socio-economic thresholds. Our immediate goals in La Amapola, in support of developing an integrated assessment model to describe holistic, long-term change towards sustainable livelihoods, are as follows:

1. To quantify the 'slow' and 'fast' variables in our conceptual model depicting ecohydrological indices of desertification (Figure 3). Slow variables set the context, both biophysical and socio-economic, for elucidating all of the important linkages between land degradation and the hydrological cycle. There are many fast variables, such as grain yield, food reserves, and interest rates, that humans depend on in their daily lives and, while important, tend to confuse the strategic debate about land degradation and desertification (Stafford Smith and Reynolds, 2002). Efforts to map and respond to degradation that affects ecosystem goods and services are perpetually distracted by the immediate effects of short-term phenomena, such as drought, or annual variability in household income, and deaths of livestock, or fast variables, which often simply reflect short-term weather variability. In reality, droughts have their greatest effect on those

families that live on degraded landscapes but have no stored capital, whether social or economic; the same drought may hardly be noticed by rich farming families, who possess healthy pastures.

2. To quantify thresholds associated with the key ‘slow’ variables. Thresholds that define the boundaries of both socio-economic and biophysical sustainability may be amenable to intervention and, if understood appropriately, may be deliberately ‘expanded’ or ‘contracted’ (Fernández *et al*., 2002; Stafford Smith and Reynolds, 2002; Walker and Meyers, 2004). From a biophysical perspective, the threshold of perennial grass cover may change as a function of cycles of above- and below-average rainfall. From a socio-economic perspective, thresholds might change owing to changes in the social capital of a community or changes in outside aid (e.g. the addition of small chicken farms). Many possibilities exist, and it will be challenging to elucidate these.

In a post-workshop survey conducted in La Amapola on potential causes of land degradation, both young (mid-30s) as well as older (>70’s) generations attributed land degradation to a ‘lack of water’ and ‘changes in climate’, especially ‘higher frequencies of heavy rainfall’ and ‘overall decreased soil water holding capacity’. Interestingly, none of the interviewed households associated land degradation to livestock and overgrazing. In a community such as La Amapola, it is important that we elucidate not only both the range of conditions in which people are able to persist (the boundaries of sustainability defined by biophysical and socio-economic thresholds) but also the underlying cultural and economic drivers, including LEK and education, and changes in the global economy and local linkages with it. The interplay between biophysical and socio-economic variables is highly dynamic, non-linear, and challenging to quantify.

Our attempt to apply the DDP to La Amapola offers an excellent opportunity to develop a research and restoration agenda for the region. In our conceptual model, which illustrates key ecohydrological indices of desertification for La Amapola (Figure 3), hydrological functions are shown as crucial elements of both the natural ecosystem (e.g. rainfall, runoff, evaporation) and the socio-economic system (e.g. drinking water, profit from crop yield, water for sanitation). The numerous feedbacks, linkages, and causal pathways between the biophysical and human dimensions suggest that hydrology is the fundamental component of the livelihoods of rural communities in this region of Mexico, and thus it is of central importance when evaluating desertification.

ACKNOWLEDGEMENTS

The authors thank two anonymous reviewers for helpful criticism on the manuscript. This research was supported by the National Science Foundation under Grant No. 0234186 (ARID*net*) and the Center for Integrated Study of the Human Dimensions of Global Change, through a cooperative agreement between the National Science Foundation (SBR-9521914) and Carnegie Mellon University. EHS acknowledges support by SEMARNAT (FOSEMARNAT 2004-410). FTM acknowledges support via a Fulbright fellowship from the Spanish Ministry of Education and Science, funded by Secretaría de Estado de Universidades and Fondo Social Europeo. JFR acknowledges support by the Humboldt Foundation (Bonn) and the Department of Plant Ecology, University of Bayreuth, during the preparation of this manuscript. Lastly, we thank all participants of the La Amapola ARID*net* workshop for their contributions to the ideas presented in this paper.

REFERENCES

Aide TM, Grau HR. 2004. Globalization, migration, and Latin American ecosystems. *Science* **305**: 1915–1916.

Alcorn JB, Toledo VM. 2002. Resilient resource management in Mexico’s forest ecosystems: the contribution of property rights. In *Linking Social and Ecological Systems. Management Practices and Social Mechanisms for Building Resilience*, Berkes F, Folke C (eds). Cambridge University Press: Cambridge; 216–249.

Archer S. 1989. Have southern Texas savannas been converted to woodlands in recent history? *American Naturalist* **l34**: 545–561.

Bahre CJ. 1991. *A Legacy of Change*. University of Arizona Press: Tucson, AZ.

Breshears DD, Barnes FJ. 1999. Interrelationships between plant functional types and soil moisture heterogeneity for semiarid landscapes within the grassland/forest continuum: a unified conceptual model. *Landscape Ecology* **14**: 465–478.

DOI: 10.1002/hyp

Busso CA. 1997. Towards an increased and sustainable production in semi-arid rangelands of central Argentina: two decades of research. *Journal of Arid Environments* **36**: 197–210.

Carpenter SR, Turner MG. 2000. Hares and tortoises: interactions of fast and slow variables in ecosystems. *Ecosystems* **3**: 495–497.

Deininger K, Bresciani F. 2001. *Mexico's Ejido Reforms: their impacts on factor market participation and land access*, Unpublished Report, The World Bank: Washington, DC.

Duda AM. 2003. Integrated management of land and water resources based on a collective approach to fragmented international conventions. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* **358**: 2051–2062.

Escurra E, Montaña C. 1990. Los recursos naturales renovables en el norte árido de México. In *Medio Ambiente y Desarrollo*, Vol. 1, Leff E (ed). Centro de Investigaciones Interdisciplinarias en Humanidades, UNAM: Porrúa, México.

Falkenmark M. 2003. Freshwater as shared between society and ecosystems: from divided approaches to integrated challenges. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* **358**: 2037–2049.

Fernández R, Archer ERM, Ash AJ, Dowlatabadi H, Hiernaux PHY, Reynolds JF, Vogel CH, Walker BH, Wiegand T. 2002. Degradation and recovery in socio-ecological systems: a view from the household/farm level. In *Do Humans Create Deserts? The Ecological, Meteorological, and Human Dimensions of Global Desertification*, Reynolds JF, Stafford Smith M (eds). Dahlem University Press: Berlin; 297–323.

Geist HJ, Lambin EF. 2004. Dynamic causal patterns of desertification. *BioScience* **54**: 817–829.

Gutiérrez JR. 1993. The effect of water, nitrogen, and human-induced desertification on the structure of ephemeral plant communities in the Chilean coastal desert. *Revista Chilena De Historia Natural* **66**: 337–344.

Hobbs RJ, Norton DA. 1996. Towards a conceptual framework for restoration ecology. *Restoration Ecology* **4**: 93–110.

INEGI. 2000. *Anuario Estatistico De San Luis Potosi. Edicion 2000*. Talleres Del INEGI: Aguascalientes, Ags.

Jackson RB, Carpenter SR, Dahm CN, McKnight DM, Naiman RJ, Postel SL, Running SW. 2001. Water in a changing world. *Ecological Applications* **11**: 1027–1045.

Khagram S, Clark WC, Raad DF. 2003. From the environment and human security to sustainable security and development. *Journal of Human Development* **4**: 289–313.

LaBaume JT, Dahl BE. 1986. Communal grazing: the case of the Mexican *ejido*. *Journal of Soil and Water Conservation* **41**: 24–27.

Lopez-Ocaña C. 1996. Effectiveness of international regimes dealing with desertification from the perspective of the South. In *Global Environmental Change and International Governance*, Young OR, Demko GJ, Ramakrishna K (eds). University Press of New England: Hanover; 125–135.

Manzano MG, Návar J, Pando-Moreno M, Martínez A. 2000. Overgrazing and desertification in northern Mexico: highlights on northeastern region. *Annals of Arid Zone* **39**: 285–304.

McCarty N, De Janvri A, Sadoulet E. 1998. Land allocation under dual individual-collective use in Mexico. *Journal of Development Economics* **56**: 239–264.

Meyers J. 2004. Rangeland change, Northern Patagonia, Argentina. Resilience Alliance. (Online.) URL: http://resalliance.org/ev_en.php?ID=2497_201&ID2=DO_TOPIC.

Middleton NJ, Thomas DSG (eds). 1997. *World Atlas of Desertification*. U.N. Environment Programme, Edward Arnold: New York; 192.

Natural Heritage Institute, 1997. Breaking the cycle: desertification and migration on the U.S.-Mexico Border. *Environmental Degradation and Migration: The U.S./Mexico Case Study*, Executive Summary of a Report to the U.S. Commission on Immigration Reform. Available at: http://www.n-h-i.org/Projects/PeopleGlobalResources/PeopleDryland/US_Mexico.html. Natural Heritage Institute: San Francisco, CA.

Neave M, Abrahams AD. 2002. Vegetation influences on water yields from grassland and shrubland ecosystems in the Chihuahuan Desert. *Earth Surface Processes and Landforms* **27**: 1011–1020.

Pyke DA, Herrick JE, Shaver PL, Pellant M. 2002. Rangeland health attributes and indicators for qualitative assessment. *Journal of Range Management* **55**: 584–597.

Resilience Alliance and Santa Fe Institute. 2004. Thresholds and alternate states in ecological and social-ecological systems. Resilience Alliance. (Online.) URL: http://resalliance.org/ev_en.php?ID=2497_201&ID2=DO_TOPIC.

Reynolds JF. 2001. Desertification. In *Encyclopedia of Biodiversity*, Vol. 2, Levin S (ed). Academic Press: San Diego, CA; 61–78.

Reynolds JF, Wu JG. 1999. Do landscape structural and functional units exist? In *Integrating Hydrology, Ecosystem Dynamics, and Biogeochemistry in Complex Landscapes*, Tenhunen JD, Kabat P (eds). John Wiley and Sons: Chichester; 275–298.

Reynolds JF, Stafford Smith DM. 2002a. Do humans cause deserts? In *Global Desertification: Do Humans Cause Deserts?* Reynolds JF, Stafford Smith DM (eds). Dahlem University Press: Berlin; 1–21.

Reynolds JF, Stafford Smith DM (eds). 2002b. *Global Desertification: Do Humans Cause Deserts?* Dahlem University Press: Berlin; 437.

Reynolds JF, Virginia RA, Schlesinger WH. 1997. Defining functional types for models of desertification. In *Plant Functional Types: Their Relevance to Ecosystem Properties and Global Change*, Smith TM, Shugart HH, Woodward FI (eds). Cambridge University Press: Cambridge; 194–214.

Reynolds JF, Stafford Smith DM, Lambin EF. 2003. ARID*net*: Seeking novel approaches to desertification and land degradation. *IGBP Global Change Newsletter* **54**: 5–9, (PDF available at: http://www.igbp.kva.se).

Reynolds JF, Maestre FT, Huber-Sannwald E, Herrick J, Kemp PR. 2005. Aspectos socioeconómicos y biofísicos de la desertificación. *Ecosistemas* URL: http://www.revistaecosistemas.net/pdfs/131.pdf.

Ripl W. 2003. Water: the bloodstream of the biosphere. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* **358**: 1921–1934.

Sanderson SRW. 1984. *Land Reform in Mexico: 1910–1980*. Academic Press: New York.

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

Schwartz L, Notini J. 1994. *Desertification and Migration: Mexico and the United States*. Research Paper. The U.S. Commission on Immigration Reform: Washington, DC.

SEMARNAT. 2003. *Secretaria De Medio Ambiente y Recursos Naturales. Evaluación de la degradación del suelo causada por el hombre en la Republica Mexicana*. Publicaciones Diamante: San Vicente Chicoloapan, Edo. de Mexico.

Stafford Smith DM, Reynolds JF. 2002. The Dahlem desertification paradigm: a new approach to an old problem. In *Global Desertification: Do Humans Cause Deserts?* Reynolds JF, Stafford Smith DM (eds). Dahlem University Press: Berlin; 403–424.

Stafford Smith DM, Reynolds JF. 2003. The interactive role of human and environmental dimensions in the desertification debate. *Annals of Arid Zone* **42**: 255–270.

Thomas DSG. 1997. Science and the desertification debate. *Journal of Arid Environments* **37**: 599–608.

Thurow TL. 1991. Hydrology and erosion. In: *Grazing Management: An Ecological Perspective*, Heitschmidt RK, Stuth JW (eds). Timber Press: Portland, OR; 141–159.

UNCCD. United Nations Convention to Combat Desertification, Intergovernmental Negotiating Committee For a Convention to Combat Desertification. 1994. *Elaboration of an International Convention to Combat Desertification in Countries Experiencing Serious Drought and/or Desertification*, *Particularly in Africa. U.N. Doc. A/AC.241/27, 33 I.L.M. 1328*. United Nations: New York.

UNEP. 1992. *United Nations Environmental Programme, World Atlas of Desertification*, Editorial commentary by Middleton N, Thomas DSG. Edward Arnold Publishers: London.

United Nations. 1994. *Earth Summit. Convention on desertification. United Nations conference on environment and development, Rio de Janeiro, Brazil, 3–14 June 1992*, Report No. DPI/SD/1576, United Nations, New York.

United Nations. 2003. *Water for People, Water for Life. World Water Development Report*. UNESCO Publishing: Barcelona.

Villers-Ruíz L, Trejo-Vázquez I. 1998. Climate change on Mexican forests and natural protected areas. *Global Environmental Change-Human and Policy Dimensions* **8**: 141–157.

Walker BH, Meyers JA. 2004. Thresholds in ecological and social—ecological systems: a developing database. *Ecology and Society* **9**: 3, [online] URL: http://www.ecologyandsociety.org/vol9/iss2/art3.

Wallace JS, Acreman MC, Sullivan CA. 2003. The sharing of water between society and ecosystems: from conflict to catchment-based co-management. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* **358**: 2011–2026.

Whisenant SG, Thurow TL, Maranz SJ. 1995. Initiating autogenic restoration on shallow semiarid sites. *Restoration Ecology* **3**: 6167, [2129].

Wichelns D. 1999. An economic model of waterlogging and salinization in arid regions. *Ecological Economics* **30**: 475–491.

Wilcox BP. 2002. Shrub control and streamflow on rangelands: a process based viewpoint. *Journal of Range Management* **55**: 318–326.

World Water Assessment Programme. 2005. UNESCO, New York, http://www.unesco.org/water/wwap/description/index.shtml.

DOI: 10.1002/hyp