Dynamic Causal Patterns of Desertification

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*Using a meta-analytical research design, we analyzed subnational case studies (*n *= 132) on the causes of dryland degradation, also referred to as desertification, to determine whether the proximate causes and underlying driving forces fall into any pattern and to identify mediating factors, feedback mechanisms, cross-scalar dynamics, and typical pathways of dryland ecosystem change. Our results show that desertification is driven by a limited suite of recurrent core variables, of which the most prominent at the underlying level are climatic factors, economic factors, institutions, national policies, population growth, and remote influences. At the proximate level, these factors drive cropland expansion, overgrazing, and infrastructure extension. Identifiable regional patterns of synergies among causal factors, in combination with feedback mechanisms and regional land-use and environmental histories, make up specific pathways of land change for each region and time period. Understanding these pathways is crucial for appropriate policy interventions, which have to be fine-tuned to the region-specific dynamic patterns associated with desertification.*

Keywords: desertification, dryland degradation, feedbacks, pathways, causes

The causes of dryland degradation, also referred to as desertification, remain controversial (Helldén 1991, Thomas 1997, Lambin et al. 2001). Local- to national-scale studies demonstrate the importance and socioecological significance of the process, but land-cover change in dryland ecosystems is poorly documented at the global scale, and its causes are not fully understood (Reynolds and Stafford Smith 2002, Lambin et al. 2003). The most authoritative definition of *desertification* remains that of the Convention to Combat Desertification: "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities" (UNEP 1994). The two major, mutually exclusive—and still unsatisfactory—explanations for desertification are single-factor causation and irreducible complexity. On the one hand, proponents of single-factor causation suggest various primary causes, such as growing populations in fragile semiarid ecosystems and irrational or unwise land management by nomadic pastoralists. Central to this understanding is the overworking of land by ever-increasing numbers of the rural poor. In its extreme form, the theory of single-factor causation leads to the notion of "man-made deserts" (i.e., the human-driven, irreversible extension of desert landforms and landscapes; Breckle et al. 2002, Le Houérou 2002). On the other hand, desertification has been attributed to multiple causative factors that are specific to each locality, revealing no distinct pattern (Dregne 2002, Warren 2002). There is a great deal of debate, not only on whether the causes of desertification lie in the socioeconomic or biophysical sphere (human-induced land degradation versus climate-driven desiccation) but also on the degree to which these causes are local or remote, and on how variables interact across organizational levels in different regions of the world and at different time periods (Pickup 1998, Lambin et al. 2002, Reynolds and Stafford Smith 2002).

In addition to chronicling the struggle to arrive at an agreed-upon understanding of the causes of desertification, the literature is rich in local case studies investigating the causes and processes of dryland change in specific localities. Our aim in this article is to preserve the descriptive richness of these local case studies while using them to generate a general understanding of the proximate causes and underlying driving forces of desertification, including cross-scalar interactions of causes and feedbacks. *Proximate causes* are human activities or immediate actions at the local level, such as cropland expansion, that originate from intended land use and directly affect dryland cover. *Underlying driving forces* are fundamental social and biophysical processes, such as human population dynamics or agricultural policies, that underpin the proximate causes and either operate at the local level or reflect influences at the national or global level. Mediating factors, such as wealth or access to resources, may shape or modify the interplay between these two broad groups of causative factors. Social and ecological responses to land-cover changes may create feedbacks that amplify or dampen land-use and land-cover change.

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We identified typical pathways of dryland change, defined as particular chains of events and sequences of cause and effect resulting in specific outcomes of desertification. These outcomes include decreases in vegetation cover; exposure of bare, rocky ground; increases in sand cover; and salinization. Pathways are made up of initial conditions, causes, and feedbacks. The environmental and land-use history of each region defines the initial conditions for each subsequent round of land use and ecosystem change (Foster et al. 2003, Lambin et al. 2003).

We analyzed the frequency of proximate causes and underlying driving forces of desertification, including their interactions with one another and their feedbacks on land use, as reported in 132 subnational case studies. Our results show that desertification is driven by a limited suite of recurrent core variables, of which the most prominent at the underlying level are climatic factors, economic factors, institutions, national policies, population growth, and remote influences. At the proximate level, these factors drive the expansion of cropland (at the expense of grazing land and natural grassland, thus leading to overstocking) and infrastructure. Regional patterns of causal-factor synergies, in combination with feedback mechanisms and regional land-use and environmental histories, make up specific pathways of land change that can be identified for a given region and time period. Understanding these pathways of dryland change is crucial for designing appropriate policy interventions. To achieve sustainable management of dryland ecosystems, interventions have to be fine-tuned to the region-specific dynamic patterns associated with desertification (Lambin et al. 2001, 2003).

Data analysis

We analyzed case studies on the causes of desertification ($n = 132$) to determine whether the proximate causes and underlying driving forces of dryland degradation fall into any pattern, using a configurational comparative research design (Ragin 1989, Matarazzo and Nijkamp 1997). This method of comparative meta-analytical research focuses on configurations of causally relevant characteristics of diverse, but substantively defined and intentionally selected cases that do not differ greatly from one each other with respect to the outcome that is being investigated (desertification). It aims at identifying cross-case pathways of causation by taking a middle way between qualitative case study and quantitative, variable-oriented research.

The study areas ranged from a small (1-hectare) site to a multiprovince area, and the cases spanned time periods from 1700 to 2000, with 1915 to 1994 being the mean period. The 132 cases of desertification were taken from 54 articles published in 28 journals covered by the citation index of the Institute for Scientific Information. We used five criteria for selecting case studies: (1) sites in human use (i.e., no "wilderness areas"); (2) in-depth field investigations; (3) consideration of clearly named factors as potential causes of desertification, including basic features of the socioeconomic setting and the natural resource endowment; (4) investigation methods that included quantitative data, particularly for assessing the rates of land change; and (5) absence of obvious disciplinary bias. We assumed that each study revealed the actual causes of desertification in the study area. Therefore, our comparative analysis of cases evaluates which causal patterns associated with desertification are most often found in different dryland regions of the world. The complete list of case studies and details of the method are given in Geist (2004), including a discussion of the limitations of the meta-analysis. For example, using *desertification* as the sole search term in identifying case studies, and not other terms such as *land degradation,* may have led us to include relatively more severe cases of dryland degradation and relatively more authors who hold a more deterministic view of the issue. We may thus have excluded relatively more cases exhibiting the complex and nonequilibrium dynamics of coupled human-environmental systems.

We identified four broad clusters of proximate causes: agricultural activities, infrastructure extension, wood extraction (and related activities), and increased aridity. Each category of proximate causation was subdivided; for example, infrastructure extension included the extension of irrigation works, human settlements, and road networks, while agricultural activities were divided into livestock and crop production. Livestock production was further subdivided into nomadic grazing, extensive grazing, and intensive livestock production; crop production was subdivided into annual, perennial, and wetland or irrigation cropping. Underlying driving forces were grouped in six broad clusters of factors (climatic, demographic, policy or institutional, economic, technological, and cultural or sociopolitical). Each category was subdivided into specific factors; for example, cultural or sociopolitical factors were partitioned into (a) public attitudes, values, and beliefs and (b) individual and household behavior (figure 1; Turner et al. 1995, Nicholson 2002, Lambin et al. 2003, Mooney et al. 2003).

Causal factors were quantified by determining the most frequent proximate and underlying factors reported in the case studies. The major interactions and feedback processes among these factors were also identified to reveal the system dynamics that commonly lead to desertification. Three modes of causation were distinguished: single-factor causation (one individual underlying factor driving one or more proximate factors), chain-logical causation (several interlinked factors in combination, leading to desertification), and concomitant occurrence (independent, separate operation of factors causing desertification). Results were broken down by broad geographical dryland regions (Middleton and Thomas 1997, Reynolds and Stafford Smith 2002). Dryland cases from Asia ($n = 51$) stemmed from the Central Asian desert and steppe region, the East Mediterranean steppe zone, the Arabian Peninsula, and the Thar Desert in India. African cases ($n = 42$) originated from the Sahelian and Sudano-Sahelian zones of West Africa, the western Mediterranean Basin (North Africa), the East African grassland zone, and the Kalahari steppe in southern Africa. European dryland cases stemmed exclu-

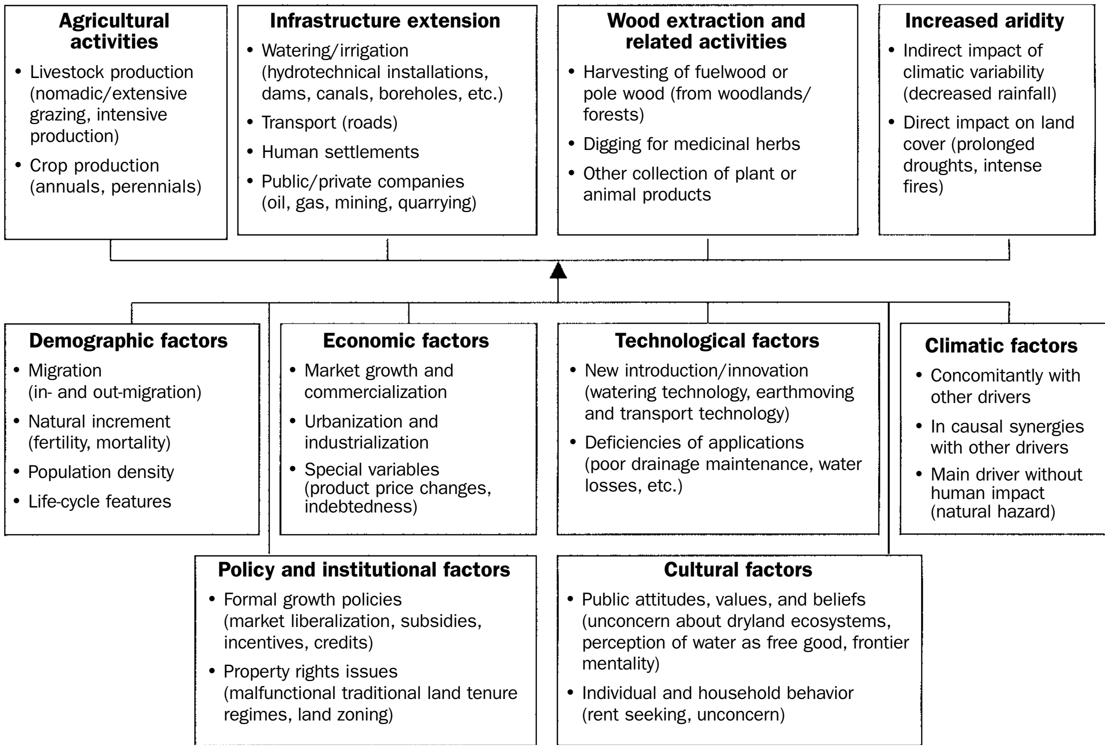

Figure 1. Causes of desertification. Six broad clusters of underlying driving forces (fundamental social or biophysical processes) underpin the proximate causes of desertification, which are immediate human or biophysical actions with a direct impact on dryland cover.

sively from the northern Mediterranean basin (*n* = 13) and Australian cases from the central part of the continent (*n* = 6). In the United States and Latin America, cases originated from the US Southwest (*n* = 6) and from Latin American sites (*n* = 14) in Mexico and Patagonia. A causative factor, or factor combination, was called "robust" if it showed little regional variation across major dryland regions.

Sites under study fell into a wide range of initial ecological and climatic conditions. Annual rainfall ranged from less than 50 millimeters (mm) in hyperarid basins or plains to more than 500 mm in subhumid mountain sites. Some sites were characterized by a uniform permafrost soil or fossil sand dune coverage, while others featured loamy, loessial, sandy, skeletal (gravel, stone-mantled), or clay soils. At some sites, the area of eroded, bare, rocky ground cover increased gradually, at an annual rate of about 1%, while at other sites it increased far more rapidly (Geist 2004).

Causes and pathways of desertification

Tables 1 through 4 list the proximate causes and underlying driving forces of desertification, broken down by broad geographical regions or subcontinents. They show the frequency of each causative variable reported in the case studies, both as an absolute number and as a relative percentage. Results are given in order of decreasing importance; factors that occurred in less than 25% of the cases are not reported. Tables 1 and 3 give only the broad clusters of proximate causes and underlying driving forces; tables 2 and 4 provide a detailed breakdown of these broad clusters into specific factors.

Proximate causes. At the proximate level, desertification is best explained by the combination of multiple and coupled social and biophysical factors rather than by single variables. Dominating the broad clusters of proximate factors is the combination of agricultural activities, increased aridity, extension of infrastructure, and wood extraction (or related extractional activities), with clear regional variations. In particular, agricultural activities and increased aridity form a robust combination, although one that often occurs with other proximate causes (table 1).

Agricultural activities or agrarian land uses are the leading proximate cause associated with nearly all cases of desertification (95%). They include extensive grazing, nomadic grazing (pastoralism), and annual cropping (table 2). Extensive livestock production, carried out under the mode of either sedentary or transhumant (seasonal nomadic) husbandry, displays low geographical variation as a cause of desertification. In contrast, activities of pastoral nomadic groups feature exclusively Asian and African cases and are reported as causing desertification only half as often as extensive grazing. Livestock production slightly outweighs crop production as a cause of desertification, but both activities remain intricately interlinked in most cases. The exceptions are the US Southwest, Latin America (Patagonia), and the Australian dry-

Table 1. Frequency of broad clusters of proximate causes in desertification, by number and relative percentage.

	All cases (*n* = 132)		Asia (*n* = 51)		Africa (*n* = 42)		Australia (*n* = 6)		Europe (*n* = 13)		United States (*n* = 6)		Latin America (*n* = 14)	
Cause	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**
Single factor														
Agriculture	7	5	6	12	1	2	0	–	0	–	0	–	0	–
Increased aridity	7	5	0	–	6	14	0	–	1	8	0	–	0	–
Infrastructure extension	0	–	0	–	0	–	0	–	0	–	0	–	0	–
Wood-related extraction	0	–	0	–	0	–	0	–	0	–	0	–	0	–
Two factors														
Agriculture, increased aridity	34	26	6	12	10	24	0	–	8	62	3	50	7	50
Agriculture, infrastructure extension	4	3	2	4	2	5	0	–	0	–	0	—	0	—
Three factors														
Agriculture, infrastructure extension, increased aridity	27	20	9	18	9	21	6	100	1	8	1	17	1	7
Agriculture, wood-related extraction, increased aridity	15	11	3	6	10	24	0	–	1	8	0	–	1	7
Agriculture, wood-related extraction, infrastructure extension	7	5	1	2	0	–	0	–	1	8	0	–	5	36
Four factors														
Agriculture, increased aridity, infrastructure extension, wood-related extraction	31	23	24	47	4	10	0	–	1	8	2	33	0	–
Total	132	98[a]	51	101[a]	42	100	6	100	13	102[a]	6	100	14	100

No., absolute number; %, relative percentage.
a. Does not total 100 because of rounding.

lands, where cropping is of little or no importance, either as land use or as a cause of desertification. In most cases, agricultural expansion into marginal rangeland areas during wet periods leaves farmers more seriously exposed to hazard when drought returns than pastoralists would have been (Glantz 1994). In fact, sedentary annual cropping is reported three times more frequently as a cause of desertification (44%) than other modes of cropping, such as wetland farming or cultivation of perennials (15% for all regions). In other cases, cropland expansion on areas previously used for pastoral activities leads to overstocking on the remaining, reduced rangeland, triggering soil degradation at sites that are not suitable for permanent agriculture.

Increased aridity is a robust proximate cause of desertification, both indirectly through greater rainfall variability and directly through prolonged droughts. Not only decreased annual precipitation but also warmer climate conditions, in combination with extreme weather events (attributed by several authors to global climate change), are chiefly characteristic of Asia. Among the other effects of increased aridity on land cover are changes in fire regimes (mainly increased fire frequencies) and greater soil erosion triggered by more frequent oscillations between warmer, drier conditions and cooler, more humid conditions. However, these effects are reported as causes of desertification only one-third as often as prolonged drought periods.

The extension of infrastructure associated with desertification is frequent mainly in cases from Asia, Africa, and Australia. Desertification is most often linked to the development of water-related infrastructure for cropland irrigation and pasture development (reservoirs, dams, canals, boreholes, and pump stations), leading to a decrease in livestock mobility (Niamir-Fuller 1999). In Asia and Africa, the buildup of irrigation infrastructure is associated with expanding human settlements, following an increase in food production and food security. Other infrastructure components, such as road extension, oil and gas industry facilities, mining, and quarrying, are far less frequently reported. The extraction of wood (fuelwood, pole wood, charcoal) from forests and woodlands is reported to influence desertification in less than half of the cases.

Among the detailed categories of proximate causes of dryland degradation for all regions, the combination of extensive livestock production, increased aridity, production of annual crops, and water-technology extension stands out. Contrary to widely held views, the evidence of these case studies suggests that overstocking is not the primary cause of desertification, but happens when cropland expands onto rangelands. The evidence also suggests that nomadic pastoralism and households' harvesting of fuelwood for domestic purposes are not the only major agents of dryland degradation.

Underlying driving forces. At the underlying level, desertification is best explained by regionally distinct combinations of multiple, coupled social and biophysical factors and drivers acting synergistically, rather than by single-factor causation. In more than half of the cases, desertification was

Table 2. Frequency of specific proximate causes in desertification, by number and relative percentage.

	All cases (*n* = 132)		Asia (*n* = 51)		Africa (*n* = 42)		Australia (*n* = 6)		Europe (*n* = 13)		United States (*n* = 6)		Latin America (*n* = 14)	
Cause	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**
Agricultural activities	125	95	51	100	36	86	6	100	13	100	5	83	14	100
Livestock production	98	74	36	71	32	76	6	100	7	54	5	83	12	86
Extensive grazing	74	56	23	45	26	62	6	100	7	54	5	83	7	50
Nomadic grazing	38	29	28	55	10	24	0	–	0	–	0	–	0	–
Crop production	78	59	40	78	20	48	5[a]	83[a]	10	77	1	17	2	14
Annual cropping	58	44	24	47	17	40	5	83	9	69	1	17	2	14
Increased aridity	114	86	42	82	39	93	6	100	12	92	6	100	9	64
Indirect impact of climatic variability	63	48	25	49	27	64	1	17	7	54	2	33	1	7
Increased precipitation deficit	37	28	3	6	24	57	1	17	7	54	1	17	1	7
Warmer, drier, more storms, and so on[b]	34	26	23	45	5	12	0	–	4	31	2	33	0	–
Direct influence on surface vegetation	62	47	17	33	21	50	5	83	6	46	5	83	8	57
Prolonged droughts	42	32	17	33	20	48	0	–	0	–	3	50	2	14
Infrastructure extension	73	55	36	71	20	48	6	100	3	23	2	33	6	43
Water technology, irrigation infrastructure	53	40	24	47	17	40	6	100	0	–	0	–	5	36
Residential infrastructure, human settlements	43	33	26	51	14	33	0	–	1	8	2	33	0	–
Wood extraction	59	45	31	61	17	40	0	–	4	31	1	17	6	43
Extraction from forests or woodlands	56	42	29	57	17	40	0	–	3	23	1	17	6	43

No., absolute number; %, relative percentage.

Note: Multiple counts are possible; percentages are related to the total of all cases for each category.

a. Cropping on an intermittent basis only at the semiarid fringe.

b. Including more droughts, more dust emissions, shifts of winter rainfall season (in low-latitude drylands), less snow cover, withdrawing glaciers, and alteration of freeze-thaw soil processes (in high-latitude drylands).

driven by the interplay of four to six factors (table 3). A recurrent and robust combination of driving forces—though differing widely in the range of specific factors involved—includes climatic factors leading to reduced rainfall, agricultural growth policies, newly introduced land-use technologies, and land-tenure arrangements that are no longer suited to contemporary dryland ecosystem management.

Climatic factors, mainly associated with a decrease in rainfall (reduced by as much as 1.5% annually over the last quarter of the 20th century in southern Africa), are prominent underlying driving forces of desertification (86%). They operate either indirectly, through changes in land use resulting from variation in rainfall (during dry years, annual precipitation deviates from the long-term average by as much as 80% at some locations in the western Kalahari steppe), or directly, affecting land cover in the form of prolonged droughts (such as the 1960–1990 period in semiarid parts of the Sudan, with the length of the wet season contracting by 1.5% on average per year). Although more than one-third of the studies mention climatic influences but fail to explicitly describe them, the most widespread mode of causation is reported to be climatic conditions operating concomitantly or synergistically with socioeconomic driving forces, such as technological changes (42%; table 4). Meteorological conditions are also part of feedback loops related to desertification (discussed below).

In many cases (69%), technological factors are robust drivers of desertification (table 4). Most strikingly, technological innovations are reported to be associated with desertification as frequently as are deficiencies of technological applications. Innovations mainly comprise improvements in land and water management through motor pumps and boreholes (at the village level) or through the construction of hydrotechnical installations such as dams, reservoirs, canals, collectors, and artificial drainage networks (for large-scale irrigation schemes). When applied, these developments are often coupled with high water losses due to poor maintenance of the infrastructure, especially in the Asian studies. In addition, they easily induce fundamental and often irreversible changes to the natural hydrographic network, altering hydrological cycles in most cases. The disaster of the Aral Sea is an extreme case of such perturbations (Saiko and Zonn 2000). Technological applications associated with desertification also include transport and earthmoving techniques (trucks, tractors, caterpillar-tracked vehicles) and new processing and storage technologies (refrigeration containers on ships and trucks). These innovations can trigger rapid increases in production at remote sites (e.g., greater numbers

Table 3. Frequency of broad underlying driving forces in desertification, by number and relative percentage.

	All cases (*n* = 132)		Asia (*n* = 51)		Africa (*n* = 42)		Australia (*n* = 6)		Europe (*n* = 13)		United States (*n* = 6)		Latin America (*n* = 14)	
Cause	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**
Single factor														
Clim	7	5	0	–	6	14	0	–	1	8	0	–	0	–
Inst	5	4	0	–	0	–	0	–	0	–	0	–	5	36
Econ	0	–	0	–	0	–	0	–	0	–	0	–	0	–
Tech	0	–	0	–	0	–	0	–	0	–	0	–	0	–
Cult	0	–	0	–	0	–	0	–	0	–	0	–	0	–
Pop	0	–	0	–	0	–	0	–	0	–	0	–	0	–
Two factors														
Pop–clim	10	8	0	–	10	24	0	–	0	–	0	–	0	–
Tech–clim	9	7	0	–	0	–	1	17	6	46	2	33	0	–
Econ–tech	2	2	2	4	0	–	0	–	0	–	0	–	0	–
Econ–inst	2	2	0	–	2	5	0	–	0	–	0	–	0	–
Cult–clim	1	1	1	2	0	–	0	–	0	–	0	–	0	–
Three factors														
Tech–inst–clim	4	3	0	–	4	10	0	–	0	–	0	–	0	–
Pop–tech–inst	4	3	3	6	0	–	0	–	1	8	0	–	0	–
Pop–econ–clim	2	2	0	–	2	5	0	–	0	–	0	–	0	–
Econ–tech–clim	2	2	0	–	1	2	0	–	0	–	1	17	0	–
Tech–cult–clim	2	2	0	–	2	5	0	–	0	–	0	–	0	–
Pop–cult–clim	3	2	1	2	0	–	0	–	1	8	1	17	0	–
Four factors														
Econ–tech–inst–clim	6	5	3	6	0	–	0	–	0	–	0	–	3	21
Pop–econ–inst–clim	4	3	3	6	1	2	0	–	0	–	0	–	0	–
Tech–inst–cult–clim	3	2	0	–	2	5	0	–	0	–	1	17	0	–
Pop–tech–inst–clim	5	4	1	2	3	7	0	–	1	8	0	–	0	–
Pop–econ–cult–clim	2	2	0	–	0	–	0	–	0	–	0	–	2	14
Econ–tech–cult–clim	1	1	1	2	0	–	0	–	0	–	0	–	0	–
Pop–econ–tech–clim	1	1	1	2	0	–	0	–	0	–	0	–	0	–
Pop–econ–tech–inst	1	1	1	2	0	–	0	–	0	–	0	–	0	–
Five factors														
Econ–tech–inst–cult–clim	15	11	1	2	5	12	5	83	0	–	0	–	4	29
Pop–econ–tech–inst–clim	12	9	11	22	1	2	0	–	0	–	0	–	0	–
Pop–econ–inst–cult–clim	5	4	4	8	1	2	0	–	0	–	0	–	0	–
Pop–econ–tech–inst–cult	4	3	3	6	1	2	0	–	0	–	0	–	0	–
Pop–econ–tech–cult–clim	3	2	0	–	0	–	0	–	3	23	0	–	0	–
Six factors														
Pop–econ–tech–cult–clim–inst	17	13	15	29	1	2	0	–	0	–	1	17	0	–
Total	132	104[a]	51	101[a]	42	99[a]	6	100	13	101[a]	6	101[a]	14	100

%, relative percentage; clim, climatic; cult, cultural; econ, economic; inst, institutional; No., absolute number; pop, demographic; tech, technological.
a. Does not total 100 because of rounding.

of irrigated garden products or herds of sheep, both destined for distant markets). We note that some research, especially in Asia, is devoted to technologies that might be used to stabilize the sand that is threatening expensive highway, railroad, and irrigation infrastructure. Thus, technology also makes it possible to mitigate some of the adverse impacts of desertification.

Among the institutional and policy factors that underlie 65% of the reported cases of desertification, modern policies and institutions are as much involved as are traditional institutions (table 4). Growth-oriented agricultural policies, including measures such as land distribution and redistribution, agrarian reforms, modern sector development projects, diffusion of agricultural intensification methods, and market liberalization policies, are as important in driving desertification as are institutional aspects of traditional land tenure, such as equal sharing of land and splintering of herds because of traditional succession law. Both traditional and modern institutions and policies thus reduce flexibility in management and increase the pressure on constant land units. The introduction of new land tenure systems, whether under private (individual) or state (collective) management, is another important factor associated with desertification. There are distinct regional variations in these factors, and the impact of policy is comparatively low in the dryland areas of Europe and North America, where agriculture is only a minor sector of the national economy.

Economic factors (60%; table 4) are reported to underlie desertification in the form of a mixture of "boom" and "bust" factors, with considerable regional variations. Boom factors

Table 4. Frequency of specific underlying driving forces in desertification, by number and relative percentage.

Cause	All cases (*n* = 132) No.	All cases %	Asia (*n* = 51) No.	Asia %	Africa (*n* = 42) No.	Africa %	Australia (*n* = 6) No.	Australia %	Europe (*n* = 13) No.	Europe %	United States (*n* = 6) No.	United States %	Latin America (*n* = 14) No.	Latin America %
Climatic factors	114	86	42	82	39	93	6	100	12	92	6	100	9	64
Synergistically or concomitantly[a]	55	42	21	41	21	50	5	83	4	31	1	17	3	21
Technological factors	91	69	42	82	20	48	6	100	11	85	5	83	7	50
Innovative developments, introductions[b]	73	55	35	69	12	29	5	83	3	23	3	50	7	50
Deficiencies of technical applications	67	51	31	61	17	40	5	83	8	62	3	50	3	21
Institutional or policy factors	86	65	45	88	20	48	5	83	2	15	2	33	12	86
Malfunctioning common property regulation	42	32	21	41	8	19	0	–	0	–	1	17	6	43
New land tenure, land zoning measures	37	28	19	37	11	26	5	83	0	–	1	17	1	7
Agricultural development policies[c]	35	27	27	53	7	17	0	–	2	15	1	17	0	–
Economic factors	79	60	45	88	15	36	5	83	3	23	2	33	9	64
Market growth, commercialization[d]	64	48	37	73	8	19	5	83	0	–	5	83	9	64
Economic depression, impoverishment[e]	48	36	22	43	9	21	5	83	3	23	1	17	8	57
Demographic factors	73	55	43	84	21	50	0	–	6	46	1	17	2	14
Population growth, increases in size	42	32	31	61	4	10	0	–	2	15	1	17	2	14
In-migration, rising population densities	33	25	15	29	14	33	0	–	3	23	1	17	0	–
Cultural and sociopolitical factors	55	42	26	51	12	29	5	83	4	31	3	50	6	43
Public attitudes, values, and beliefs	52	39	30	59	10	24	5	83	1	8	1	17	5	36
Individual and household behavior	53	40	18	35	10	24	5	83	3	23	3	50	9	64

No., absolute number; %, relative percentage.

Note: Multiple counts are possible; percentages are related to the total of all cases for each category.

a. In causal synergy or concomitant occurrence with other socioeconomic drivers.

b. New land and water management technology (new crop varieties, hydrotechnical installations), new transport and earthmoving technology, and improvements in research and veterinary services.

c. Growth and reform-oriented policies (agrarian reforms, land distribution or redistribution, rural development projects), including agricultural market liberalization.

d. Export-oriented market production, responding to high external demand for products such as cotton, beef, rice, and oil; increased land demand for raising livestock and producing grain; and industrialization and urbanization.

e. Land scarcity, low labor availability, low investments, unviable farm sizes, indebtedness, rural unemployment, and lack of nonagrarian income opportunities.

relate to market growth and commercialization, mainly entailing export-oriented market production, industrialization, and urbanization. Farmers respond to market signals reflecting high external demands for cotton, beef, and grain, with land increasingly put under rain-fed or irrigated production. Bust factors relate to the overuse of land because of land scarcity, low investments, low labor availability, indebtedness, lack of employment in the formal nonagrarian sector, or poverty. In dryland zones of Asia, cases of desertification are mainly driven by remote influences such as urbanization and commercialization. In many cases from Australia and Latin America, local farmers' response to an unfavorable economic situation, coupled with cycles of low rainfall, is reported to underlie desertification: Declining prices in the export-oriented sheep sector cause farmers to go into debt when their farms are no longer economically viable, inducing the overuse of scarce natural resources, especially during droughts.

Demographic factors (55%) show distinct regional clustering, with Asian and African cases of desertification most commonly cited as reflecting human population dynamics (table 4). Most widespread are cases in which population growth, overpopulation, or population pressure is reported as a driver of desertification. The growth or increased economic influence of urban population often triggers migration of poor cultivators or herders from high-potential, periurban zones into marginal dryland sites. Consequently, the sometimes rapid increases in the size of local human populations are often linked to the immigration of cultivators into rangelands or regions with large-scale irrigation schemes, or of herders into hitherto unused, marginal sites, resulting in rising population densities there. Unexpectedly, the case studies reveal that population increase due to high fertility rates of impoverished rural groups, at a local scale and over a time period of few decades, is not a primary driver of desertification; it is reported to intervene in only 3% of the cases.

Prominent examples of migration-driven desertification stem from ancient or historical irrigation (oasis) sites in Central Asia, such as the Tarim and Hei River basins or the Aral Sea region. Until recently, traditional irrigation-farming practices in these regions had a relatively small impact on dryland ecosystems. Only in the second half of the 20th century did advances in hydrotechnical infrastructure synergize with population influx from remote zones and with outside economic demands such as attaining national self-sufficiency in clothing and food. Cotton monocultures and irrigated food crops (e.g., grain, rice, vegetables, fruits, grapevines), which are water-demanding, became key crops in areas of rapid settlement. In the period 1949–1985 alone, population in the Hei River basin almost doubled, from 55 million to 105 million people, with the total irrigated area tripling from 8 million to 24 million hectares and the number of reservoirs increasing from 2 to 95 in the same period of time (Genxu and Guodong 1999). Often the state-driven opening up of oil or gas industries, mining activities, or power plants adds to the pressures on water resources stemming from growing population and agriculture.

Among cultural or sociopolitical factors (42%; table 4), public attitudes, values, and beliefs are as frequently associated with cases of desertification as is individual or household behavior, but there are regional variations. In Asia, land-use change leading to desertification is reported to be strongly driven by government encouragement of a frontier mentality (such as the official support for land consolidation in the northwestern territories of China) and by efforts to improve living standards and attain self-sufficiency in food. Such land-use change is very often linked to the belief that water is a "free good" and that grazing is "inefficient" when compared with grain production. Contrasting with this pattern are the Latin American cases, in which desertification seems to be predominantly driven by the individual responses or motivations of ranchers, and the Australian cases, in which a frontier mentality is not explicitly promoted by the state but seems to reflect a private attitude. War, insurgency, and violent conflicts over land lead to the disruption of land management, and thus to land degradation, in 8% of the cases.

Factor interactions. Desertification usually results from interactions among multiple causal factors. In most cases, three to five underlying causes drive two to three proximate causes. A frequent pattern of causal interactions, driven mostly by policy, economic, and technological factors, stems from the creation of water-related infrastructure that results in the expansion of irrigated croplands and pastures (Pickup 1998, Genxu and Guodong 1999, Saiko and Zonn 2000, Dube and Pickup 2001, Lin et al. 2001). Typically, new irrigation infrastructure prompts farmworkers to migrate into dryland areas, and it often stirs commercial and industrial developments as well as the growth of human settlements and related service economies. New irrigation infrastructure is often part of a larger infrastructure development related to regional economic growth. Commonly, road extension and the availability of earthmoving equipment for dam construction pave the way for the subsequent extension of irrigation and for urban or semiurban land uses. Underlying these proximate factors in the developing world are national policies aimed at consolidating territorial control over remote, marginal areas and attaining self-sufficiency in food and clothing. Rice and cotton are the key irrigated crops in dryland zones worldwide.

Paramount examples of desertification resulting from irrigation schemes are found in dry, hot river and lake basin ecosystems worldwide, with annual rainfall in the range of 30 to 300 mm and average summer temperatures at 23 degrees Celsius (°C) to 31°C. In Central Asia, the establishment during the second half of the 20th century of large hydrotechnical installations with low water-use efficiency disrupted fragile hydrographic ecosystems that had sustained flexible nomadic grazing or small-scale, settled oasis farming for centuries or even millennia. Consequently, severe and partly irreversible water degradation (salinization, drop in water tables, reduced volume of discharge), soil and vegetation degradation, and even "sandification" (the encroachment of sand into cultivated land through the activation of fixed or semifixed dunes) are reported from the Aral and Caspian Sea regions (Saiko and Zonn 2000, Kharin 2003) and the Hei and Tarim River basins (Genxu and Guodong 1999, Lin et al. 2001). Similar problems are found in Africa, in the Senegal River basin (Venema et al. 1997).

Artificial watering points and roads can lead to expanding pastures and livestock populations (mainly cattle and sheep) and thus to desertification. Paramount examples of this pattern are found in major rangeland zones such as the East African grasslands, Kalahari steppe, and diverse rangeland ecosystems of Patagonia and Australia (Keya 1998, Pickup 1998, Aagesen 2000, Dube and Pickup 2001). Another pattern, seen mostly in the African Sudano-Sahelian zone, in East Africa, and in northern China, comes from growth-oriented development policies that favor cropping at the expense of herding (Mwalyosi 1992, Turner 1999, Runnström 2000). The changing opportunities created by markets and policies often involve the introduction of new, mostly private land tenure in conjunction with zoning (e.g., into grazing or irrigation districts and reserved land). Outside policy interventions, such as newly introduced development projects, and the growth of agricultural commercialization send powerful market signals to local farmers. Customary land-manage-

Table 5. Driving forces of desertification, by scale of influence.

	Demographic factors[a] (n = 73)		Economic factors (n = 79)		Technological factors (n = 91)		Institutional factors (n = 86)		Cultural factors (n = 55)		Climatic factors (n = 114)	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Individual scales												
Local[b]	17	23	14	18	26	29	10	12	1	2	0	–
Regional[c]	0	–	0	–	0	–	0	–	8	15	0	–
National	0	–	10	13	0	–	17	20	2	4	0	–
Global	0	–	3	4	0	–	5	6	0	–	14	12
Total	17	23	27	34	26	29	32	37	11	20	14	12
Cross-scalar interactions (interplays)												
Local–regional	8	11	0	–	10	11	21	24	16	29	40	35
Local–national	13	18	34	43	41	45	15	17	17	31	17	15
Local–global	0	–	9	11	14	15	4	5	0	–	11	10
Regional–national	0	–	0	–	0	–	4	5	11	20	0	–
Regional–global	0	–	0	–	0	–	0	–	0	–	0	–
National–global	0	–	9	11	0	–	10	12	0	–	0	–
Total	21	29	52	66	65	71	54	63	44	80	68	60
No data, unknown (scale not specified)	35	48	0	–	0	–	0	–	0	–	32	28

No., absolute number; %, relative percentage.
Note: Percentages may not total 100 because of rounding.
a. "Rising population densities" were coded as a local phenomenon, but "increase in population" was coded as unspecified in terms of scale of impact.
b. Farm, household, society, community, or small ecosystem.
c. District or province.

ment institutions, such as inherited succession law or flexible common-property regulations, conflict with the new requirements. In herding, labor investments are low and livestock mobility is restricted, thus triggering overstocking on the few remaining pastures. In cropping, inappropriate or unwise land management is practiced. This may include the undue extension of cereal crops onto marginal lands, despite high rainfall variability and the suitability of these marginal lands only for mobile grazing. Uncertain land tenure may arise from the overlapping of conflicting property-rights regimes, often leading to violent conflicts about land and thus reducing the adaptive capacity of herding and farming populations. In Asia and Africa, rapidly growing local population densities interact with other driving forces underpinning the proximate causes of desertification.

Mediating factors and cross-scalar interactions. Some factors intervene in the interplay of underlying driving forces and proximate causes, and not all causative factors are important at the same hierarchical level of organization. Ethnic affiliation, access to resources such as cattle and land, and the type of land management practiced (e.g., monoculture versus agroforestry, small-scale versus large-scale) act as mediating or shaping factors in dynamic patterns of desertification. The impoverished conditions of land managers are the most important and robust mediating factors, increasing their vulnerability to dryland degradation (such as drought-induced crop failures and livestock decimation). In cases reported in Asia, Africa, Latin America, and Australia, economically deprived local farmers overuse their limited farmland in an effort to make ends meet. They do so either through continuous cultivation that leads to soil nutrient depletion or through year-round grazing that diminishes forage productivity and triggers the exposure of bare, eroded ground cover. In the latter half of the 20th century, the area of undegraded vegetation cover at sites in northwestern China (e.g., *Populus euphratica*) and northern Burkina Faso was reduced at maximum annual rates of 3%–4% and 5%–6%, respectively, while the area of degraded vegetation cover increased at average annual rates of more than 4%.

Although proximate causes are linked to local scales, cross-scalar interactions of underlying factors are more frequently found than causative factors operating at individual scales (table 5). Driving forces originating from an individual scale reportedly matter in 10% to 35% of the case studies (with local factors at the farm, household, community, or small-ecosystem levels outweighing the importance of upper-level factors). Interactions among driving forces from multiple scales dominate, with 30% to 80% of the studies reporting such cross-scalar interactions; the interplay between causes at the local and national levels is the most important. Global driving forces were less frequently mentioned in the desertification case studies than they were in case studies of tropical deforestation (Geist and Lambin 2002, Lambin and Geist 2003).

Feedbacks. The evidence of the case studies suggests that, among causative factors, more positive feedback loops are at work that amplify desertification than negative feedbacks that could attenuate the process. Desertification thus leads to a vicious circle of resource degradation and impoverishment. One robust mechanism is a self-perpetuating process that involves expansion of cropland and grazing land, leading to soil degradation and overstocking in dryland areas affected by erratic rainfall fluctuations. Given a sustained demand for more land to be put under production, land degradation leads to further expansion of cultivated land or to further overuse of the land already under cultivation. In many cases from Asia and Africa, the development of grazing land (e.g., through improved grass varieties and aerial seed) does not happen in isolation, but is nearly always accompanied by the encroachment of crops onto rangelands. Thus, most improvements to grazing land do not result in a development for the better, because overstocking occurs on the shrinking rangelands (Mwalyosi 1992, Manzano et al. 2000).

Another positive feedback loop, which is most common in Africa and Asia, links rainfall deficit and high rainfall variability with land-use changes (agriculture, wood extraction, water-use schemes), accelerating land degradation (Dube and Pickup 2001, Zhou et al. 2002). A local variant of this mechanism, found in Africa, is a biophysical feedback loop that links land degradation (triggered by land-use change), changes in albedo and evapotranspiration, and decreases in precipitation, amplifying the impact of human activities on land cover (Zeng et al. 1999, Taylor et al. 2002). Another variant relates to hydrological stress and the process of degradation itself, which lead to an increase in the spatial heterogeneity of vegetation cover (Schlesinger et al. 1990, Seixas 2000). Linked to this feedback mechanism are changes in floristic composition, mainly of shrubs, and a shift toward woody species that are less palatable for livestock, further increasing the need for land to be put under production (Brown et al. 1997, Keya 1998).

Regional pathways of desertification. Dominant causative factors and feedbacks, combined with environmental and land-use histories, allow the identification of typical regional pathways of desertification. In Central Asia, notably northern China, the most spectacular outcome of desertification is a widespread increase in desertlike sand cover, which is linked to the exceptionally strong impact of socioeconomic driving forces such as centrally planned frontier colonization and (sometimes forced) population movements (Jiang 2002, Sneath 2002). But the spread of sand cover is also linked to the region's predominantly sandy soils and loess formations and to the geological and climatic predisposition for desert formation of vast basins and plateaus. In ancient times, under various dynasties, climatic variations and destructive land uses operated in causal synergy to expand the oscillating desert margins, resulting in a sandy, desiccated landscape with the highest rates of dryland degradation worldwide. Two central pathways of partly irreversible desertification in Central Asia are the invasion of grain farming into steppe grazing land, triggering soil degradation as well as overstocking, and of large-scale hydraulic cultures into desert ecosystems that historically supported only localized, traditional oasis farming (Zhou et al. 2002, Kharin 2003).

In contrast, a typically African pathway of desertification involves the spatial concentration of pastoralists (as a result of the shift from a nomadic to a sedentary way of life) and farmers around infrastructure nuclei. This local concentration of population results in overgrazing, extensive fuelwood collection, and high cropping intensities, ultimately leading to degraded vegetation and declining soil productivity during periods of drought (Mwalyosi 1992, Dube and Pickup 2001).

"Beefing up" of fragile dryland ecosystems, with little or no involvement of cropping, frequently characterizes the desertification pathways of Australia and of North and South America. Historically, these rangeland zones typically shared common patterns of land use, such as the rapid introduction by European settlers of exotic livestock species and commercial pastoralism into ecosystems that had not undergone these uses before. Since about the 1950s, however, the cost-price squeeze affecting agriculture in industrialized countries has led to different variants of this trajectory. In Australia, the livestock industry and its complex of related infrastructure developed sufficient flexibility to counterbalance droughts and avoid spectacular desertification (Pickup 1998). In the US Southwest, principal land uses shifted away from cattle ranching to meet urban-driven aspirations (Fredrickson et al. 1998). In both areas, dryland-cover change happened episodically and was linked to shifts in rainfall and land use. Rates of desertification reached historical peaks in the late 19th and early 20th centuries but have largely subsided since then. Patagonia and northern Mexico, by contrast, suffered from a lack of advanced technologies to deal with the vagaries of oscillating natural resource productivity and, in general, from a lack of alternative land uses or diversification options. Local farmers were forced to continue raising livestock, sometimes under conditions of impoverishment and deprivation. Consequently, dryland degradation in these areas is not just a historical phenomenon, but continues to advance (del Valle et al. 1998, Manzano et al. 2000).

Another common trajectory of dryland change is found in the Mediterranean basin of southern Europe. A millennia-old tradition of agropastoral land use has removed nearly all forest cover but has favored a highly resilient phrygana (shrub) vegetation, reflecting various stages of soil degradation. The still-valuable agricultural base is at risk only when the mechanization of farming on skeletal soils induces further soil erosion, or when grazing on remote mountain ranges is followed by devastating fires (Margaris et al. 1996, Kosmas et al. 2000).

Discussion

Our meta-analysis does not provide support for either of the two large groups of explanations for dryland degradation (Watts 1985, Helldén 1991, Thomas 1997). Our results do not reflect irreducible complexity (Dregne 2002, Warren 2002); on the contrary, they reveal distinct patterns. Nor do they identify a single cause responsible for an irreversible extension of desert landforms and landscapes (Breckle et al. 2002, Le

Houérou 2002), be it irrational land management by nomadic pastoralists, growing population, macroeconomic forces, unjust class and power relations, or climatic factors. Rather, we identified multiplicity as the most common theme reported: multiple agents; multiple uses of land; multiple responses to social, climatic, and ecological changes; multiple spatial and temporal scales in the causes of and responses to desertification; multiple connections in social and geographical space; and multiple ties between people and land in dryland areas (Rindfuss et al. 2003). The theoretical framework that best accounts for this complexity is system dynamics (Lambin et al. 2003), with special emphasis on the history (initial conditions) and adaptation of the system, the heterogeneity of the actors, the hierarchical levels of organization, and the nonlinear dynamics caused by feedback mechanisms. It is important to note that this complexity is associated with a limited number of recurrent pathways of desertification, which makes the problem tractable (Reynolds and Stafford Smith 2002).

Most of the case studies of desertification report variants of a general syndrome that derives from resource scarcity and leads to a gradual pressure of production on resources (Mooney et al. 2003, Geist 2004). These studies report an increased intensity (per unit area) of rural labor investment and other artificial investments, such as watering infrastructure, to increase the production of land. The proximate factors related to this syndrome include the addition of new and more livestock species (Keya 1998), year-round grazing (Aagesen 2000), increased soil preparation through ploughing and continuous cropping (Mwalyosi 1992, Kosmas et al. 2000), and increased diversion of artificially gained water onto marginal land (Genxu and Guodong 1999). Most of these factors involve greater input commitments per unit land area compared with traditional dryland uses (Margaris et al. 1996, Niamir-Fuller 1999) such as nomadic pastoralism or shifting cultivation. Could it be that the final link in the causal chain tying social to environmental change is land-use intensification in dryland ecosystems that had been immune from such land uses before, thus increasing these ecosystems' vulnerability to dry episodes (Pickup 1998, Manzano et al. 2000, Lin et al. 2001, Kharin 2003)? Some cases seem to show that intensive land use may follow from production pressure on a fluctuating resource base, but that such intensive land use does not necessarily lead to desertification (Rasmussen et al. 2001). There are examples of integrated animal husbandry and cropping systems in West Africa (Mortimore et al. 1999) but also of land abandonment and disinvestment in labor in southern Europe (Kosmas et al. 2000). A critical point is that pressures derive not only from changes in the intensity and magnitude of resource extraction but also from the way that resources are extracted (Watts 1985, Turner 1999). This suggests that future case studies should strive for a better understanding of the material reality of land use, which is shaped not only by an oscillating resource base (rainfall, biomass) (Zeng et al. 1999, Seixas 2000, Nicholson 2002) but also by labor processes (Turner 1999, Fernandez et al. 2002) and the social relations of livestock production and farming operations over time (Rasmussen et al. 2001, Zhou et al. 2002). In particular, a more nuanced population analysis is needed (Lambin et al. 2003).

Another recurrent theme in desertification case studies is that sociocultural changes have modified the adaptive strategies of dryland societies in the face of natural variability (which is inherent to dryland ecosystems) and have therefore reduced the resilience of socioecological systems, creating instability. In traditional rural societies, land productivity has often been multiply constrained, and cultural organizations have been adapted to episodic but recurrent changes. In the West African Sudan-Sahel, for example, land productivity is linked to oscillating rainfall and constrained by a nested system of seasonally differentiated rights to use each piece of land, distributed among various sedentary farming and pastoral groups (households, lineages, villages, groups of settlements, pastoral clans) (Turner 1999). During periods of drought, modifications of land management have been negotiated among all of these groups. Adaptation requires a high degree of flexibility and cooperation in the highly mobile grazing systems practiced by nomads (Niamir-Fuller 1999). In modern societies, cultural change becomes directional rather than cyclical, because land users as well as investors and consumers of agricultural produce embrace the promise of progress, particularly in technology and material well-being (Fernandez et al. 2002, Jiang 2002). In many cases, we found strong directionality manifested in land-use intensification, which could be interpreted as an increasing tendency to view the environment as a medium for rapid material or economic gains. With the shift from traditional to modern rural societies, cultural change brings about a directional transformation of the environment as well. In a few cases from the Sudan-Sahel in which land productivity has continued to be multiply constrained, rates of dryland degradation are low to nil. In some instances, highly intensive agrosilvopastoral production systems, developed under semiarid conditions, have been able to mitigate the vagaries of natural climatic fluctuations, markets, and even population pressure. Data from some densely populated village areas in the Kano close-settled zone of northeastern Nigeria, for example, suggest that the transformation of woodland or shrubland into farmland not only added economic value to farming but also led to an increase of plant biomass on farmed parkland as well as high livestock densities on crop residues (Mortimore et al. 1999).

Our meta-analysis of case studies found that the relative weight and particular sequence of causes of desertification vary from region to region. The results highlight the interplay of proximate causes and underlying driving forces, both socioeconomic and biophysical, in the processes of desertification. Our analysis also revealed more complex dynamic patterns of dryland degradation, given the importance of mediating factors, feedback loops, and initial conditions. These elements make it possible to identify regional pathways of dryland change. This illuminates the causative mechanisms of desertification far more than previous compilations of causes, which were often static, did not differentiate between proximate and fundamental causes, and failed to trace the pathways connecting various causes in a structured way. Our analysis suggests that claims that desertification is either a human-made or a purely natural (i.e., climate-driven) process should be more nuanced. Indeed, case studies indicate that desertification is a coupled biophysical and socioeconomic process (Puigdefábregas 1998, Reynolds and Stafford Smith 2002), the details of which need to be specified for the various regions affected by desertification.

Conclusions

Evidence from empirical case studies that identify both proximate causes and underlying forces of desertification shows that dryland degradation—with desertification as a potential but not necessary outcome—is determined by different combinations of proximate causes and underlying driving forces in varying geographical contexts. Nearly all of these combinations include coupled socioeconomic and biophysical factors. Some of the combinations are geographically robust (such as the spread of watering and related infrastructure driven by growth-oriented policies and economic demands, which in turn are stirred by demographic changes), but most of them are region and time specific.

The observed causal-factor synergies and pathways of dryland change challenge single-factor explanations that put most of the blame for desertification on the overworking of land by increasing numbers of rural poor and by nomadic populations. Rather, our analysis reveals that, at the underlying level, public and individual decisions largely respond to national-scale policies promoting advanced land-use technologies and creating new economic opportunities. These responses are mediated by land-tenure systems and other local-scale institutions. Our analysis further reveals that, at the proximate level, regionally distinct modes of increased aridity, expansion of cropping and grazing activities, infrastructure extension, and, to a lesser degree, wood extraction prevail in causing desertification. Two major implications of this evidence are, first, that no global set of indicators to assess desertification status could reveal the complexity of human-environment systems inherent to dryland change, and second, that no universal policy for mitigating desertification can be conceived for all the dryland areas of the globe. Rather, a detailed understanding of the complex set of proximate causes and underlying driving forces affecting dryland-cover change in a given location is required before any assessment and policy intervention.

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