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Global Desertification: Building a Science for Dryland Development

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In this millennium, global drylands face a myriad of problems that present tough research, management, and policy challenges. Recent advances in dryland development, however, together with the integrative approaches of global change and sustainability science, suggest that concerns about land degradation, poverty, safeguarding biodiversity, and protecting the culture of 2.5 billion people can be confronted with renewed optimism. We review recent lessons about the functioning of dryland ecosystems and the livelihood systems of their human residents and introduce a new synthetic framework, the Drylands Development Paradigm (DDP). The DDP, supported by a growing and well-documented set of tools for policy and management action, helps navigate the inherent complexity of desertification and dryland development, identifying and synthesizing those factors important to research, management, and policy communities.

Drylands cover about 41% of Earth's land surface and are home to more than 38% of the total global population of 6.5 billion (*1*, *2*). Some form of severe land degradation is present on 10 to 20% of these lands [medium-confidence conclusion of (*2*)] (*3*), the consequences of which are estimated to affect directly some 250 million people in the developing world, an estimate likely to expand substantially in the face of climate change and population growth (*4*). The United Nations has periodically focused on desertification and drylands, notably adopting the Convention to Combat Desertification (CCD) in 1992 (*3*) and designating 2006 as the International Year of the Desert and Desertification.

One contribution of the CCD was to enshrine a definition of desertification as "land degradation in arid, semi-arid, and dry subhumid areas resulting from various factors, including climatic variations and human activities," that is, encompassing both biophysical and social factors (*5*). However, the CCD and related efforts receive comparatively little exposure in the popular and scientific media (*6*), in part because of the absence of a focused international science program (*7*). Advances in various aspects of science relevant to drylands and community development practices in recent years suggest a common framework for managing dryland systems.

The DDP presented here centers on the livelihoods of human populations in drylands, and their dependencies on these unique ecosystems, through the study of coupled human-environmental (H-E) systems (*8*). The DDP responds to recent research and policy trends (Fig. 1) that link ecosystem management with human livelihoods in order to best support the large, and rapidly expanding, populations of dryland dwellers (*9*). The DDP represents a convergence of insights and key advances drawn from a diverse array of research in desertification, vulnerability, poverty alleviation, and community development (Table 1).

Fig. 1. The focus on global drylands is shifting from an emphasis on negative images of desertification (upper: drought-stricken cattle on an eroded grassland in central Australia. Photo: M. Stafford Smith) to a more forward-looking perspective concerning human livelihoods, based on interactions between and among human activities and natural-world processes (lower: farmer spraying organic pesticide on domesticated quinoa in southern Bolivia. Photo: J. Reynolds). Either way, great challenges to the future security of some 250 million people remain (*4*).

Research and practice in these fields have increasingly converged on a set of five general lessons concerning the condition and dynamics of H-E systems as they apply to sustainable development in drylands. (i) Both researchers and practitioners need to adopt an integrated approach: Ecological and social issues are fundamentally interwoven, and so are the options for livelihood support and ecological management. (ii) There needs to be a heightened awareness of slowly evolving conditions: Short-term measures tend to be superficial and do not resolve persistent, chronic problems nor deal with continual change. (iii) Nonlinear processes need to be recognized: Dryland systems are not in equilibrium, have multiple thresholds, and thus often exhibit multiple ecological and social states. (iv) Cross-scale interactions must be anticipated: Problems and solutions at one scale influence, and are influenced by, those at other scales. (v) A much greater value must be placed on local environmental knowledge (LEK): Its

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practice is central to the management of most drylands but is often undervalued.

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Building on earlier efforts (*10*), we synthesize and formalize these lessons more explicitly in the DDP. The issues that the DDP principles highlight arise from a suite of biophysical and socioeconomic features that together constitute a "drylands syndrome," such that dryland populations are among the most ecologically, socially, and politically marginalized populations on Earth (*11*). Sustainable development in drylands is determined by five key features of the drylands syndrome (noted as ds-1 to ds-5 below), which dominate the dynamics of H-E systems.

Dryland syndrome. Drylands—which include arid, semi-arid, and dry subhumid areas—are by definition (*12*) areas where precipitation is scarce and typically more-or-less unpredictable (ds-1: high variability). High air temperatures, low humidity, and abundant solar radiation result in high potential evapotranspiration. Many dryland soils contain small amounts of organic matter and have low aggregate strength (ds-2: low fertility). Both tillage and grazing by domesticated animals can quickly have major impacts, so drylands are sensitive to degradation (*1*, *2*). These and other biophysical features have profound social and economic implications.

Compared to mesic areas, and a few major desert cities notwithstanding, the human populations of drylands are usually sparser (ds-3: sparse populations), more mobile, more remote from markets (ds-4: remoteness), and distant from the centers (and priorities) of decision-makers (ds-5: distant voice). It is also harder to deliver services efficiently, and institutional arrangements devised in other regions may be dysfunctional when imposed on drylands. As a result, dryland populations tend to lag behind populations in other parts of the world on a variety of economic and health indices, even controlling for "ruralness" (*2*), with higher infant mortality, severe shortages of drinking water, and much lower per capita gross national product.

Principles of the DDP. The DDP consists of five principles (Table 2), which are based on the aforementioned lessons but that are also consistent with the dryland syndrome.

Principle 1. Dryland H-E systems are coupled, dynamic, and coadapting, with no single target equilibrium point (*13*). They are the coevolved product of complex interactions between biophysical (e.g., climate, soil, biota) and

Table 1. Selected fields of activity relevant to dryland development, showing some key advances in research and lessons for management and policy over the past two decades, and which provide the basis for the new synthesis presented in Table 2. P1 to P5 indicate how the specific advances and lessons foreshadow principles 1 to 5 and their implications as given in Table 2.

Fields of activity	Some key advances in drylands research	Some key lessons learned for drylands practitioners
Desertification and rangelands ecology: Understanding the biophysical (*59*, *60*) and socioeconomic (*61*) drivers of dryland degradation, as part of global environmental change research	Many case studies of chronic dryland degradation—caused by interactions between biophysical and social drivers—have been documented [e.g., land uses that exhaust available water resources or are unsuited to highly variable precipitation regimes (*62*)]. The debate about drylands being disequilibrium systems has been resolved in favor of a more dynamic, nonequilibrium view (*13*). [→P1, P2, P3]	Desertification is the emergent outcome of a suite of social and biophysical causal factors, with pathways of change that are specific in time and place (*23*). Poor resource management is compounded by weak institutions, poorly implemented technologies, or exploitative economic and political systems [thus emphasizing links between coupled H-E systems (*63*)]. [→P1, P2]
Vulnerability: Understanding the integrated environmental, social, economic, and political exposure of human welfare to a range of potentially harmful perturbations (*64*)	Vulnerability involves multiple stressors across multiple temporal and spatial scales, and emerges from the interactions of social actors, the environment, and institutions (*65*). Thresholds of critical risks are dynamic in space and time and are rooted in historical structural causes [e.g., construction of wells during a severe drought in the Sahel interrupted herd movements, creating new vulnerabilities (*22*)]. [→P1, P3, P4]	Expansion of cropping into rangelands during wet periods changes system thresholds and often results in crises and environmental collapse when dry conditions return, e.g., the 1930s U.S. Dust Bowl (*66*) and "sandification" in China's Ordos Plateau (*31*). With adequate preparedness, early-warning systems can reduce the human toll of natural hazards and livelihood-based measures can reduce longer-term vulnerability [e.g., community adaptation to drought in Kordofan, Sudan (*67*)]. [→P2, P3]
Poverty alleviation: Elucidates human welfare–land degradation relationships (*68*)	"Poverty trap" thresholds exist (*69*) from which it is difficult for individuals and households to extract themselves without outside intervention. Livelihood diversification, which is increasingly promoted in drylands, reduces dependence on highly variable natural resources (*2*). [→P2, P3]	Development schemes in drylands justified as alleviating poverty have often been driven by divergent, higher-level political or economic objectives [e.g., forced relocation of Ethiopian Highlands peoples after the 1980s famine (*70*)]. Low productivity often means that interregional flows of labor, capital, and skills (e.g., by migration to urban or more humid areas) are needed to sustain poverty reduction in drylands. [→P3, P4]
Community-driven development: Seeks to enlarge the role of local communities in policy and to strengthen local autonomy in governance (*71*)	"Top-down" development policies often contradict local practices and undermine sustainable development [e.g., conflicts between state and local perspectives on burning in Mali (*72*)]. Community-driven management, though more sensitive to local conditions and knowledge, is not a universal solution (*73*). [→P4, P5]	An increased role for local communities and land users is needed for win-win (environment-development) outcomes (*74*) requiring rights to participate and capacity-building initiatives. Proper engagement of local people (and local environmental knowledge) with scientists (and scientific knowledge) can contribute to sustainable management (*75*, *76*). [→P5]

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human (e.g., demographic, economic, institutional) subsystems (*14*), complete with a history and geography, and are constantly changing in response to both external (e.g., climate, prices) and internal (e.g., feedbacks between soil nutrients and plant growth, a farmer's economic decisions regarding land use) drivers. An example of the coevolution of H-E systems is provided by Mortimore and Harris (*15*) for the Kano Close-Settled Zone in Nigeria, covering the period 1962 to 1996 (*16*). Given this scenario, approaches to development must simultaneously consider both biophysical and socioeconomic dimensions of the dryland system in question [key implication 1 (ki-1) in Table 2] (*17*). Trends in soil fertility or biodiversity, for example, must be linked to factors such as labor, settlement patterns, and livelihood system dynamics, and vice versa, with appropriate temporal and spatial definitions (*18*).

Principle 2. The critical dynamics of dryland systems are determined by "slow" variables, both biophysical and socioeconomic [as exemplified by the coevolution of the coupled H-E systems of Maradi, Niger (Box S1, supporting online text)]. Slow variables (e.g., soil fertility, household capital wealth) have lengthy turnover times and are thus useful for gaining insights into long-term H-E changes, resource collapses, potential surprises, and new opportunities (*19*). The vagaries of precipitation, pest outbreaks, and other strongly fluctuating variables characteristic of drylands tend to generate noise, making such "fast" variables with relatively rapid turnover times (e.g., crop yield, household disposable cash) poor indicators of land degradation or the need for intervention (*17*). Nevertheless, both research and human exploitation of resources are often based on relatively fast variables (*19*), which for drylands has confused the debate about strategic development needs (*20*, *21*).

Given the complex, multivariate structure of H-E systems, it is important to recognize that not all variables carry equal weight (*17*). It is often possible to identify combinations of interrelated variables that can be grouped together as syndromes of degradation (*22*), thus simplifying analysis and intervention (ki-2, Table 2) (*23*).

Principle 3. Slow variables possess thresholds that, if crossed, cause the system to move into a new state or condition. The importance of thresholds is widely recognized in both the ecological and socioeconomic literature (*24*) and, although this usually focuses on one, dominant "shift," Kinzig *et al.* (*25*) show that most regional-scale systems have a number of actual or potential regime shifts, in different domains (ecological, social, economic) and at different scales, such that one shift may trigger or preclude others. Thresholds may vary as a function of internal dynamics at other scales, and in some instances can be deliberately altered. For example, the provision of piped water or solar cookers in remote villages can dramatically alter the income threshold at which women have spare time to invest in small business or education by reducing the time taken to collect water or fuel (*26*).

Table 2. Principles of the Drylands Development Paradigm, with a brief overview of their importance vis-à-vis the five main components of the dryland syndrome (ds-1 to ds-5, see text) and their implications for research, management, and policy. [Based on Stafford Smith and Reynolds (*77*)] H-E, human-environmental systems; LEK, local environmental knowledge.

Principles	Why important in drylands	Links to dryland syndrome (ds-1 to ds-5)	Key implications (ki) for research, management, and policy
P1: H-E systems are coupled, dynamic, and coadapting, so that their structure, function, and interrelationships change over time.	The close dependency of most drylands livelihoods on the environment imposes a greater cost if the coupling becomes dysfunctional; variability caused by biophysical factors as well as markets and policy processes, which are generally beyond local control, means that tracking the evolving changes and their functionality is relatively harder and more important in drylands.	ds-1: variability; ds-4: remoteness	ki-1: Understanding dryland desertification and development issues always requires the simultaneous consideration of both human and ecological drivers, and the recognition that there is no static equilibrium "to aim for."
P2: A limited suite of "slow" variables are critical determinants of H-E system dynamics.	Identifying and monitoring the key slow H and E variables is particularly important in drylands because high variability in "fast" variables masks fundamental change indicated by slow variables.	ds-1: variability	ki-2: A limited suite of critical processes and variables at any scale makes a complex problem tractable.
P3: Thresholds in key slow variables define different states of H-E systems, often with different controlling processes; thresholds may change over time.	Thresholds particularly matter in drylands because the capacity to invest in recovering from the impacts of crossing undesirable thresholds is usually lower per unit (area of land, person, etc); and, where outside agencies must be called upon, the transaction costs of doing so to distant policy centers are usually higher.	ds-1: variability; ds-2: low productivity; ds-4: remoteness; ds-5: distant voice	ki-3: The costs of intervention rise nonlinearly with increasing land degradation or the degree of socioeconomic dysfunction; yet high variability means great uncertainty in detecting thresholds, implying that managers should invoke the precautionary principle.
P4: Coupled H-E systems are hierarchical, nested, and networked across multiple scales.	Drylands are often more distant from economic and policy centers, with weak linkages; additionally, regions with sparse populations may have qualitatively different hierarchical relationships between levels.	ds-3: sparse population ds-4: remoteness; ds-5: distant voice;	ki-4: H-E systems must be managed at the appropriate scale; cross-scale linkages are important in this, but are often remote and weak in drylands, requiring special institutional attention.
P5: The maintenance of a body of up-to-date LEK is key to functional coadaptation of H-E systems.	Support for LEK is critical in drylands because experiential learning is slower where monitoring feedback is harder to obtain (owing to more variable systems, larger management units, in sparsely populated areas) and, secondarily, where there is relatively less research.	ds-1: variability; ds-3: sparse population	ki-5: The development of appropriate hybrid scientific and LEK must be accelerated both for local management and regional policy.

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As an H-E system moves further from some desirable condition or state, the cost of intervention to “return” the system to that condition also increases. Sudden changes or nonlinearities associated with thresholds (e.g., run-off from overland flow to gullies; labor withdrawn due to war or out-migration) tend to amplify the costs of intervention (ki-3, Table 2). In impoverished drylands, these costs are further exacerbated by economic limits to local investment capacity, thus triggering the call for external resources that further increase transaction costs in remote areas [examples in (*17*, *27*)] (*28*).

Principle 4. The involvement of multiple stakeholders, with highly differing objectives and perspectives, illustrates the need to pay attention to the multilevel, nested, and networked nature of H-E systems. Operating hierarchically and across scales, linkages between stakeholders embed the system in question within others (*10*, *29*). Such scale issues are especially important in drylands because so many of them are sparsely occupied and remote, e.g., from city-based agencies or company headquarters, which weakens political and economic empowerment (*30*). In addition, slow variables at one scale of interest are affected by slow and fast variables operating at other scales, such that interventions at one scale generally alter the system at the next [e.g., (*31*)].

However, not every problem need be viewed as encompassing all scales of concern. Berkes and Jolly (*32*), for example, argue that short-term coping mechanisms are displayed at the household and individual scales, whereas long-term adaptive strategies, such as change in cultural values, are expressed at broader scales. In general, intervention on, and management of, a particular process must occur at the appropriate scale (ki-4, Table 2). For example, inasmuch as management is affected by institutions (rules of governance), the two should be scale-matched (*33*).

Principle 5. The key to maintaining functional coadaptation of coupled H-E systems is an up-to-date body of “hybrid” environmental knowledge that integrates local management and policy experience with science-based knowledge, all of which must be mediated through an effective institutional framework. Local environmental knowledge, which encompasses a wide range of activities, may develop rapidly or over generations (*34*) and has served long-persisting groups well [e.g., native Americans (*35*)].

In the modern world, however, the traditional role of LEK is threatened by rapid changes in both biophysical (e.g., exotic-species introductions, shifts in climate) and socioeconomic (e.g., population growth, changing technologies, new economic demands) drivers. Furthermore, in the variable environments of drylands, especially those subject to climate change, acquiring new LEK through learning from experience is particularly slow, so identifying new alliances of local and science-based knowledge systems to speed up this acquisition is particularly important (*27*) (ki-5, Table 2). Examples of the products of such alliances include local climate forecasts (*36*) and soil classifications (*37*).

Application of the DDP

The DDP serves two purposes: One is conceptual, providing a holistic synthesis of the disparate lessons drawn from previous work on desertification and development (Table 1) in the setting of the unique features of drylands (the dryland syndrome); the other is practical, providing a template whereby each of the five principles (Table 2) can be thoroughly examined and tested in case studies.

Other complex, integrated approaches to environment and development issues that have been entertained in the past, such as farming systems research [e.g., (*38, 39*)], have faced the genuine difficulties that researchers, managers, and policy-makers have with tackling complexity. To address the global problem of desertification realistically, an integrative approach is required, not only because of synergy between elements of coupled H-E systems (*14*), but also because programmatic and policy concerns about each have implications that often conflict if treated individually (*21*). The real challenge that the DDP aims to satisfy is to develop efficient and effective approaches to understanding complex H-E interactions in drylands, while respecting and recognizing the capacity of local communities and policy-makers to deal with their complexity.

The DDP is being tested by the ARID*net* network (*40*) with interdisciplinary workshops of 15 to 25 participants. To date, ARID*net* workshops have addressed local questions of land degradation in rural, dryland H-E systems in Bolivia, Mexico (*41*) (Box S3), and Honduras (*42*). The DDP is most effective when conceptualizing and framing local issues, and their potential solutions, because it is open to the many different lenses through which dryland use and development are viewed by multiple stakeholders. In these workshops, the implementation phase was found to be most challenging, requiring that all stakeholders jointly work through the DDP principles, agreeing on the specific implications of each. The Mexican and Honduran case studies revealed that it is necessary to allow people to explore problems in their own words and gradually work specific issues into the DDP framework.

Dryland development issues occur also in more developed countries. In Australia, for example, the Desert Knowledge initiative (*43*) seeks sustainable livelihoods and viable desert settlements, and in the United States, the Central Arizona–Phoenix Long Term Ecological Research project (*44*) seeks to understand the relation between land-use decisions and ecological consequences. These projects share the long-term goal of improving dryland ecosystems and regional economies and, building on DDP-like analyses, seek economic livelihoods that may emerge from sustainable use of dryland environments yet reach out successfully to markets beyond these regions.

The DDP does not purport to represent an exhaustive set of programs, tools, and approaches for dryland development. In fact, in recent years there has been substantial improvement in the suite of toolsets available to the policy, management, and research communities concerned with dryland development [e.g., (*2*, *45*–*49*)]. Rather, the DDP serves as an analytical framework through which specific problems may be identified and opportunities implemented with greater insight. We are confident that further application and testing of the DDP through case studies will lead to continued refinement of a parsimonious set of theoretical, systems-oriented principles for analyzing dryland development issues in any particular region of the world, to the betterment of the 2.5 billion people who live in drylands globally.

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4. The precise numbers of the dryland population affected by desertification is contentious (*50*), but 250 million is a widely cited approximation (*2*, *3*). For comparison, the Global Fund estimates annually 1 million deaths and 300 to 500 million new infections for malaria, 3 million deaths and 40 million new infections for AIDS/HIV, and 2 million deaths and 8 million new infections for tuberculosis (www.theglobalfund.org).
5. There has been extensive debate concerning definitions of desertification and degradation (*51*). Although the CCD definition is now formalized internationally, a summary of the debate is given in (*10*, *52*).
6. In a search of *Science* for July 1996 through June 2006, “climat* change” appears in 634 titles/abstracts, and “biodiversity” (or “biological diversity”) appears in 211, whereas “desertification” (and biophysical forms of “degradation”) appears in only 4. Meanwhile, the Convention on Climate Change occurs in 7 abstracts, the Convention on Biological Diversity occurs in 4, and the CCD appears in 1. Similar findings are true for *Nature*.
7. We suggest that in the past this has been exacerbated by a polarization of the research and practitioner communities over the phenomena and processes of study, including tensions between environmental and development agendas and conceptual differences between top-down, expert-driven managerial solutions and bottom-up, local knowledge and capacity-building approaches (*53*). Such polarizations and differences are now ameliorating.
8. We use H-E interactions to encompass a broad interpretation of the mutual interactions between and among human activities and natural-world processes—an emerging field of science that has evolved in response to the need to elucidate complex relationships between sustainable resource use by humans and their environment (*54*). Also termed “social-ecological

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systems" by The Resilience Alliance (www.resalliance.org/1.php), H-E systems are more complex than the binary nature of these terms implies (*25*). Hence, developing a predictive understanding of them is a major challenge for modern science (*55*), a challenge that is particularly accentuated in drylands.

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28. In wealthy economies, there are enough resources for technological-managerial intervention to compensate for declines in critical variables of the H-E system (e.g., through large-scale water transport) or to shift the entire dryland-use system (e.g., suburban expansion of the American Sunbelt) (*58*).
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40. ARID*net* is an international network (Box S2) established to conduct case studies of dryland H-E systems, the goal of which is to facilitate field-level interactions between researchers, local stakeholders (farmers, landowners, developers), and decision-makers.
41. E. Huber-Sannwald, F. T. Maestre, J. E. Herrick, J. F. Reynolds, *Hydrol. Process.* **20**, 3395 (2006).
42. Millions of rural poor in the subhumid and semi-arid regions of Guatemala, Honduras, Nicaragua, and El Salvador face severe food deficits and poor opportunities for generating income to improve their livelihoods. The Quesungual Slash and Mulch Agroforestry System (QAS) was developed as a development strategy to improve rural livelihoods in the Lempira Department, Honduras, and has now been adopted by more than 6000 farmer households. This alternative to slash-and-burn agriculture builds strongly on local knowledge to deliver a doubling in crop yields and cattle-stocking rates and considerable reduction in costs associated with agrochemicals and labor, as well as much improved resilience to droughts and cyclones thanks to enhanced landscape water-holding characteristics. To examine the QAS in the context of the DDP framework, an ARID*net* workshop (13 to 20 November 2005)—involving 20 natural and social scientists working in conjunction with local communities and decision-makers—conducted a systematic analysis of long-term sustainability in the Candelaria region of Lempira. An analysis of findings showed that increased rates of soil erosion associated with inappropriate management practices in southern Honduras and northern Nicaragua can push these hillside agroecosystems across hydrologic thresholds (principle 3 in Table 2, i.e., P3; P1 to P5 and ki-1 to ki-5 refer to principles 1 to 5 and key implications 1 to 5, respectively, in Table 2) when coarse-textured surface horizons are lost. Intervention costs rise nonlinearly (ki-3) for both biophysical (soil profile development) and socioeconomic reasons (more-motivated farmers emigrate in early stages of yield decline) (P1, ki-1). The QAS, based on local environmental knowledge (P5), effectively addresses the key slow biophysical variables (soil depth and forest cover) by increasing the stability over time of the fast biophysical (soil moisture availability) and socioeconomic variables (income is diversified with fuelwood and tree-crop production) (P2). The system is supported by an extensive set of government and nongovernment relationships at multiple levels (P4, ki-4). The DDP analysis, and the development of related conceptual models, helped workshop participants identify the key factors and processes addressed by the QAS (P5). For another example, from Mexico, see Box S3.
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Supporting Online Material

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Boxes S1 to S3

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