Chapter 14

Spatial Nonlinearities: Cascading Effects in the Earth System

Debra P.C. Peters · Roger A. Pielke Sr. · Brandon T. Bestelmeyer · Craig D. Allen · Stuart Munson-McGee · Kris M. Havstad

14.1 Introduction

Nonlinear behavior is prevalent in all aspects of the Earth System, including ecological responses to global change (Gallagher and Appenzeller 1999; Steffen et al. 2004). Nonlinear behavior refers to a large, discontinuous change in response to a small change in a driving variable (Rial et al. 2004). In contrast to linear systems where responses are smooth, well-behaved, continuous functions, nonlinear systems often undergo sharp or discontinuous transitions resulting from the crossing of thresholds. These nonlinear responses can result in surprising behavior that makes forecasting difficult (Kaplan and Glass 1995). Given that many system dynamics are nonlinear, it is imperative that conceptual and quantitative tools be developed to increase our understanding of the processes leading to nonlinear behavior in order to determine if forecasting can be improved under future environmental changes (Clark et al. 2001).

Although most global change studies have examined nonlinear behavior through time (e.g., Pascual and Ellner 2000; Gill et al. 2002; Gerber et al. 2004), it is increasingly recognized that spatial interactions, transport processes, and landscape complexity are important in generating nonlinear behavior through time *and* across space (Aber et al. 1999; Reiners and Driese 2001, 2004). In particular, contagious processes that propagate nonlinearly through time from small to broad spatial extents (i.e., spatial nonlinearities) often generate surprising behavior where dynamics at one scale cannot be easily predicted based on information obtained at finer or broader scales (Holling 1992, 1996; Nieminen 2003). These cascading effects often result in severe consequences for the environment and human welfare (i.e., catastrophes) that are expected to be particularly important under conditions of changes in climate and land use (NRC 2001; Steffen et al. 2004). A key challenge to Earth System science in the face of global change is to understand and predict these cascading effects and their catastrophic consequences (Steffen et al. 2004).

Earlier frameworks have described nonlinear, catastrophic behavior in terms of spatial propagation, positive feedbacks, and thresholds. Holling's (1973) seminal work linked disturbances to alternative stable states and thresholds between them through feedback mechanisms. The concept of self organized criticality introduced the notion that perturbations at critical thresholds may involve self-propagating changes at a variety of spatial and temporal scales (Bak et al. 1988; Chen et al. 1991). Together, these ideas linked spatial and temporal pattern to describe how dynamics may be self-organized. This linkage illustrated the value of recognizing coupled spatial and temporal patterns in ecosystems at multiple scales, and underlies the search for feedback mechanisms (Folke et al. 2004), critical thresholds of connectivity in applications of percolation theory (Davenport et al.1998) and the recognition of patch- to landscape pattern to explain catastrophic shifts in the pattern of vegetation (Rietkerk et al. 2004).

Despite these advances, our understanding of and ability to predict events that propagate across scales (i.e., cascade) and produce catastrophic changes remains limited. For example, this class of ecological problems includes insect outbreaks that spread nonlinearly from fine to broad scales (Swetnam and Lynch 1993). Because the rate and extent of an insect outbreak may be related to climatic patterns (Speer et al. 2001) and interactions with disturbance (Scheller and Mladenoff 2005), changes in climate and land use are expected to have large effects on these dynamics. Similarly, single lightning strikes can initiate broad-scale wildfires as a result of positive feedbacks among weather, fire behavior, land-use patterns, and vegetation interacting across multiple scales. Nonlinear patterns in connectivity of fires are often related to spatial variation in fuel loads (Miller and Urban 2000). Extensive and rapidly expanding fires may be driven by feedbacks with the atmosphere. Although fire (and other) behaviors have been described with respect to the internal forces of self-organized criticality (Drossel and Schwabl 1992), they have not been considered with reference to the role of feedbacks involving a variety of external drivers.

In this chapter, we *first* briefly describe a general conceptual and mathematical framework for understanding and forecasting spatially nonlinear responses to global change in driving variables. The *second* goal of this chapter is to illustrate the utility of our framework in describing the spread of catastrophic events using one historical example (the Dust Bowl) and two current examples (wildfires, invasive species and desertification). *Finally*, we discuss the consequences of applying these ideas to forecasting future dynamics under a changing global environment. Given the continuing challenges associated with global change, our synthetic approach that crosses disciplinary boundaries to include interactions and feedbacks across multiple scales shows great potential to increase our ability to forecast catastrophic events and to develop strategies for minimizing their occurrence and impacts.

14.2 Conceptual Framework

In our framework, we focus on catastrophic events that start small, and propagate nonlinearly to influence broad spatial extents (described in detail in Peters et al. 2004). Mathematically, spatial nonlinearities can be illustrated as:

$$\mathrm{d}Y/\mathrm{d}t = g(I_g, E_g) + f(Y, E_f) + D(Y, E_D) + c(Y, E_c)$$

where each term is associated with one of the four stages in the general model, and is a function of different parameters. All terms except g depend, at least in part, on properties of Y. As the rate of change in Y increases (decreases) through time, it is increasingly governed by terms towards the right (left) [from $g(I_g, E_g)$ to $c(Y, E_c)$] as the amount, connectivity, and spatial extent of Y increases (decreases). Three thresholds occur between the various stages. Stage 14.1 (initiation of Y) is defined by $g(I_g, E_g)$ where (I_g) is internal factors and (E_g) is external factors (e.g., weather) that influence initiation. Stage 14.2 (within patch spread of Y) is defined by $f(Y, E_f)$ where Y is within patch properties and (E_f) is external factors that influence patch heterogeneity (e.g., local weather). Stage 14.3 (spread of Y among patches) is defined by $D(Y, E_D)$ where Y is among patch heterogeneity in Y and E_D is external factors that influence among patch spread (e.g., template heterogeneity). Stage 14.4 (land-atmosphere feedbacks that influence the spread of Y) is defined by $c(Y, E_c)$ where Y is broad scale properties of Y and E_c is broad scale processes or forcing functions.

Our framework includes cross scale interactions, threshold behavior, and feedback mechanisms that generate spatial nonlinearities. There are four key characteristics of our framework: (1) feedback mechanisms are prevalent at a number of scales, (2) thresholds in the dynamic behavior of the system are crossed through time with broader scale consequences, (3) the dominant process controlling system dynamics changes through time and across space, and (4) connectivity along spatial units is important to the generation of cascading dynamics. Although the significance of feedbacks and thresholds is recognized in many disciplines (Elsner and Tsonis 1992; Zeng et al. 1993; Hethcote 2000; Scheffer et al. 2001; Tsonis 2001), the incorporation of processes across spatial scales that cross traditional disciplinary boundaries is required to understand and forecast these events.

14.3 Insights to Global Change Issues

14.3.1 Historical Example: the Dust Bowl of the 1930s

Extreme climatic events have played important roles in ecosystem dynamics historically (Swetnam and Betancourt 1998), and are expected to become increasingly important if the frequency, intensity, and magnitude of extreme events increase with time (Easterling et al. 2000). One historical event that was related to extreme climate interacting with land use was the Dust Bowl that occurred in the 1930s in the United States. This catastrophic event involved localized wind erosion from individual agricultural fields that propagated nonlinearly to generate massive dust storms that were accompanied by mass migrations and economic hardship felt throughout the U.S. Insights gained by examining this historical event within the context of our new cross scale framework can improve our ability to understand, mitigate, and forecast similar catastrophic events.

The Dust Bowl or the "Dirty Thirties" was characterized by a series of years with very low rainfall and high temperatures that generated intense drought conditions throughout the central Great Plains (Worster 1979). Recent analyses indicate that these atmospheric conditions were likely caused by anomalous tropical sea surface temperatures (Schubert et al. 2004). Although these atmospheric conditions were unusual for the 20th century, major droughts have occurred in this region once or twice a century for the past 400 years (Woodhouse and Overpeck 1998). Thus, it is unlikely that extreme climatic conditions alone were sufficient to result in the Dust Bowl, but rather that land-atmosphere interactions increased its severity (Schubert et al. 2004).

Importantly, the Dust Bowl was preceded in the 1920s with government policies that favored cultivation of drought sensitive crops on increasingly marginal land (Hurt 1981). Thus, the landscape consisted of a mosaic of cultivated, drought-susceptible land interspersed with small areas of native grassland. Hot, dry weather combined with strong winds in the 1930s resulted in decreased plant cover and high plant mortality on these cultivated fields (Fig. 14.1a); similar patterns were observed on native grassland, but the effects were not as severe (Weaver and Albertson 1936, 1940; Albertson and Weaver 1942). Low plant cover and strong winds resulted in localized wind erosion and blowing dust at the scale of individual fields (Fig. 14.1b). At the landscape scale, these small dust storms became aggregated among fields (Fig. 14.1c) to generate massive dust storms ("black blizzards") that

Fig. 14.1. **a** Drought in the 1930s resulted in decreased plant cover and high plant mortality at the scale of individual fields (Morton County, Kansas, 1938. Photo courtesy of USDA-ARS-Wind Erosion Research Unit and Kansas State University, http://www.weru.ksu.edu/), **b** wind erosion from within a field in South Dakota, (R. Lord, 1938. Miscellaneous Publication No. 321, U.S. Department of Agriculture. Photos courtesy of the National Oceanic and Atmospheric Administration, http://www.photolib.noaa.gov), **c** dust rising from a landscape of agricultural fields (photo courtesy of USDA-ARS-Wind Erosion Research Unit and Kansas State University, http://www.weru.ksu.edu/), and **d** aggregation of dust storms resulted in Black Sunday April 14, 1935 (photo courtesy of USDA-ARS-Wind Erosion Research Unit and Kansas State University, http://www.weru.ksu.edu/)

spread to the regional and continental scales (Fig. 14.1d). Blowing soil from the Great Plains was documented as far as the East coast, over 1 500 km away (Miller 1934). Although it was not documented at the time, it is likely that these large dust storms had important feedbacks to the weather through high atmospheric dust loading and high albedo (Fig. 14.2). These changes would have reduced rainfall (Rosenfeld et al. 2001) and increased temperatures, similar to land-atmosphere feedbacks documented in Saharan Africa (Clausen et al. 1999).

Mass migrations, reduced quality of life, and agricultural depression as a result of these dust storms had economic and social ripples to other parts of the country (Lockeritz 1978). Approximately 35 million acres of formerly cultivated land was destroyed with >200 million acres of cropland with reduced topsoil (Yearbook of Agriculture 1934). In April 1935, the U.S. Congress declared soil erosion "a national menace". Federal drought assistance to farmers has been estimated at $1 billion (in 1930s dollars) (Warrick 1980). In addition, migration of people from the Dust Bowl region created economic strain in other parts of the U.S.

We can understand the sequence of processes leading to the Dust Bowl using our conceptual framework that includes multiple stages, thresholds, and a change in dominant process through time and across space. The Dust Bowl was initiated (Stage 14.1) by two interacting conditions: consecutive years with extreme weather com-

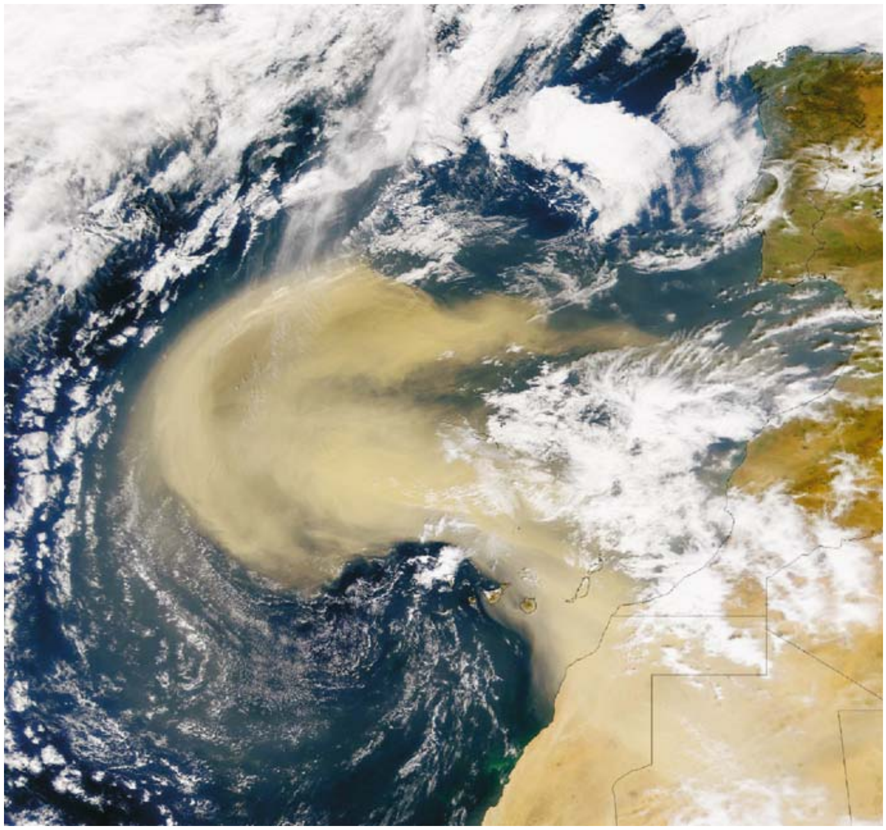

Fig. 14.2.
Land-atmosphere interactions can result in regional- to continental-scale dust storms, such as this one from the African Sahara, February 26, 2000 (photo courtesy of SeaWiFS and NASA Goddard Space Flight Center, http://visibleearth.nasa.gov)

bined with individual farmer decisions to cultivate increasingly marginal farmland. Onset of the drought would have resulted in high mortality of plants and an increase in the amount of bare soil on individual fields. Strong winds would have generated soil erosion from individual fields after thresholds in wind velocity and plant cover were crossed (Stage 14.2). Because a number of farmers made the same decisions about crop and field selection, and the drought conditions were widespread, a second threshold would have been crossed related to connectivity among fields such that dust storms developed and spread across the landscape (Stage 14.3). At this stage, the rate and spatial extent of wind erosion would have been determined by the number, size, and spatial arrangement of fields interacting with regional scale weather conditions (Fig. 14.3). As the spatial extent of wind erosion continued to increase, another threshold would have been crossed where land-atmosphere interactions would have become operative to generate positive feedbacks and the creation of massive dust storms at the regional to continental scale (Stage 14.4).

It was recognized during the Dust Bowl period that a complex set of interactions were involved that included weather, vegetation, soils, and human activity (Great Plains Committee 1937). Although the committee stated that "all too frequently what appears to be good to the individual in the long run is not good for the people of the region" (Great Plains Committee 1937), our understanding about how these individual decisions interact with climate and ecological systems has remained limited. For example, conservation practices remain focused on the protection of individual fields or a small collection of fields rather than reducing connectivity among a large number of fields. Our framework suggests that limiting connectivity among fields is key to reducing the severity of these kinds of events.

Drought and other extreme climatic events (e.g., floods, hurricanes) will continue to occur in the Earth System (Easterling et al. 2000). Nonlinear interactions and positive feedbacks among climate, land use, and land cover can result in the propagation of impacts across broad spatial scales in relatively short time periods. However, the spatial extent and impact of these events can be mitigated, and possibly forecast, by understanding how these spatial nonlinearities develop and spread. In some cases, limiting landscape scale connectivity can reduce these impacts.

14.3.2 Wildfire

Wildfires are dominant forces shaping the structure and dynamics of forests, savannas, and grasslands as well as their neighboring or imbedded urban areas worldwide (Scholes et al. 2003). Policies associated with natural areas, particularly in developed countries, have often promoted the development of nearly continuously distrib-

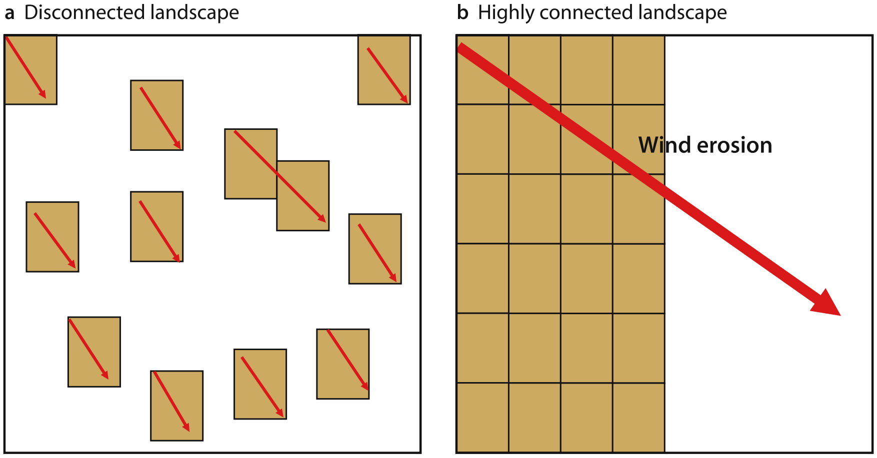

Fig. 14.3. Potential for wind erosion is less for landscapes consisting of a few, widely distributed bare fields (**a**) compared with a landscape that is mostly bare fields (**b**). Farming practices in the 1920s and 1930s in the U.S. predisposed these landscapes to high connectivity resulting from interactions between drought and strong winds, thus leading to the Dust Bowl

uted fuel loads that increasingly allow large, rapidly spreading fires to emerge (USDA 1978). The costs of wildfires are substantial: annual wildfire suppression costs in the U.S. now routinely exceed US$1 billion yr^{-1}. In addition, wildfires can have substantial impacts on atmospheric carbon monoxide (CO) and fine particulates (Scholes et al. 2003). For example, fires in Southeast Asia (2001) resulted in plumes of CO that extended across the Pacific Ocean to the west coast of North America (Steffen et al. 2004). Regional effects are also important: CO emitted by the Hayman fire in Colorado, USA (2003) was at least five times the annual amount produced by industrial sources in that state (Graham 2003). These pulse emissions occurred over a period of days with longer-term impacts on rainfall from the fine particles that extended hundreds of kilometers downwind.

Although it is recognized that short- and long-term weather conditions interacting with the amount, moisture content, and spatial distribution of fuels affect the extent, rate of spread, and severity of wildfires (Graham 2003), the factors that determine if a wildfire can be contained or if it will "blow up" and create catastrophic conditions have not been quantified. For example, 14 firefighters were killed during the Storm King Mountain fire in western Colorado USA (1994) following a sudden wind shift that created surface winds exceeding 55 km h^{-1} and flames 60–90 m high (Butler et al. 1998). Highly connected fuels interacted nonlinearly with the heat of the fire and with a larger scale wind shift to create this rapid change in wind direction and speed. In addition, positive feedbacks among landscape structure, fire, and weather can occur if the climate in the region warms (Laurance and Williamson 2001; McKenzie et al. 2004). Thus, the explosive spread of wildfires across landscapes is not easily forecast based either on fine scale fire behavior or broad scale atmospheric conditions. Our framework that focuses on spatial nonlinearities resulting from connectivity within and among patches of vegetation, and feedbacks to the atmosphere provides new insights into these complex fire dynamics.

We distinguish four major stages of wildfire behavior that are associated with three thresholds or nonlinear changes in the rate of fire spread through time and across space (Peters et al. 2004). This model is supported by published data from two fires in Colorado, USA with similar behavior, yet very different spatial extents (Peters et al. 2004). Similar patterns of fire spread have been documented for other major fires.

In Stage 14.1, fire that is ignited naturally or started by human activities can either spread or stop (Fig. 14.4a). The fire can cross a threshold (T1) to Stage 14.2 by spreading within a patch if local weather conditions, fuel load, and connectivity are sufficient (Fig. 14.4b) (Whelan 1995). For canopy fires to spread, the trees must be sufficiently close for flames to move from one tree to another within a patch. For surface fires to spread, threshold amounts and spatial connectivity of herbaceous fuels must be present. In addition, surface fires can move upward into tree canopies when vertically continuous "ladder" fuels (e.g., small subcanopy trees) connect the burning surface fuels with canopy fuels, generating localized torching.

A second threshold (T2) is crossed when the fire enters Stage 14.3 and burns from one patch to another at varying rates that depend on connectivity and spatial distribution of fuel load as well as interactions with local weather conditions (Fig. 14.4c). Patches that are poorly connected to other patches have low probabilities of the fire spreading whereas fire frequently spreads among patches that are highly connected. Parts of the landscape with low fuel connectivity often burn more slowly and less completely than highly connected parts of the landscape (Turner et al. 2003). As the fire continues to increase in extent and intensity, a third threshold can be crossed (T3) to move the fire into Stage 14.4 that depends on interactions and feedbacks between the fire and the atmosphere. As heated gases from the fire rise into the atmosphere, low air pressure pulls air into the fire, thus creating strong winds. These surface winds drive fire behavior by accelerating fire

Fig. 14.4. The four stages and three thresholds involved in wildfires: **a** a lightning strike can initiate a fire that either goes out or **b** spreads within a patch. Through time, the fire can **c** spread among patches across a landscape and **d** blow up when the heat and intensity of the fire interact with atmospheric conditions to provide a positive feedback to the fire

intensity and rate of spread. These positive feedbacks between fire activity and wind circulation develop rapidly resulting in a "blowup" of the fire with preheating of fuel and "spotting" ahead of the fire front (Fig. 14.4d). Explosive fire activity of this sort can generate large pyrocumulus clouds, particularly when atmospheric conditions are unstable and susceptible to convectional cloud formation (Byram 1954). Under these "blowup" conditions, all parts of the landscape burn, often at higher temperatures, regardless of fuel load or connectivity.

Although general stages of fire behavior have been documented previously and wildfires have been extensively studied at individual scales, we are still missing a clear understanding of the key processes and conditions that lead to catastrophic fire behavior (Steffen et al. 2004). Our approach provides a framework for linking these extensive datasets and models that were developed for specific applications and scales. Understanding cross-scale interactions and feedbacks will improve our ability to identify the key processes generating fire behavior across scales, and to forecast the conditions under which fine scale processes cascade nonlinearly to impact broad spatial extents with consequences for land-atmosphere interactions. Understanding these cross scale interactions will improve our ability to forecast fire behavior under changing weather and land-use regimes that include the continued use of fire as a management tool for many regions of the world (Scholes et al. 2003).

14.3.3 Invasive Species and Desertification

We illustrate the spread of invasive species using woody plant encroachment into perennial grasslands and associated land degradation (i.e., desertification). A wide range of native and exotic species exhibit similar patterns and dynamics (e.g., Hobbs and Humphries 1995; Mack et al. 2000). Desertification is a major problem globally: ca. 40% of the Earth's land surface consists of drylands that are susceptible to desertification and support ca. 20% of the world's human population (Reynolds and Stafford Smith 2002). Conversion of grasslands with homogeneous plant cover to shrublands or woodlands with discontinuous cover interspersed with bare areas often results in local to global consequences, such as increased soil erosion by wind with dust generation to the atmosphere (Schlesinger et al. 1990; Tegen and Fung 1995; Husar et al. 2001). The problem of desertification is complicated by the presence of multiple interacting processes, threshold behavior, and feedbacks with meteorological, hydrological, ecological, and human dimensions (e.g., Rietkerk and van de Koppel 1997; Zeng et al. 1999; Ludwig and Tongway 2000; Reynolds and Stafford Smith 2002; Wilcox et al. 2003). Although numerous studies have been conducted on desertification, a clear consensus is missing regarding the key processes involved and how they produce a variety of responses under apparently similar conditions as well as similar ecological consequences under different conditions (Peters et al. 2006). We propose that cross-scale linkages among three system elements are key determinants of desertification dynamics: (1) local soil and grass degradation associated with large herbivore grazing and other factors, (2) connectivity of erosion processes at multiple scales, and (3) land-atmosphere feedbacks.

Desertification is initiated by the introduction of woody plant seeds into a grass-dominated system (Stage 14.1) as a result of vectors, such as wind, water, and cattle, which transport seeds from woody plant-dominated areas to grasslands (Brown and Archer 1987). In some cases, initiation events fail because microenvironmental conditions are insufficient for establishment. In other cases, particularly when excessive grazing by large herbivores reduces grass cover and competitiveness with a resulting decrease in fire frequency, shrub establishment events succeed and a threshold is crossed (T1) where shrub invasion proceeds (Fig. 14.5). Local spread of a patch of established woody plants within a grassland then occurs (Stage 14.2), either through vegetative expansion or local seed dispersal followed by establishment (Archer 1990). Feedback mechanisms among woody plants and soil properties influence the rate of within-patch expansion. As woody plant size or density increase within a patch, the spatial extent of bare area between woody plants increases, such

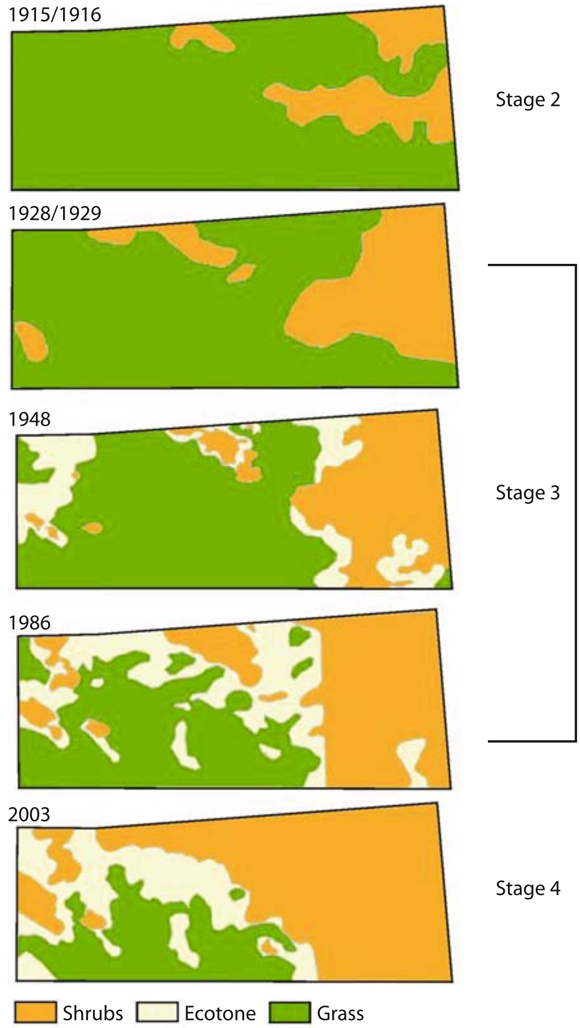

Fig. 14.5. The four stages and three thresholds in desertification. The five panels (942 ha total area) show three classes of vegetation: grasslands, ecotones containing grasses and shrubs, and shrublands through time in the Chihuahuan Desert of southern New Mexico. Field surveys (1915, 1928–1929; Gibbens et al. 2004), black and white (1948) and color infrared photos (1986) and Quickbird satellite images (2003) were scanned at 1200 dpi and geometrically corrected to the satellite image. Boundaries of three classes were manually digitized and areas were calculated in ArcGIS (data shown in Peters et al. 2004). *Stage 14.1:* Desertification begins with the introduction of shrub seeds into a grass-dominated system. In some cases, initiation events fail, and in other cases, they succeed and a threshold is crossed (*T1*) where shrub proliferation (Stage 14.2) proceeds. At this site in NM, this initiation occurred prior to 1915. *Stage 14.2:* Established shrubs proliferate around initial colonizers to form expanding patches (shown in 1915 map). *Stage 14.3:* As the size and density of woody plants continue to increase through time, a second threshold is crossed (*T2*) where contagious processes among patches, in particular wind erosion of bare soil patches, become the dominant factors governing the rate of desertification. *Stage 14.4:* Eventually sufficient land area is converted from grassland (low bare area, low albedo) to a shrubland (high cover of bare area, high albedo) that atmospheric conditions are affected, in particular wind speed, temperature, and precipitation, and a third threshold in crossed (*T3*). Because 92% of the land area of the surrounding research site was shrub dominated in 1998 (Gibbens et al. 2004), we hypothesize that *T3* occurred after 1986

that wind and water can redistribute resources in bare interspaces to areas beneath shrubs, thus forming resource islands (Schlesinger et al. 1990). Seed availability within shrub patches also increases the probability of new initiation events that result in isolated woody plants within the neighboring grassland matrix.

As the size and density of woody plants continue to increase through time, a second threshold is crossed (T2) where contagious processes among patches become the dominant factor governing the rate of desertification (Stage 14.3). This dispersion of woody plants often depends on the connectivity and spatial extent of bare areas that are influenced by wind or water erosion or their combination (Breshears et al. 2003). Bare areas influence woody plant establishment and survival as well as grass mortality with effects on vegetation patterns and dynamics.

Through time, erosion continues to increase the size and connectivity of bare soil patches, grass mortality, and hence woody plant dominance, such that adjoining areas of the landscape can be affected by wind-deposited soil (Youlin et al. 2001). Sufficient land surface area is converted from grasslands with low bare area and low albedo to woodlands with high percentage cover of bare area and high albedo. This broad-scale change in land-cover type can affect regional atmospheric conditions, in particular temperature and precipitation (e.g., Charney et al. 1977; Balling et al. 1998; Xue and Fennessy 2002) such that a third threshold is crossed (T3) in which land-atmosphere interactions with feedbacks to plants strongly influence vegetation dynamics (Stage 14.4) (Pielke 2001; Kabat et al. 2004). These climatic feedbacks to broad-scale vegetation patterns as a result of desertification have been documented: biophysical feedbacks may have resulted in a drier climate and a shift to desert vegetation ca. 5 500 years ago in the Sahara region of Africa (Claussen et al. 1999; deMenocal et al. 2000). Increased wind erosion and deposition of sand off the coast of West Africa may have resulted from this change in climate and shift in vegetation (deMenocal et al. 2000). Dust and other airborne particles can reduce water droplet sizes in clouds to result in reduced rainfall (Rosenfeld et al. 2001) that would then generate feedbacks to the vegetation.

Interactions among climate, land use, and land management will continue to be important drivers in future desertification dynamics. In these water-stressed environments, directional changes in climate or increases in its variability could increase aridity and push these systems to states and dynamics that go beyond current and past experience. For example, an increase in the frequency or severity of drought will likely interact nonlinearly with land management decisions to result in nonlinear increases in the rate and extent of desertification (Squires 2001). By accounting for cross-scale interactions, our approach provides new directions for combating desertification that are currently constrained by observations and models based on particular scales (Peters et al. 2004). Developing site-specific remedies requires quantification of cross-scale interactions among human activities, livestock grazing, drought, and other factors that are coupled by spatial patterns of vegetation at multiple scales. Data collected according to our interdisciplinary framework can be used to identify the key processes governing patterns and rates of desertification as well as thresholds. These data will indicate optimal strategies for manipulating connectivity across scales in order to minimize negative impacts and to capitalize on opportunities for remediation.

14.4 Forecasting Spatial Nonlinearities and Catastrophic Events

Catastrophic events resulting from spatial nonlinearities often result in major changes in ecosystem properties and services as well as loss of life or quality of life, and economic hardship. Our ability to forecast these events, particularly in the presence of environmental and societal changes, is constrained by our limited understanding of the processes, feedbacks, and nonlinear interactions that result in these spatially complex dynamics (Sarewitz et al. 2000). Most of our ecological understanding is based on experiments, observations, and simulation modeling from individual spatial or temporal scales. Experiments are most often conducted at fine scales whereas observations and simulation modeling can include multiple scales from fine to broad. Results from these single or multiple scale studies are often unable to detect cross scale interactions and dynamics that propagate across space (Peters et al. 2004).

We advocate experimental, observation, and modeling networks of studies that explicitly address cross scale interactions as the most fruitful approach to forecasting catastrophic events resulting from spatial nonlinearities. Existing networks of research sites, such as the U.S. National Science Foundation supported Long Term Ecological Research program, provide invaluable site-based information, often with historical and spatial context (Hobbie et al. 2003). However, there is currently insufficient spatial coverage by existing sites as well as insufficient integration, infrastructure, and measures of connectivity across scales, both within and among sites, to assess whether skillful forecasting is possible of how, when, and why small events cascade nonlinearly to result in broad-scale catastrophic impacts. Networks that attempt to address these types of national level, continental scale problems are on the horizon (e.g., National Ecological Observatory Network; http://www.neoninc.org/) that will provide the necessary information to improve our understanding and ability to forecast and mitigate these events.

14.5 Summary and Conclusions

Given the complexity of the issues in Earth System science, future research will need to adopt approaches that cross traditional disciplinary boundaries in order to address cross scale interactions, threshold behavior, and feedback mechanisms leading to catastrophic events (Steffen et al. 2004). Our understanding of broad-scale patterns and dynamics has improved through collaborative efforts among ecosystem ecologists and atmospheric scientists (e.g., Rial et al. 2004). In addition, human dimensions are increasingly recognized by ecologists as integral to explaining system dynamics (e.g., Reynolds and Stafford Smith 2002). However, cross-disciplinary studies are needed to understand and forecast nonlinear dynamics and threshold behavior through time and across space (Peters et al. 2004). The blending of ideas and terms across scientific disciplines by our framework is an important step in this new level of cross-disciplinary research. Future steps include integrated experiments and modeling studies that synthesize technologies and expertise from diverse disciplines. Our ability to show similarities in system dynamics from seemingly disparate disciplines indicates that much is to be gained by cross disciplinary efforts that capitalize on the strengths of each discipline.

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