Chapter 5—What Can Be Done?

Because there is significant potential for abrupt or threshold-type changes in ecosystems in response to climate change, what changes must be made in existing management models, premises, and practices to manage these systems in a sustainable, resilient manner? What can be managed and at what scales, given that climate change is global in nature but manifests itself at local and regional scales of ecosystems? This section reviews the management models that predict how ecosystems will respond to climate change and examines their adequacy for addressing threshold behavior.

5.1 Integration of Management and Research

With ongoing climate change and the threat that ecosystems will experience threshold changes, managers and decisionmakers are facing more new challenges than ever. Strong partnerships between research and management can help in identifying and providing adaptive management responses to threshold crossings. Because decisionmakers are dealing with whole new ecosystem dynamics, the old ways of managing change do not apply. A new paradigm in which research and management work closely together is needed. The following sections highlight some of the needs of managers.

5.1.1 Need for Conceptual Models

Most frameworks for nonlinear ecosystem behavior are hierarchical so a small number of structuring processes control ecosystem dynamics; each process operates at its own temporal and spatial scale (O'Neill *et al.*, 1986). Finer scales provide the mechanistic understanding for behavior at a particular scale, and broader scales provide the constraints or boundaries on that behavior. Functional relationships between pattern and process are consistent within each domain of scale so that linear extrapolation is possible within a domain (Wiens, 1989). Thresholds occur when pattern-and-process relationships change rapidly with a small or large change in a pattern or environmental driver (Bestelmeyer, 2006; Groffman *et al.,* 2006), although both external stochastic events and internal dynamics can drive systems across thresholds (Scheffer *et al.,* 2001). Crossing a threshold can result in a regime shift where there is a change in the direction of the system and the creation of an alternative stable state (Allen and Breshears, 1998; Davenport *et al.,* 1998; Walker and Meyers, 2004). Under some conditions, thresholds may be recognized when changes in the rate of fine-scale processes within a defined area propagate to produce broad-scale responses (Gunderson and Holling, 2002; Redman and Kinzig, 2003). In these cases, fine-scale processes interact with processes at broader scales to determine system dynamics. A series of cascading thresholds can be recognized where crossing one pattern-and-process threshold induces the crossing of additional thresholds as processes interact (Kinzig *et al.*, 2006).

5.1.2 Scaling

Recent theories and ideas about system behavior have used hierarchy theory as a basis for describing interactions among processes at different scales. Such theories include complex systems (Milne, 1998; Allen and Holling, 2002), self-organization (Rietkerk *et al.*, 2004), panarchy (Gunderson and Holling, 2002), and resilience (Holling, 1992; Walker *et al.,* 2006). Cross-scale interactions (CSIs) (processes at one spatial or temporal scale interacting with processes at another scale that often result in nonlinear dynamics with thresholds) are an integral part of all of these ideas (Carpenter and Turner, 2000; Gunderson and Holling, 2002; Peters *et al.,* 2004). These interactions generate emergent behavior that can not be predicted based on observations at single or multiple, independent scales (Michener *et al.,* 2001). Cross-scale interactions can be important for extrapolating information about fine-scale processes to broad-scales or for down-scaling the effects of broad-scale drivers on fine-scale patterns (Ludwig *et al.,* 2000; Diffenbaugh *et al.,* 2005). The relative importance of fine- or broad-scale pattern-and-process relationships can vary through time and compete as the dominant factors controlling system dynamics (*e.g.,* Rodó *et al.,* 2002; King *et al.*, 2004; Yao *et al.*, 2006).

Because CSI-driven dynamics are believed to occur in a variety of systems, including lotic invertebrate communities in freshwater streams (Palmer *et al.,* 1996) and lakes (Stoffels *et al.,* 2005), mouse populations in forests (Tallmon *et al.,* 2003), soil microbial communities (Smithwick *et al.*, 2005), coral reef fish recruitment in the ocean (Cowen *et al.,* 2006), human diseases (Rodó *et al.,* 2002), and grass-shrub interactions in deserts (Peters *et al.*, 2006), it is critical that ecologists find ways to measure CSI. It is important to identify the key processes involved in these changing pattern-and-process relationships so that thresholds can, at a minimum, be understood and predicted if not averted through proactive measures.

Recently, a framework was developed to explain how patterns and processes at different scales interact to create nonlinear dynamics (Peters *et al.*, 2007). This framework focuses on intermediate-scale properties of transfer processes and spatial heterogeneity to determine how pattern-and-process relationships interact from fine to broad scales (fig. 5.1). In this framework, within a domain of scale (*that is*,, fine, intermediate, or broad), patterns and processes can reinforce one another and be relatively stable. Changes in external drivers or disturbances can alter pattern-and-process relationships in two ways.

First, altered patterns at fine scales can result in positive feedbacks that change patterns to the point that new processes and feedbacks are induced. This shift is manifested in a nonlinear threshold change in pattern and process rates. For example, in arid systems, disturbance to grass patches via heavy livestock grazing can reduce the competitive ability of grasses and allow shrub colonization. After a certain density of shrubs is reached in an area and vectors of propagule transport (for example, livestock, small animals) are available to spread shrubs to nearby grasslands, shrub colonization and grass loss can become controlled by dispersal processes rather than by competition. Shrub expansion rates can increase dramatically (Peters *et al.*, 2006). As shrub colonization and grazing diminish grass cover over large areas, broad-scale wind erosion may govern subsequent losses of grasses and increases in shrub dominance. These broad-scale feedbacks downscale to overwhelm fine-scale processes in remnant grasslands. Once erosion becomes a pervasive landscape-scale process, neither competition nor dispersal effects have significant effects on grass cover.

Second, direct environmental effects on pattern-and-process relationships at broad scales can similarly overwhelm fine-scale processes. For example, regional, long-term drought can produce widespread erosion and minimize the importance of local grass cover or shrub dispersal to patterns in grasses and shrubs.

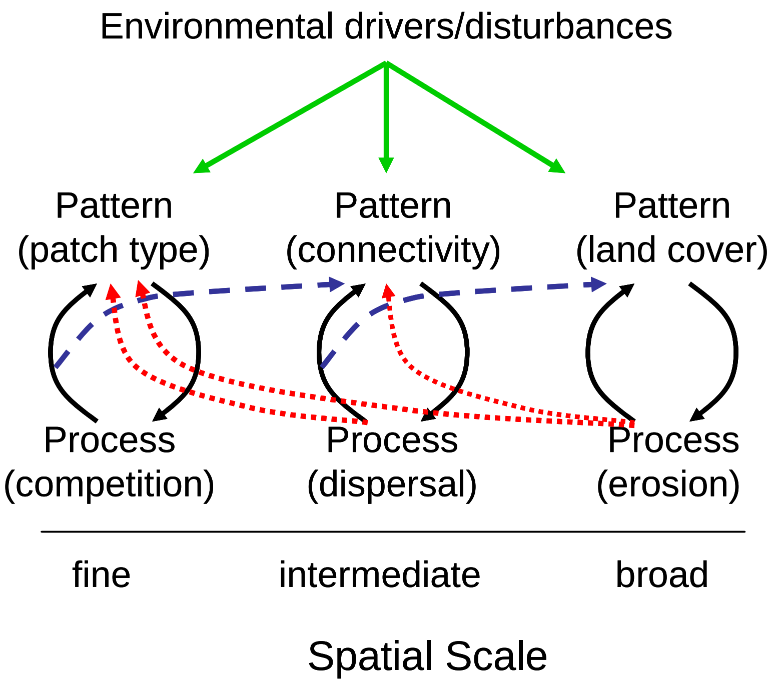

Figure 5.1. Diagram representing cross-scale interactions. Solid arrows represent pattern-and-process feedbacks within three different scale domains with one example of pattern and process shown for each domain. Green arrows indicate the direct effects of environmental drivers or disturbances on patterns or processes at different scales (*e.g.*, patch disturbance versus climate). Blue arrows indicate the point at which altered feedbacks at finer scales induce changes in feedbacks at broader scales (*e.g.*, fine-scale changes cascade to broader scales). Red arrows indicate when changes at broader scales overwhelm pattern-and-process relationships at finer scales.

5.1.3 Applying Models from Other Disciplines

Climate is, by definition, interdisciplinary. Recent and global environmental changes, including climatic change, changes in atmospheric composition, land-use change, habitat fragmentation, pollution, and the spread of invasive species, have the potential to affect the structure and functions of some ecosystems, and the services they provide. Many ecological effects of global environmental change have the potential for feedbacks (either positive or negative) to climatic and other environmental changes. Furthermore, because many global environmental changes are expected to increase in magnitude in the coming decades, the potential exists for more significant effects on ecosystems and their services.

As climate change manifests itself at local and regional scales of ecosystems, it is necessary not only to downscale forecasting models but also to ensure that models used for predictions take into account not just the physical parameters that support ecosystems but also the biotic aspects of the ecosystems. Biomes and ecosystems do not shift as entities in response to climate change, but they change through the responses of individual species (Scott and Lemieux, 2005). The biogeochemical, temperature, and precipitation requirements of individual species need to be taken into account when predicting these shifts thus the need for the use of interdisciplinary models that address these variables and their dynamic feedback. Our current understanding suggests that using interdisciplinary models will very likely reduce scientific uncertainties about the potential effects of global change on ecosystems and provide new information on the effects of feedbacks from ecosystems on global change processes. The challenge is to create a framework in which interdisciplinary models can work interactively to consider all the feedbacks involved.

5.2 Adaptive Management to Increase Resilience

The process of selecting, implementing, monitoring, assessing, and adjusting management actions is called adaptive management or, in the context of this report, adaptive ecosystem management (AEM) (Holling 1978; Walters 1986; Prato 2004, 2007a). AEM can be done passively or actively. If passive AEM is used, the decision to adjust management actions or not depends on whether the indicators or multiple attributes of the outcomes of management actions suggest that the ecosystem is becoming more resilient or more variable and might cross a threshold. If active AEM is used, the decision of whether or not to adjust management actions is determined by testing hypotheses about how the ecosystem state is responding to management actions. Active AEM treats management actions as experiments. Unlike passive adaptive management, active AEM yields statistically reliable information about ecosystem responses to management actions although it is more expensive and difficult to apply than passive AEM and requires sufficient monitoring (Lee 1993, Wilhere 2002).

To increase ecosystem resilience, a number of approaches have been put forth for use in adaptive management. These include avoiding landscape fragmentation and its converse, restoring connectivity; ensuring that refugia are protected so that recolonization of species is possible; focusing protection on keystone species where applicable; reducing other stressors such as pollution; removing introduced invasive species; and reducing extraction of ecosystem services for humans (for example, ensuring water flows for aquatic ecosystems under stress) (Scott and Lemieux 2005, Groffman et al. 2006). For each ecosystem, AEM potentially provides quantitative documentation as to the relative efficacy of the different approaches to improving resilience (Keeley 2006; Millar et al. 2007: Parker et al. 2007).

5.2.1 Role of Monitoring

Because climate change effects are likely to interact with patterns and processes across spatial and temporal scales, it is clear the monitoring strategies must be integrated across scales. First and foremost, the Earth’s surface must be hierarchically stratified [for example, using the U.S. Department of Agriculture (USDA)-National Resources Conservation Service (NRCS) Major Land Resource Area/Ecological Site Description System and U.S. Forest Service ecoregions), and conceptual or simulation models of possible impacts must be specified for each stratum (Herrick *et al.*, 2006). The models are used to develop scenarios and to identify key properties and processes that are likely to be associated with abrupt changes. Second, simultaneous multiple-scale monitoring should be implemented at up to three spatial scales based on these scenarios and the recognition of pattern-and-process coupling developed in the models (Bestelmeyer, 2006), which may feature cross-scale interactions (Peters *et al.*, 2004).

Remote sensing platforms can be used to monitor some broad-scale spatial patterns, including significant shifts in plant community composition, vegetation production, changes in plant mortality, bare ground and soil and water surface temperatures, and water clarity. These platforms may also be used to detect rates of change in some contagious processes, such as the spread of readily observable invasive species. Changes in variance across space and time derived from such measures may be a primary indicator of incipient nonlinear change (Carpenter and Brock, 2004). These measures should be coupled with ground-based measures at mesoscale to patch scales. Mesoscale monitoring often requires widely distributed observations across a landscape (or ocean) acquired with rapid methodologies including sensor networks. Such widely distributed monitoring is necessary because incipient changes may materialize in locations that are difficult to predict in advance (such as with tidal wave warning systems). In other cases, however, more targeted monitoring is necessary to detect mesoscale discontinuities in smaller areas that are likely to first register broad-scale change, such as at ecotone boundaries (Neilson, 1993). Finally, patch-scale monitoring can feature methodologies that focus on pattern-and-process linkages that scale up to produce systemwide threshold changes, such as when vegetation patches degrade and bare patches coalesce to result in desertification (Rietkerk *et al.*, 2004; Ludwig *et al.*, 2005). The involvement of land users is particularly important at this scale because recognition of processes that degrade resilience may be used to mitigate climate-driven thresholds by way of local management decisions. Consequently, technically-sophisticated approaches should be balanced with techniques suitable for the public at large (for example, Carpenter *et al.,* 1999; Pyke *et al.,* 2002).

Monitoring data across scales must then be integrated, and interpretations generated for key strata. Ground-based monitoring, for example, may reveal key changes not detected through remote sensing, or conversely, remote sensing may explain apparently idiosyncratic patterns in ground-based data to reveal key vulnerabilities. Multiagency institutions and a “network of networks” could be organized with such efforts in mind and could periodically review data gathered across scales and from different partners (Parr et al., 2003; Betancourt et al., 2007; Peters et al., 2008).

Nutrient export via streamflow is a sensitive metric for identifying changes in ecosystem structure and function at the watershed scale that may be difficult to detect on complex and spatially heterogeneous systems. For example, nitrate concentration in streams has been used as a sensitive indicator of forest nitrogen saturation (Stoddard, 1994; Swank and Vose, 1997; Lovett *et al.,* 2000; Aber *et al.,* 2003), effects of insect pest outbreaks (Eshleman *et al.*, 1998), and effects of short-term climate perturbations (Mitchell *et al.,* 1996; Aber *et al.,* 2002). Stream chemistry monitoring, particularly at gauges sites where discharge is also monitored, can provide sensitive signals of changes in ecosystem biogeochemical cycles.

5.2.2 Role of Experiments

It is critical to identify the conditions or systems that are susceptible to threshold behavior and interactions across scales that include transport processes at intermediate scales. One approach is to measure responses at multiple scales simultaneously and then test for significant effects of variables at each scale (for example, Smithwick *et al.,* 2005; Stoffels *et al.,* 2005). Experimental manipulations can also be used to examine processes at fine and intermediate scales and to isolate and measure impacts of broad-scale drivers under controlled conditions (for example, Palmer *et al.*, 1996; King *et al.,* 2004). Stratified-cluster experimental designs are methods for considering multiple scales in spatial variables and for accounting for distance as related to transport processes in the design (Fortin *et al.,* 1989; King *et al.,* 2004). Regression (gradient)-based experimental designs may be superior to analysis of variance (ANOVA)-type designs for predicting thresholds in ecological response to linear or gradual changes in climate or other drivers.

Quantitative approaches also show promise in identifying key processes related to threshold behavior. Statistical analyses based on nonstationarity (Rodó *et al.,* 2002) and nonlinear time series analysis (Pascual *et al.*, 2000) are useful for identifying key processes at different scales. Spatial analyses that combine traditional data layers for fine- and broad-scale patterns with data layers that use surrogates for transfer processes at intermediate scales (for *example.*, seed dispersal) can isolate individual processes and combinations of processes that influence dynamics in both space and time (for example, Yao *et al.*, 2006). Simulation models that use fine-scale models to inform a broad-scale model can be used to examine the relative importance of processes and drivers at different scales to system dynamics as well as interactions of processes and drivers (Moorcroft *et al.*, 2001; Urban, 2005). Coupled biological and physical models that include population processes and connectivity among populations as well as broad-scale drivers have been used to show the conditions when connectivity is important, and to identify the locations that are more susceptible or resilient to management decisions (Cowen *et al.*, 2006).

5.3 Management by Coping

If there is a high potential for abrupt or threshold-type changes in ecosystems in response to climate change, existing management models, premises, and practices must be modified in order to manage these systems in a sustainable, resilient manner (Millar et al. 2007). Existing management paradigms may have some limited value because of the assumption that the future will be similar to the past; this assumption, however, fails to take into account the underlying uncertainty of the trajectories of ecological succession in the face of climate change. Managers can insteadtake a dynamic approach to natural resource management, emphasizing processes rather than composition, to best maintain, restore and enhance ecological functions (Walker et al., 2002; Millar in press). The following sections address some of the mechanisms that can be used to plan for future ecosystem resilience and achieve a balance of positive and negative feedbacks (Millar et al., 2007; Millar in press).

5.3.1 Reducing Multiple Stressors

The key to reducing stressors is to identify the factors that influence resilience. In many cases management practices that increase resilience can be designed from existing knowledge; in other cases, however, it is not clear what management practices will enhance resilience (Millar et al., 2007). For example, connectivity in a fragmented landscape can be restored by creating corridors for species movement between suitable habitat patches (Gustafson, 1998). Alternatively, inadvertent connectivity that has been established and utilized by invasive species can be removed to reduce stress on the native populations remaining.

To potentially mitigate for threshold crossing, it is *likely* that a variety of approaches, including both long-term and short-term strategies based on new information for natural resource management, will need to focus on increasing ecosystem resilience and resistance as well as assisting ecosystems to adapt to the inevitable changes as climates and environments continue to shift (Millar et al. 2007; Parker et al. 2000). Increasing management adaptive capacity is the operative action taken to increase resilience in ecosystems. For instance, increasing water storage capacity can provide a buffer against reaching the trigger point for a drought-induced threshold crossing that would permanently change an arid-land ecosystem. The concept of critical loads for organisms is well-established but can be productively applied to ecosystems.

Based on gaps in the literature identified through the development process for this SAP and the synthesis team's expertise, tools to analyze and detect nonlinearity and thresholds from monitoring data will need to be developed. Increases in the variance of an important ecosystem metric have been suggested as an early sign of system instability. As negative feedbacks weaken and positive feedbacks strengthen, the likelihood that a threshold will be reached and crossed increases. As identified by the synthesis team in producing this SAP, there is a need for more nonlinear modeling and statistics to be applied to the threshold issue to identify the point at which positive feedbacks dominate.

5.3.2 Triage

Scientific evidence shows that climate change in the 21st century will most likely result in new vegetation successions, water regimes, wildlife habitat and survival conditions, permafrost and surface ice conditions, coastal erosion and sea-level change, and human responses (Welch 2005). Triage is a process in which things are ranked in terms of importance or priority. The term environmental or ecological triage has been used to describe the prioritization process used by policy makers and decisionmakers to determine targets and approaches to dealing with resource allocation (for example, health of ecosystems) that are in high demand and rapidly changing. In the planning process resource managers can address ecological triage under three different priorities: 1) *Status quo* or do nothing; 2) Reaction after disturbance; or 3) Proactive intervention (Holt and Viney 2001). Triage is a useful tool to prioritize actions, especially in cases where highly valued resources are at stake, conditions are changing rapidly, and decisions are urgent. The approaches to apply after triage are adaptive management, and mitigation and adaptation strategies. Enabling ecosystems to respond to climate change will help to ease the transition from current to future stable and resilient states, and minimize threshold changes (Fitzgerald 2000; Holt and Viney 2001; Millar et al. 2007; Millar in press).

5.3.3 System-Level Planning and Policy

Expanding management to regional levels is also key because climate change may be pushing ecosystems to regional synchrony. An example is that wildland fire is synchronously increasing throughout the western United States and could lead to major recruitment events for species such as lodgepole pine or trigger beetle outbreaks at unprecedented scales. These recruitment events could lead to supercohorts that develop with succession following subcontinental scale disturbance. There is little management precedent for these types of outcomes that are threshold events on a continental scale even if they are common on local scales.

Adaptive management and structured decisionmaking will almost certainly be required to deal with increased temperature effects on threshold crossings and the different trajectories of succession that follow in the western United States. Natural systems are out of sync with climate, leading to the greatest potential for new species combinations in many centuries. Therefore, new actions may be considered, such as planting different tree genotypes after large-scale fires, with appropriate followup monitoring to learn from the results.

5.3.4 Capacity Building and Awareness

There is, and will be, an urgent need to adapt where climate change-induced thresholds are crossed and a new ecosystem state will be a reality for the foreseeable future. Capacity building basically increases the resilience of the socioeconomic system to tolerate different states of natural resources and ecosystem functioning (Scott and Lemieux, 2005). If ecosystems become more variable in providing essential ecosystem services, greater flexibility is needed on the human side. An example is the need to add storage capacity for capturing mountain ecosystem water if a threshold in snow persistence is crossed, leading to smaller and more variable snowpacks. Building stakeholder tolerance for change is part of the adaptation that will be necessary (Scott and Lemieux, 2005).

Adaptation can take many forms. Scenario planning provides descriptions of plausible future conditions. Scenario planning, done at the local level, makes stakeholders aware of the scope of uncertainty, facilitates tolerance for change, and motivates the desire to build capacity to better handle threshold changes. Multiscenario approaches used with ecosystem modeling can also be used to develop a range of possible post-threshold conditions to better inform strategic decisionmaking and planning for natural resource managers (Lemieux and Scott 2005). Impact assessments on specific resources (for example, individual species population viability) can be expanded to examine the underlying viability of protected areas designed to maintain ecosystems (Scott et al. 2000). These assessments can prepare managers by broadening the scope of planning and ensuring that institutional action plans remain flexible.

5.4 Summary

As this synthesis makes clear, climate change increases the likelihood that ecosystems will undergo threshold changes. The underlying mix of interacting feedback mechanisms that drive these thresholds are poorly understood. Monitoring of ecosystems to detect early indicators, such as increasing variability in system behavior, is generally inadequate even when it is known what aspect of the system to monitor. Based on gaps in the literature identified by the synthesis team, there is little scientific or natural resource management experience in dealing with ecosystems undergoing threshold changes. The degree to which we can reverse a threshold change is largely unknown. These knowledge gaps present scientists and resource managers with severe challenges in anticipating and coping with threshold changes to the natural systems.

The gaps identified include the need to increase the resilience of ecosystems and reduce multiple stressors to avoid threshold crossing. Both of these challenges are difficult to plan for but also are consistent with managing ecosystems under conditions of uncertainty such as climate change. After a threshold occurs, viable options are to increase coping mechanisms, adaptive capacity, and stakeholder tolerance. The publication of SAP 4.2 will bring the state of scientific understanding to the forefront of the natural resource management paradigm, identifying a need for greater scientific research on thresholds and ecosystem response to adequately manage natural resources for the future.