Executive Summary

Introduction

In the past three decades, climate change has become a pronounced driver of ecosystem change. Changes in phenology, range shifts of species, and increases in disturbances such as wildland fires have all reflected ecosystem scale responses to a warming biosphere. There have also been abrupt, nonlinear changes in ecosystems where the levels of response to incremental increases in global temperature have suddenly changed trajectories. These thresholds of ecological change are not well understood but are potentially critical to adaptation strategies for managing natural resources in a rapidly changing world. Sudden, unanticipated shifts in ecosystem dynamics make planning and preparation by managers intensely difficult. One of the primary goals of the ecosystems research element and of goal 4 of the Climate Change Science Program (CCSP) is to enhance the understanding and ability to predict and forecast effects of climate change on ecosystems. This synthesis is intended to evaluate the current state of understanding of thresholds and recommend possible actions to improve knowledge and adjust management priorities even with incomplete understanding of what drives thresholds of change and when they will occur. The focus is on North American ecosystem threshold changes and what they mean for human society.

Definitions

This report defines an ecological threshold as the point where there is an abrupt change in an ecosystem quality, property, or phenomenon or where small changes in an environmental driver produce large, persistent responses in an ecosystem, which is not likely to return to the previous more stable state. Fundamental to this definition is the idea that positive feedbacks or instabilities drive the domino-like propagation of change that is therefore potentially irreversible.

"Systemic" risk or risk that affects the whole organism (ecosystem or economic system), not just isolated parts, provides a useful example. It corresponds to widespread coordinated system failure characterized by a catastrophic change in the overall state of the system. Again, such run-away changes are propagated by positive feedbacks (nonlinear instabilities) that are often hidden in the complex web of interconnected parts. They may be slower to recover than to collapse, and they may be irreversible in that the original state may not be fully recoverable.

Development of Threshold Concepts

Because the original ideas supporting ecological thresholds evolved as largely theoretical concepts based on simple model examples, there have been difficulties translating these mathematical ideas to field scenarios to establish a solid empirical basis for documenting and understanding them. Even though the connection of our informal thinking about threshold transitions to more rigorous theory is sometimes not as clear it should be, there are numerous examples of sudden ecological change that fit our current qualitative definition, and that more specifically were likely triggered by climatic changes such as warming temperatures. A clear example from the arctic tundra can be seen in the effects of warmer temperatures reducing snow cover duration, leading to reduced albedo (*i.e.*, reflectivity of the landscape), great absorption of solar energy, and local warming, accelerating the loss of snow cover. This amplified, positive feedback effect quickly leads to warmer conditions that foster invasion of shrubs into the tundra and the new shrubs themselves further reduce albedo and add to the local warming. The net result is a relatively sudden domino-like conversion of the arctic tundra triggered by a relatively slight temperature increase.

Principles of Thresholds

Systems consist of mixtures of positive and negative feedbacks, with positive feedbacks tending to alter the nature of the system, and negative feedbacks tending to minimize these changes (Chapin *et al.*, 1996). Changes that strengthen positive feedbacks (*e.g.*, invasion and spread of a highly flammable grass in deserts) can lead to a change in conditions (*e.g.*, fire regime) that may exceed the tolerance of other components of the system, leading to threshold changes.

Ecosystems tend to be at some maximum capacity, controlled by limiting factors such as water-limited net primary productivity in the case of terrestrial ecosystems. Persistant drought greatly increases positive feedback strength of the limiting factors to the threshold of plant physiological tolerance, leading to system change, until a new state (with different, more drought-tolerant species) is achieved where negative feedbacks again minimize changes.

Complex *interactions* between multiple feedbacks can lead to even greater nonlinear changes in dynamics (e.g interaction of drought and overgrazing together triggering desertification). The situations are often beyond forecasting or predictive capabilities, creating surprises for managers.

Disturbance mechanisms, such as fire and insect outbreaks, shape many landscapes and may predispose many of them to threshold change when the additional stress of climate change is added.

Climate change will alter the disturbance mechanisms themselves (e.g. more frequent fire) and, on a global scale, altered disturbance regimes may influence rates of climate change (e.g. fires releasing more carbon dioxide).

Human actions (e.g. introducing exotic, invasive plants) interact with natural drivers of change (e.g. ecotonal shifts in response to drought) to produce complex changes in ecosystems that have important implications for the services provided by the ecosystems.

Case Studies

Selected case studies provided below give concrete examples of threshold principles and underscore the complexities of change that provide daunting challenges for natural resource managers.

In recent decades, Alaska has warmed at more than twice the rate of the rest of the United States. This has caused earlier snowmelt in the spring (Dye, 2002; Stone et al., 2002; Dye and Tucker, 2003; Euskirchen et al., 2006, 2007), a reduction of sea ice coverage (Stroeve et al., 2005), a retreat of many glaciers (Hinzman et al., 2005), and a warming of permafrost (Osterkamp 2007). Consequently, increases in the frequency and spatial extent of insect disturbance and wildfire, dramatic changes in the wetlands of interior Alaska, vegetation changes in the tundra of northern Alaska, and ecological changes that are affecting fisheries in the Bering Sea have occurred. These changes have reflected threshold-like behavior. For instance, during the 1990s, south-central Alaska experienced the largest outbreak of spruce bark beetles in the world (Juday et al., 2005). A response to milder winters and warmer temperatures increased the over-winter survival of the spruce bark beetle and allowed the bark beetle to complete its life cycle in 1 year instead of the normal 2 years. This was superimposed on 9 years of drought stress between 1989 and 1997, which resulted in spruce trees that were too distressed to fight off the infestation. This illustrates the principle of multiple climate-triggered stresses amplifying each others' effects to cause a profound ecosystem change.

The Prairie Pothole Region (PPR) of north-central North America is one of the most ecologically valuable freshwater resources of the Nation (van der Valk 1989) and contains 5-8 million wetlands which provides critical habitat for continental waterfowl populations and provides numerous valuable ecosystem services for the region and nation. PPR wetlands are also highly vulnerable to climate change. A warmer, drier climate is indicated by general circulation models for the PPR (Ojima and Lackett 2002). This will affect wetland hydroperiod, ratio of emergent plant cover to open water, species composition, wetland permanence, and primary and secondary productivity, among others (van der Valk 1989). In an analysis of impacts on prairie wetland distribution across this region, Carter *et al.*, (2005) reported a large reduction in optimal waterfowl breeding habitat with a 3°C warming and almost *complete* elimination of habitat if precipitation declines by 20% as well. Such a threshold change to a major waterfowl flyway would permanently impact a vital resource of the U.S.

Semiarid forests and woodlands in the southwestern U.S. respond strongly to climate-driven variation in water-availability, with major pulses of woody plant establishment and mortality commonly corresponding to wet and dry periods (Swetnam and Betancourt 1998). Higher temperatures, coupled with drier mean conditions, means more frequent water stress for vegetation. Climate change-induced water stress can trigger rapid, extensive, and dramatic forest dieback (Breshears et al. 2005), shift ecotones between vegetation types (Allen and Breshears 1998) and alter regional distributions of overstory and understory vegetation (Gitlin et al. 2006, Rich et al. 2008). Rapid forest dieback also has nonlinear feedbacks at multiple spatial scales with other ecological disturbance processes such as fire and erosion (Allen 2007), potentially leading to additional nonlinear threshold behaviors. Massive forest mortality is an example of a threshold phenomenon with substantial implications for management of lands undergoing such changes (Millar et al. 2007).

Potential Management Responses

If climate change is pushing more ecosystems toward thresholds, what can be done by federal land managers and others to better cope with the threat of transformative change? The SAP 4.2 committee identified potential actions below that are further explained in this report.

Develop Better Threshold Knowledge.—While conceptually robust and widely acknowledged as occurring already, thresholds have had relatively few empirical studies addressing them. Reliable identification of thresholds across different systems should be a national priority because of the potential for substantive surprises in the management of our natural resources.

Monitor Multiple Drivers.—Consideration should be given to monitoring indicators of ecosystem stress rather than solely the resources and ecological services of management interest.

Collate and Integrate Information Better at Different Scales.—Because agencies and institutions have different management mandates, there can be a focus on those resources to the exclusion of others but better information sharing has great potential for better understanding thresholds and identifying when they might occur.

Reduce Other Stressors.—The trigger points for abrupt change in ecosystems that are responding to climate change are rarely known because human civilizations have not witnessed climate change of this magnitude. However, other stressors for which reliable information exists can be reduced.

Manage Threshold Shifts.—There may be constraints to reducing or reversing climate change-induced stresses to components of an ecosystem. If a threshold seems likely to occur but the uncertainties remain high as to when it will occur, contingency plans should be created. These can be implemented when the threshold shift begins to occur or can be carried out in advance if the threshold is clear.

Project Impacts to Water Supply, Biodiversity, and Resource Extraction.—There are many efforts to project climate change (*e.g.*, GCMs) and ecosystem responses to climate change (*e.g.*, mapped atmosphere-plant-soil systems) using simulation modeling and other tools. These models generally project ecosystem trends and shifts, but do not explicitly consider the possibility of thresholds. A concerted effort must be made to understand, model, and project ecosystem responses to climate change with explicit acknowledgment of thresholds.

Recognize Need for Subcontinental Decisionmaking.—Much of the recent information on climate change impacts suggests that changes are occurring more quickly than forecast only a few years ago. It is also apparent that many changes are causing secondary, or cascading, changes in other parts of ecosystems. Management policies, which were developed during relatively stable climate conditions, may be inadequate for a variable world with more surprises. To meet these challenges, there must be a shift away from managing locally and toward larger scales of information integration and subsequent decisionmaking.

Instigate Institutional Change To Increase Adaptive Capacity.—The current institutional structure promotes disciplinary and jurisdictional isolation by agencies and, therefore, does not lead to much synthesis across resources or issues. The capacity for synthesis will be critical for identifying potential thresholds in ecosystem processes on multiple scales.

Identify Recommendations for Monitoring and Research.—The major research needs and priorities that will enhance the ability in the future to forecast and detect abrupt changes in ecosystems caused by climate change must be articulated. The ubiquity of threshold problems across so many fields suggests the possibility of finding common principles at work. The cross-cutting nature of the problem of large-scale system change suggests an unusual opportunity to leverage effort from other fields and apply it to investigating systemic risk of crossing thresholds.

Recommendations

To better prepare for ecological threshold crossings, there is a need to increase resilience of ecosystems to slow or prevent the crossing of thresholds, identify early warning signals of impending threshold changes, and employ adaptive management strategies to deal with new successional trajectories and combinations of species. Better integration of existing monitoring information across great spatial scales will be needed to detect potential thresholds, and research will need to focus on ecosystems undergoing a threshold shift to better understand the underlying processes. Finally, natural resource managers will have to adjust their goals for desired states of resources away from historic benchmarks that are not likely to be achieved in a world being altered by climate change.