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Peer Review Draft

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Synthesis and Assessment Product 4.2

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Thresholds of Change in Ecosystems

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1 **Executive Summary**

2 *Introduction*

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

19 *Definitions*

20 This report defines an ecological threshold as the point where there is an abrupt
21 change in an ecosystem quality, property, or phenomenon or where small changes in an
22 environmental driver produce large, persistent responses in an ecosystem, which is not
23 likely to return to the previous more stable state. Fundamental to this definition is the idea

1 that positive feedbacks or instabilities drive the domino-like propagation of change that is
2 therefore potentially irreversible.

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

10 *Development of Threshold Concepts*

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

1 relatively sudden domino-like conversion of the arctic tundra triggered by a relatively
2 slight temperature increase.

3 *Principles of Thresholds*

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

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

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

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

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

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

8 *Case Studies*

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

12 In recent decades, Alaska has warmed at more than twice the rate of the rest of the
13 United States. This has caused earlier snowmelt in the spring (Dye, 2002; Stone et al.,
14 2002; Dye and Tucker, 2003; Euskirchen et al., 2006, 2007), a reduction of sea ice
15 coverage (Stroeve et al., 2005), a retreat of many glaciers (Hinzman et al., 2005), and a
16 warming of permafrost (Osterkamp 2007). Consequently, increases in the frequency and
17 spatial extent of insect disturbance and wildfire, dramatic changes in the wetlands of
18 interior Alaska, vegetation changes in the tundra of northern Alaska, and ecological
19 changes that are affecting fisheries in the Bering Sea have occurred. These changes have
20 reflected threshold-like behavior. For instance, during the 1990s, south-central Alaska
21 experienced the largest outbreak of spruce bark beetles in the world (Juday et al., 2005).
22 A response to milder winters and warmer temperatures increased the over-winter survival
23 of the spruce bark beetle and allowed the bark beetle to complete its life cycle in 1 year

1 instead of the normal 2 years. This was superimposed on 9 years of drought stress
2 between 1989 and 1997, which resulted in spruce trees that were too distressed to fight
3 off the infestation. This illustrates the principle of multiple climate-triggered stresses
4 amplifying each others' effects to cause a profound ecosystem change.

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

18 Semiarid forests and woodlands in the southwestern U.S. respond strongly to
19 climate-driven variation in water-availability, with major pulses of woody plant
20 establishment and mortality commonly corresponding to wet and dry periods (Swetnam
21 and Betancourt 1998). Higher temperatures, coupled with drier mean conditions, means
22 more frequent water stress for vegetation. Climate change-induced water stress can
23 trigger rapid, extensive, and dramatic forest dieback (Breshears et al. 2005), shift

1 ecotones between vegetation types (Allen and Breshears 1998) and alter regional
2 distributions of overstory and understory vegetation (Gitlin et al. 2006, Rich et al. 2008).
3 Rapid forest dieback also has nonlinear feedbacks at multiple spatial scales with other
4 ecological disturbance processes such as fire and erosion (Allen 2007), potentially
5 leading to additional nonlinear threshold behaviors. Massive forest mortality is an
6 example of a threshold phenomenon with substantial implications for management of
7 lands undergoing such changes (Millar et al. 2007).

8 *Potential Management Responses*

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

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

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

21 *Collate and Integrate Information Better at Different Scales.*—Because agencies
22 and institutions have different management mandates, there can be a focus on those

1 resources to the exclusion of others but better information sharing has great potential for
2 better understanding thresholds and identifying when they might occur.

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

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

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

19 *Recognize Need for Subcontinental Decisionmaking.*—Much of the recent
20 information on climate change impacts suggests that changes are occurring more quickly
21 than forecast only a few years ago. It is also apparent that many changes are causing
22 secondary, or cascading, changes in other parts of ecosystems. Management policies,
23 which were developed during relatively stable climate conditions, may be inadequate for

1 a variable world with more surprises. To meet these challenges, there must be a shift
2 away from managing locally and toward larger scales of information integration and
3 subsequent decisionmaking.

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

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

16 *Recommendations*

17 To better prepare for ecological threshold crossings, there is a need to increase
18 resilience of ecosystems to slow or prevent the crossing of thresholds, identify early
19 warning signals of impending threshold changes, and employ adaptive management
20 strategies to deal with new successional trajectories and combinations of species. Better
21 integration of existing monitoring information across great spatial scales will be needed
22 to detect potential thresholds, and research will need to focus on ecosystems undergoing a
23 threshold shift to better understand the underlying processes. Finally, natural resource

- 1 managers will have to adjust their goals for desired states of resources away from historic
- 2 benchmarks that are not likely to be achieved in a world being altered by climate change.
- 3

1 **Chapter 1—Introduction and Background**

2 *1.1 The Problem of Sudden Change in Ecological Systems*

3 The carbon dioxide (CO₂) concentration in the Earth's atmosphere has reached
4 385 parts per million (ppm), a level that is unprecedented over the past one-half million
5 years (based on ice core data) to 24 million years (based on soil data) (Hoegh-Guldberget
6 al.et al. 2007). CO₂ levels have been increasing during the past 150 years, with most of
7 the change occurring in just the past few decades. Global mean temperature has risen in
8 response to increased CO₂ concentration and is now higher than at any time in the past
9 1,000 years (based on tree rings) to 160,000 years [based on oxygen 18 (¹⁸O) and
10 deuterium (D) isotopes in ice]. The relatively sudden increase in the energy balance of
11 the planet has led to abrupt global climate changes that alter physical processes and
12 biological systems on many scales and will certainly affect ecosystems that support
13 human society. One of the ways that a rapidly changing climate will affect ecosystems is
14 by causing sudden, irreversible effects that fundamentally change the function and
15 structure of the ecosystem with potentially huge impacts to human society.

16 Even small, gradual change can induce threshold changes. For instance, in 1976-
17 77, major shifts occurred in sea surface temperatures, fisheries landings, zooplankton
18 abundance, and community composition in the North Pacific (Hare and Mantua, 2000).
19 Later analysis suggested that nonlinear regime shifts operate in this ecosystem, such that
20 even small changes in physical conditions (for example, an increase in temperature from
21 global warming) can provoke a regime shift that may not be easily or symmetrically
22 reversed (Hsiehet al.et al. 2006). This tendency can be compounded by additional
23 environmental stressors that predispose ecosystems to experience threshold changes in

1 response to climate change. For example, in North America in the late 1990s, forests,
2 woodlands, grasslands, and shrublands exhibited extensive dieback across the arid
3 southwestern United States as overgrazing, fire suppression, and climate variability led to
4 massive insect outbreaks and an unprecedented breadth of area consumed by fire (Allen,
5 2007).

6 Abrupt changes in ecosystems may result in dramatic reductions in ecosystem
7 services, such as water supplies for human use. In the Klamath River basin in the Pacific
8 Northwest, for example, the delicate socioecological balance of water allocation between
9 needs for irrigated agriculture and habitat for endangered species of fish, which had been
10 established in 1902, collapsed in 2002 during a multiyear drought because the system's
11 resilience to maintain water quality in the face of climatic variability was degraded by
12 long-term nutrient loading.

13 Thresholds pose perhaps the greatest challenge currently facing climate change
14 scientists. There is clear evidence that climate change has the potential to increase
15 threshold changes in a wide range of ecosystems, but the basic and practical science
16 necessary to predict and manage these changes is not well developed (Groffman et al.
17 2006). In addition, climate change interacts with other natural processes to produce
18 threshold changes. Disturbance mechanisms, such as fire and insect outbreaks (Krutzen
19 and Goldammer 1993, Lovett et al. 2002, respectively), shape landscapes and may
20 predispose many of them to threshold change when the additional stress of climate
21 change is added (Swetnam and Betancourt 1998). To complicate matters further, climate
22 change can alter the disturbance mechanisms themselves and, on a global scale, altered
23 disturbance regimes may influence rates of climate change. Another challenge is the

1 multidisciplinary nature of threshold changes. These changes almost always involve
2 coupled socioecological dynamics where human actions interact with natural drivers of
3 change to produce complex changes in ecosystems that have important implications for
4 the services provided by the ecosystems (Wamelink et al. 2003).

5 A sense of urgency regarding thresholds exists because of the increasing pace of
6 change, the changing features of the drivers that lead to thresholds, the increasing
7 vulnerabilities of ecosystem services, and the challenges the existence of thresholds poses
8 for natural resource management. These challenges include the potential for major
9 disruption of ecosystem services and the possibility of social upheaval that might occur
10 as new ways to manage and adapt for climate change and to cope with the unanticipated
11 change are required.

12 Research on ecological thresholds is being assessed critically. The Heinz Center
13 conducted several workshops that presented case studies of likely threshold change and
14 began looking at possible social and policy responses. Another study included numerous
15 case studies focused on nonlinearities in ecological systems (Burkett et al. 2005) and
16 considered how thresholds are nonlinear responses to climate change. Recently, specific
17 requests for proposals have been issued for research on thresholds (for example, see
18 *es.epa.gov/ncer/rfa/2004/2004_aqua_sys.html*), and there are active efforts to bridge the
19 gap between research and application in this area (see, for example,
20 *www.ecothresholds.org*). Assessment of the “state of the science” as it relates to
21 ecosystems in the United States and for articulation of critical research needs is needed.

22 *1.2 The Response of the Climate Change Community*

1 Climate change is a very complex issue, and policymakers need an objective
2 source of information about the causes of climate change, its potential environmental and
3 socioeconomic consequences, and the adaptation and mitigation strategies to respond to
4 the effects of climate change. In 1979, the first World Climate Conference was organized
5 by the World Meteorological Organization (WMO). This conference expressed concern
6 about man's activities on Earth and the potential to "cause significant extended regional
7 and even global changes of climate" and called for "global cooperation to explore the
8 possible future course of global climate and to take this new understanding into account
9 in planning for the future development of human society." A subsequent conference in
10 1985 focused on the assessment of the role of CO₂ and other greenhouse gases in climate
11 variations and associated impacts, concluding that an increase of global mean
12 temperature could occur that would be greater than at any time in humanity's history. As
13 a follow up to this conference, the Advisory Group on Greenhouse Gases (AGGG), a
14 precursor to the Intergovernmental Panel on Climate Change (IPCC), was set up to
15 ensure periodic assessments of the state of scientific knowledge on climate change and
16 the implications of climate change for society. Recognizing the need for objective,
17 balanced, and internationally coordinated scientific assessment of the understanding of
18 the effects of increasing concentrations of greenhouse gases on the Earth's climate and on
19 ways in which these changes may potentially affect socioeconomic patterns, the WMO
20 and the United Nations Environment Programme (UNEP) coordinated to establish an ad
21 hoc intergovernmental mechanism to provide scientific assessments of climate change.
22 Thus, in 1988, the IPCC was established to provide decisionmakers and others interested
23 in climate change with an objective source of information about climate change.

1 The role of the IPCC is to assess on a comprehensive, objective, open, and
2 transparent basis the scientific, technical, and socioeconomic information relevant to
3 understanding the scientific basis of risk of human-induced climate change, its potential
4 impacts, and options for adaptation and mitigation and to provide reports on a periodic
5 basis that reflect existing viewpoints within the scientific community. Because of the
6 intergovernmental nature of the IPCC, the reports provide decisionmakers with policy-
7 relevant information in a policy neutral way. The first IPCC report was published in
8 1990, with subsequent reports published in 1995, 2003, and 2007.

9 In 1989, the U.S. Global Change Research Program (USGCRP) began as a
10 Presidential initiative and was codified by Congress in the Global Change Research Act
11 of 1990 (Pub.L. 101–606), which mandates development of a coordinated interagency
12 research program. The Climate Change Science Program (CCSP)
13 (www.climatescience.gov), a consortium of Federal agencies that perform climate
14 science, integrates the research activities of the USGCRP with the U.S. Climate Change
15 Research Initiative (CCRI).

16 The CCSP integrates federally supported research on global change and climate
17 change as conducted by the 13 U.S. Government departments and agencies involved in
18 climate science. To provide an open and transparent process for assessing the state of
19 scientific information relevant to understanding climate change, the CCSP established a
20 synthesis and assessment program as part of its strategic plan. A primary objective of the
21 CCSP is to provide the best science-based knowledge possible to support public
22 discussion and government and private sector decisionmaking on the risks and
23 opportunities associated with changes in the climate and related environmental systems.

1 The CCSP has identified an initial set of 21 synthesis and assessment products
2 (SAPs) that address the highest priority research, observation, and decision-support needs
3 to advance decisionmaking on climate change-related issues. This assessment, SAP 4.2,
4 focuses on abrupt ecological responses to climate change, or thresholds of ecological
5 change. It examines the impacts to ecosystems when thresholds are crossed. It does not
6 address those ecological changes that are caused by major disturbances, such as
7 hurricanes. These externally driven changes, or exogenous triggers, are distinguished
8 from changes caused by shifts in the ecosystem's response to a driver, such as a gradual
9 rise in temperature. These internal changes in system response, or endogenous triggers,
10 are the focus of this SAP. This SAP is one of seven reports that address the Ecosystems
11 research element and Goal 4 of the CCSP strategic plan to understand the sensitivity and
12 adaptability of different natural and managed ecosystems and human systems to climate
13 and related global changes.

14 *1.3 The Goal of SAP 4.2*

15 This SAP summarizes the present state of scientific understanding regarding
16 potential abrupt state changes or regime shifts in ecosystems in response to climate
17 change. The goal is to identify specific difficulties or shortcomings in our current ability
18 to identify the likelihood of abrupt state changes in ecosystems as a consequence of
19 climate change.

20 Questions addressed by this SAP include:

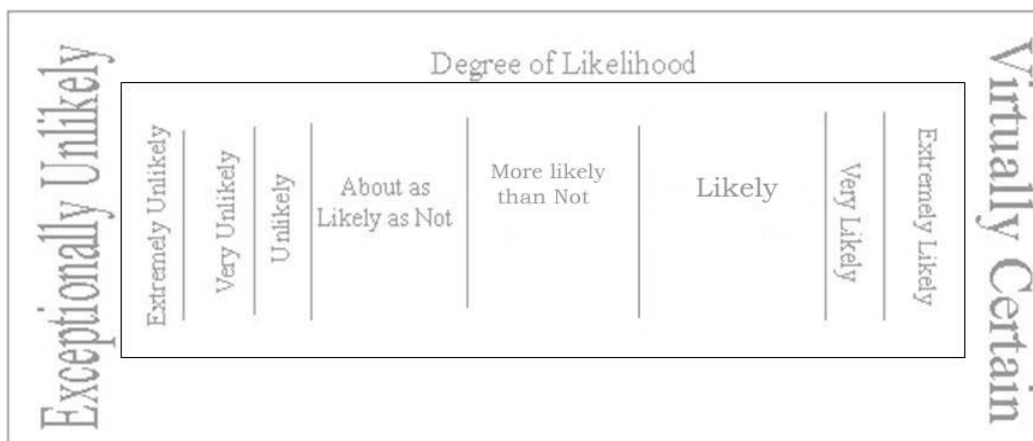
- 21 1. What specifically is meant by abrupt state changes or regime shifts in the
22 structure and function of ecosystems in response to climate change?

- 1 2. What evidence is available from current ecological theory, ecological modeling
2 studies, or the paleoecological record that abrupt changes in ecosystems are likely
3 to occur in response to climate change?
- 4 3. Are some ecosystems more likely to exhibit abrupt state changes or threshold
5 responses to climate change?
- 6 4. If abrupt changes are likely to occur in ecosystems in response to climate change,
7 what does this imply about the ability of ecosystems to provide a continuing
8 supply of ecosystem goods and services to meet the needs of humans?
- 9 5. If there is a high potential for abrupt or threshold-type changes in ecosystems in
10 response to climate change, what changes must be made in existing management
11 models, premises, and practices in order to manage these systems in a sustainable,
12 resilient manner?
- 13 6. How can monitoring systems be designed and implemented, at various spatial
14 scales, in order to detect and anticipate abrupt or threshold changes in ecosystems
15 in response to future climate change?
- 16 7. What are the major research needs and priorities that will enhance the ability in
17 the future to forecast and detect abrupt changes in ecosystems caused by climate
18 change?

19 *1.4 Standard Terms*

20 The 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment
21 Report (AR4) (*IPCC, 2007*) is the most comprehensive and up-to-date report on the
22 scientific assessment of climate change. This assessment (SAP 4.2) uses the standard
23 terms defined in the IPCC's AR4 with respect to the treatment of uncertainty and the

1 likelihood of an outcome or result based on expert judgment about the state of that
2 knowledge. The definitions are shown in figure 1.1. This set of definitions is for
3 descriptive purposes only and is not a quantitative approach from which probabilities
4 relating to uncertainty can be derived.



5

6 **Figure 1.1. Degrees of outcome likelihood as defined in the IPCC's Fourth Assessment**
7 **Report (AR4) (IPCC, 2007).**

1 **Chapter 2—Ecological Thresholds**

2 *2.1 Introduction*

3 Temperature, precipitation, and related climate variables are fundamental
4 regulators of biological processes and it is reasonable to expect that significant changes in
5 the climate system may alter linkages and feedbacks between ecosystems and regional
6 climate systems. Increasing focus is being placed on the existence and likelihood of
7 abrupt state changes or threshold responses in the structure and functioning of ecosystems
8 (Holling, 1986; Scheffer et al., 2001; Higgins et al. 2002; Foley et al. 2003;
9 Schneider, 2004; Burkett et al. 2005; Hsieh et al. 2005). Various interrelated
10 terms are employed in the scientific literature to characterize these types of discontinuous
11 and rapid changes in ecosystems, including ecosystem tipping points, regime shifts,
12 threshold responses, alternative or multiple stable states, and abrupt state changes. Our
13 current understanding of thresholds and ecosystem responses makes it *unlikely* that we
14 can predict such discontinuities in ecosystems, and these discontinuities are *likely* to result
15 in profound changes to natural resources that are sensitive to climate changes, as well as
16 to human societies that depend on ecosystem goods and services, this assessment, based
17 on the literature and the synthesis teams' expertise, indicates that thresholds are *likely* to
18 represent large-scale risk and uncertainty and can *likely* be a major challenge to natural
19 resource managers.

20 Abrupt transitions have occurred in numerous ecosystems where incremental
21 increases in global temperature have produced sudden and dramatic changes in the state
22 of and the dynamics governing these systems (Anderson et al. 2008). These thresholds of
23 magnified ecological change are a consequence of the underlying nonlinear nature of

1 ecosystems and are *very likely* critical to adaptation strategies for managing natural
2 resources in a rapidly changing world. Sudden, unanticipated shifts in ecosystem
3 dynamics are a major source of risk and uncertainty for managers and make planning and
4 preparation difficult. One of the primary objectives of this report (SAP 4.2) is to enhance
5 the understanding and ability of managers to predict and forecast the effects of climate
6 change on ecosystems.

7 As discussed elsewhere in this chapter, the occurrence of threshold, or abrupt
8 changes in ecosystems, is suggested by current ecological theory and models, and is
9 documented with laboratory and field examples and even in the paleoecological record.
10 However, on a predictive level, thresholds remain poorly understood, particularly in
11 terms of the underlying causal mechanisms and the general factors that predispose
12 systems to threshold effects. For example, it is unclear under what circumstances climate
13 change, both in its mean state and in its variance in space and time, including occurrence
14 of extreme weather events, might cause ecosystem threshold shifts, instead of more
15 gradual, continuous changes in ecosystems and species. Further, it is not known what the
16 resulting effects of climate thresholds on ecosystems will be. Thus, while the
17 phenomenology of rapid transitions in ecosystems is clear, reaching a level of
18 understanding that enables one to anticipate or actually predict threshold effects is the
19 main bottleneck to producing results useful to managers (Muradian, 2001; Bestelmeyer,
20 2006; Groffman et al. 2006; Kinzig et al. 2006).

21 *2.2 Early Development*

22 The concepts of ecological thresholds, multiple stable states, and regime shifts
23 originated in early theoretical work on the stability or persistence of ecosystems

1 (Margalef, 1963; Lewontin, 1969; Odum, 1969; Holling, 1973; May 1973, 1977). The
2 two key components of stability were considered to be the system's "resilience," or the
3 speed at which it would return to its current "stable equilibrium" , and its "resistance," or
4 ability to maintain its current "stable" state in the face of disturbance of a given
5 magnitude. According to this early thinking, given enough disturbance, systems could be
6 pushed into alternative stable states. This theoretical work was complemented (however
7 sparsely) with early empirical demonstrations of multiple stable states in marine
8 experimental systems (Sutherland, 1974) and with field data combined with model
9 analysis for terrestrial ecosystems (Ludwig et al. 1978).

10 "Stability" as a well-defined mathematical concept was central to these early
11 theoretical discussions of thresholds. Lewontin (1969) reviewed mathematical models of
12 stability and discussed the forces required to move an ecosystem out of a basin of
13 attraction or stable state. May (1973) presented a precise definition of stability and a
14 crater and ball analogy to illustrate the concepts and later (1977) focused attention on the
15 existence of alternative stable states and multiple equilibrium points with an emphasis on
16 the thresholds between them. Holling (1973) drew attention to the ability of ecosystems
17 to absorb and respond to disturbance and introduced the concept of robustness (although
18 he used the term resilience). Again, robustness focuses on dynamics far from equilibrium
19 and was used to measure the magnitude of perturbations from which recovery of a system
20 was no longer possible.

21 Although mathematically tractable and well defined in static engineering contexts,
22 "stability" and the implication of "equilibrium" in ecological systems began gradually to
23 give way in the 1990s to growing evidence that real ecological systems are not static nor

1 even well approximated, as such. Notions of stable equilibrium, which continue to
2 dominate much of our thinking and research to date (for example, Maximum Sustainable
3 Yield as written into the 2006 reauthorization of the Magnusson-Stevens Act), are based
4 on models and controlled experiments (for example, on paramecia and flour beetles) from
5 the middle of the last century where singular static equilibrium was the ideal. Cracks in
6 the equilibrium view began to appear as quantitative evidence mounted from natural
7 systems, that “change” rather than “constancy” is the rule, and that nonlinear instability,
8 thresholds, and chaos can be ubiquitous in nature (Dublin et al. 1990; Sugihara and
9 May, 1990; Tilman and Wedin, 1991; Grenfell, 1992; Knowlton, 1992; Hanski et al.
10 1993; and Sugihara 1994). The possibility that so-called “pathological” nonequilibrium,
11 nonlinear behaviors seen in theoretical treatments could be the rule in nature as opposed
12 to a mathematical curiosity, opened the door for credible studies of thresholds. Indeed,
13 now threshold changes appear to be everywhere. Recognition and documentation of
14 sudden, not readily reversible changes in ecosystem structure and function have become a
15 major research focus during the past 10 to 20 years (Scheffer et al. 2001; Scheffer
16 and Carpenter, 2003).

17 Perhaps the most important driver of the current interest in nonlinear ecosystem
18 behavior and, in particular, threshold effects has been the recognition of the importance
19 of indirect effects of climate change. Although much climate change research has
20 focused on the direct effects of long-term changes in climate on the structure and function
21 of ecosystems, there has been increasing recognition that the most dramatic consequences
22 of climate change may occur as a result of indirect effects, including threshold changes
23 (Vitousek, 1994; Carpenter, 2002; Schneider, 2004).

1 2.3 *Current Discussions of Threshold Phenomena*

2 As ecologists were exploring the existence of alternative stable states in
3 ecosystems, oceanographers were documenting the impacts of major climatic events on
4 the North Atlantic Ocean (Steele and Henderson, 1984), North Pacific Ocean, and Bering
5 Sea ecosystems. They eventually used the term “regime shift” to describe the sudden
6 shifts in biota that are driven by ocean climate events (Steele, 1996; Hare and Mantua,
7 2000). More recently, for the California Current Ecosystem (CCE), regime shifts in the
8 biota have been distinguished from random excursions in the ocean climate based on the
9 nonlinear signature of the time series (Hsieh et al. 2006). The main idea here is that
10 regimes represent different rules governing local dynamics (that is, they depend on
11 environmental context), and that nonlinear instabilities (latent positive feedbacks) drive
12 the system across thresholds into different dynamical domains. Thus, regime shifts in
13 marine ecosystems are an amplified biological response to ocean climate variation
14 (mainly temperature variation) rather than a simple tracking of environmental variation
15 (Anderson et al. 2008). On the other hand, ocean climate for the CCE in the 20th
16 century did not have this nonlinear signature insofar as the dynamical rules were the same
17 in both warm and cold periods. Hsieh and others (2006) and Anderson and others (2008)
18 suggest nonlinear forecasting methods as a rigorous way to make this distinction that
19 avoids the circularities of statistical methods for detecting regimes and thresholds. The
20 dynamics of regime shifts are considered to be the essential fingerprint. Current interest
21 in regime shifts and thresholds in marine science have focused on understanding the
22 factors that determine thresholds and on ways of extracting dynamics from observational
23 data to make predictions.

1 Muradian (2001) and Walkers and Meyers (2004) used a definition of regime shift
2 developed by Sheffer and Carpenter (2003) emphasizing changes in the threshold level of
3 a controlling variable in a system, such that the nature and extent of feedbacks change
4 and result in a change in the system itself (which was based on Rene Thom's (1975) fold
5 catastrophe model). Scheffer and Carpenter (2003) built on work in shallow lakes to
6 demonstrate empirically the concept of threshold-like hysteric change and used these
7 examples to further reinforce the idea that ecosystems are never stable but are dynamic
8 and that fluctuations (in populations, environmental conditions, or ecosystems) are more
9 the rule than not.

10 Given the move in thinking among many ecologists toward nonequilibrium and
11 unstable dynamics, the broader technical concept that may eventually replace
12 "equilibrium" in this context is a more general notion concept that includes equilibrium,
13 stable limit cycles, and nonequilibrium dynamics or chaos (Sugihara and May, 1990;
14 Hsiehet al.et al. 2006). Depending on whether the control variable is thought of as part of
15 the system (an intrinsic coordinate of the state space) or as external to the system (an
16 extrinsic variable), threshold behavior may be thought of as a ridge of instability that
17 separates control variables. From a more descriptive point of view, the idea suggests that
18 there are particular states or characteristic combinations of species (grasslands, chapparel,
19 oak-hickory forests, and so forth) that make up the biological component, and that
20 ecosystem thresholds can be identified in the physical part of the system. Part of the
21 nonlinearity or nonequilibrium nature of ecosystems comes from the fact that the biology
22 (especially the dynamics) of the system is contingent on its own particular state (suite and
23 abundance of species), as well as on the physical context in which it resides.

1 The field of range science has a parallel and largely independent literature on
2 thresholds, resilience, regime shifts, and alternative stable states that has engendered a
3 lively debate over how these terms are used in that field. Bestelmeyer (2006) argued that
4 there is a lack of clarity in the use of the term “threshold” and its application to state-and-
5 transition models (STMs) used in range management. STM’s describe alternative states
6 and the nature of thresholds between states. Bestelmeyer’s argument reflects a broad lack
7 of consensus or understanding among range scientists about how best to define and use
8 the threshold concept. Watson and others (1996) criticized a focus on the consequences
9 of threshold shifts at the expense of the processes that precede them. Many definitions of
10 threshold phenomena emphasize relatively rapid, discontinuous phenomena (for example,
11 Wissel, 1984, and Denoel and Ficetola, 2007). Others emphasize the points of instability
12 at which systems collapse (Radford et al. 2005), or the point at which even small
13 changes in environmental conditions lead to large changes in state variables (Suding et
14 al. 2004). Still other definitions emphasize changes in controlling variables.
15 According to Walker and Meyers (2004), “a regime shift involving alternative stable
16 states occurs when a threshold level of a controlling variable in a system is passed.”

17 There is clearly a need in range science for more rigorous and consistent use and
18 application of the ecological threshold concept and its associated terminology. One point
19 of consensus underlying both the theoretical and empirical approaches to the topic of
20 thresholds is that changes from one ecological condition to another take place around
21 specific points or boundaries. But further advancement and agreement is limited by the
22 small number of empirical studies that address this topic. Some believe that further
23 advancement will depend on rigorous statistical testing for reliable identification of

1 thresholds across different systems (Huggett, 2005), while many in fields outside of range
2 science see the danger of circularity in such arguments and suggest dynamic tests for
3 determining threshold behavior (Hsieh et al. 2005).

4

5 *2.4 Ecological Thresholds Defined for SAP 4.2*

6 Because of the variety of ways that the concept of thresholds has been developed,
7 this assessment (SAP 4.2) uses the following general definition of ecological thresholds:
8 *An ecological threshold is the point at which there is an abrupt change in an ecosystem*
9 *quality, property, or phenomenon, or where small changes in an environmental driver*
10 *produce large, persistent responses in an ecosystem.* Fundamental to this definition is the
11 idea that positive feedbacks or nonlinear instabilities drive the domino-like propagation
12 of change that is potentially irreversible.

13 In line with this definition, threshold phenomena are particular nonlinear
14 behaviors that involve a rapid shift from one ecosystem state (or dynamic regime) to
15 another that is the result of (or that provokes) instability in any ecosystem quality,
16 property, or phenomenon. Such instability always involves nonlinear amplification
17 (positive feedback in some form) and is often the result of the particular structure of the
18 interactions or the complex web of interactions. This definition distinguishes thresholds
19 from other biological changes that are simple responses to external environmental
20 change. Thus, bifurcation cascades (the point in which events take one of two possible
21 directions with important final consequences, making dynamical systems evolve in a non-
22 linear way with successive disruptions/divergences/breaks from previous trends),
23 nonlinear amplification (Dixon et al. 1999), hysteresis, and the propagation of

1 positive feedback (instabilities) through complex webs of interactions are all interrelated
2 attributes that fit our general working definition of threshold phenomena.

3 “Systemic” risk, or risk that affects the whole ecosystem rather than just isolated
4 parts of the system provides a useful analogy. Systemic risk corresponds to widespread
5 change in an ecosystem characterized by a break from previous trends in the overall state
6 of the system. Runaway changes are propagated by positive feedbacks (nonlinear
7 instabilities) that are often hidden in the complex web of interconnected parts. The
8 changes may be hysteretic in the sense that recovery may be much slower to achieve than
9 the collapse, and they may be irreversible in that the original state may not be fully
10 recoverable (Chapin et al. 1995).

11 Other specific examples of threshold crossings or transitions that illustrate this
12 definition are (following Groffman, 2006)—

- 13 1. The interactions of drought and overgrazing that trigger runaway desertification.
- 14 2. The exceeding of some critical load, as with the toxicity limit of a contaminant or
15 elimination of a keystone species by grazing, so that when one component of the
16 system fails, it provokes a domino-like cascade of instability that substantially
17 alters the rest of the system.

18 These and other examples are discussed in more detail in the case studies presented in
19 Chapter 3.

20 These simplistic metaphors for our concept of threshold transitions include so-
21 called bifurcation cascades where, for example, small changes in a controlling variable,
22 such that the nature and extent of feedbacks change, leads to a sudden destabilization of
23 the system, which follows the classic fold-catastrophe model as first described by Rene

1 Thom (1975). Thus our operational notion of ecological threshold covers sudden changes
2 of state and sudden changes in the dynamical behavior of ecosystems. The overriding
3 theme of interest for natural resource managers is the uncertainty and lack of predictability
4 that surrounds such large-scale system-wide changes.

5

6 *2.5 Factors That Influence Persistence, Resilience, and Robustness*

7 At a general level, systems can be viewed as consisting of mixtures of positive
8 and negative feedbacks, with positive feedbacks tending to alter the nature of the system,
9 and negative feedbacks tending to minimize these changes (Chapinet al.et al. 1996).
10 Changes that strengthen positive feedbacks (for example, the invasion and spread of
11 highly flammable grass in a desert) can lead to a change in conditions (for example, the
12 fire regime) that may exceed the tolerance of other components of the system. This, in
13 turn, leads to destabilization and threshold changes. Thresholds occur when positive
14 feedbacks amplify changes in system characteristics in ways that exceed the buffering
15 capacity of negative feedbacks that tend to maintain the system in its current state or the
16 current limits of the control variables. Viewed from a management perspective,
17 thresholds occur when changes in the system exceed the adaptive capacity of the system
18 to adjust to change. Because systems are tuned to the natural variability experienced in
19 the past, anything that disrupts that variability can make them vulnerable to further
20 change and amplified instability (Walker et al. 2006; Folke, 2006).

21 The following is a partial list of factors that are believed to come into play in
22 determining a system's persistence, robustness, resilience, and sensitivity to threshold
23 behavior (see also May and McLean, 2007):

- 1 1. A higher diversity of very weakly connected and substitutable components are
2 thought to enhance robustness. Such arguments were made in the classic stability
3 complexity debate (see reviews by Pimm 1984 and McCann 2000).
- 4 2. Compartmentalization of interactions into guilds is a way to make model
5 ecosystems more robust to systemic events (Mayet al.et al. 2008).
6 Compartmentalization acts as a fire-break that prevents the spread of a system's
7 collapse.
- 8 3. A predominance of weak linkages in the system with a few strong linkages leads
9 to relatively low connectance (McCann, 2000; Mayet al.et al. 2008) and is
10 thought to increase resilience. Real ecological systems are thought to have a
11 lognormal distribution of interaction strengths, which has been associated with
12 increased resilience (Sala and Graham, 2002).
- 13 4. Ecosystems are robust by virtue of their existence. They are the selected survivors
14 of billions of years of upheaval and perturbation (continental drift, meteor
15 extinctions, and so forth), and show some remarkable constancy in structure that
16 persists for hundreds of millions of years (for example, the constancy of
17 predator/prey ratios). As such, enumerating the common attributes of these
18 diverse naturally selected surviving systems could be of interest to understanding
19 thresholds.
- 20 5. Higher measured nonlinearity (greater instability) in the dynamics that provoke an
21 increase in boom and bust population variability (Anderson et al. 2008) is
22 directly associated with regime shifts. This is true in exploited marine fish
23 populations, which show greater swings in abundance than their unexploited

1 counterparts from the same environment. Exploited species show an amplified
2 response to regime shifts, with greater extremes in abundance.

3 6. In line with the so-called “paradox of enrichment” (Rosenzweig, 1971), fertilizing
4 a system to increase growth rates and carrying capacity can provoke a rapid loss
5 of species to a much simpler state.

6 7. Increasing time lags involved in population regulatory responses can destabilize
7 systems (May 1977), and this effect becomes more pronounced with higher
8 growth rates. This is analogous to a large furnace (rapid growth) with a poor
9 thermostat (regulatory delay), which tends to produce undershooting and
10 overshooting of temperature in a way that predisposes the system to large-scale
11 failure.

12 8. Reductions in variance, as might occur when managing systems for a stable flow
13 of one particular good or service, tends to favor those species and components
14 that are typical of this set of conditions at the expense of species that function
15 more effectively under other conditions. Consequently the species as a whole
16 remains stable under a narrower range of conditions.

17 *2.6 The Bottom Line*

18 To manage risks associated with ecological thresholds, it is essential to be able to
19 forecast such events and to plan for and study alternative management scenarios. Better
20 integration of existing monitoring information from the local to the largest possible
21 spatial scales will be required to monitor and identify ecosystems that are approaching
22 and undergoing critical transitions. Field research that focuses on ecosystems undergoing
23 a threshold shift can help clarify the underlying processes at work. And natural resource

1 managers may *very likely* have to adjust their goals for the desired states of resources
2 away from historic benchmarks that may no longer be achievable in a nonequilibrium
3 world that is continually changing and now being altered by climate change. Such
4 changes in methods and outlook as the following may be required—

- 5 • Abandon classic management strategies that assume a constant world in
6 equilibrium (for example, MSY-models, and mass-balance equilibrium
7 models).
- 8 • Acknowledge in our management strategies and in our models that
9 ecosystems are nonlinear, interdependent, and nonequilibrium systems.
- 10 • Use near-term forecasting tools, statistical and otherwise, that are
11 appropriate to this class of system (for example, nonlinear time series
12 prediction coupled with scenario models).
- 13 • Increase our understanding of the potential mechanisms involved both
14 generically and on a case-by case basis.
- 15 • Continue to identify the characteristics of systems that make them more or
16 less vulnerable.
- 17 • Continue to identify early warning signals of impending threshold changes
18 (and to monitor for those signals).
- 19 • Survey and triage the major biomes to identify which systems might be
20 most vulnerable to current climatic trends.
- 21 • Employ adaptive management strategies, such as skillful short-term
22 forecasting methods coupled with scenario exploration models that are

1 capable of dealing with new successional scenarios and novel
2 combinations of species.

3

4

1 **Chapter 3—Case Studies**

2 Thresholds of ecological change can occur at many spatiotemporal scales and in a
3 diversity of ecosystems. The following examples were chosen to illustrate that thresholds
4 probably have already been crossed in ecosystems in response to climate change and that
5 the crossing of these thresholds will likely have implications at continental and global
6 scales. Because these changes will likely impact American society significantly, these
7 examples make clear the usefulness of considering thresholds in the monitoring and
8 management of natural resources.

9 Four case studies are presented below in detail; they cover distinctly different
10 types of ecosystems, all of which are potentially undergoing threshold-type changes.
11 These studies are arranged in order of latitude, beginning with the highest. The first study
12 is of a latitude in the far north where climate change has resulted in large temperature
13 changes. The next study is of the midlatitude PPR where continental drying is expected
14 because the subtropical high-pressure zone is broadening. The third case study is of
15 forests of the West and Southwest, which are at a slightly lower latitude, are generally
16 already water-limited, and will be sensitive to the decreased water availability that would
17 profoundly impact the western half of the United States. Finally, in the lowest latitude
18 example, the effects of climate change in forcing threshold changes in coral reef
19 ecosystems are examined.

20 *Case Study 1. Ecological Thresholds in Alaska*

21 In recent decades, Alaska has warmed at more than twice the rate of the rest of the
22 United States. The Statewide annual average temperature has increased by 3.4°F since the
23 mid-20th century, and the increase is much greater in winter (6.3°F). A substantial

1 portion of the increase occurred during the shift of the Pacific decadal oscillation in the
2 1970s. The higher temperatures of recent decades have been associated with changes in
3 the physical environment, such as earlier snowmelt in the spring (Dye, 2002; Stone et al.
4 et al. 2002; Dye and Tucker, 2003; Euskirchen et al. 2006, 2007), a reduction of sea ice
5 coverage (Stroeve et al. 2005), a retreat of many glaciers (Hinzen et al. 2005),
6 and a warming of permafrost (Osterkamp, 2007). In parallel with these changes in the
7 physical environment, substantial changes in ecological systems have been observed,
8 including dramatic increases in the frequency and spatial extent of (stet) (Balshi *et al.*,
9 2008) wildfire (Westerling et al. 2006), wildfire, dramatic changes in the wetlands of
10 interior Alaska (Yoshikawa and Hinzen, 2003), vegetation changes in the tundra of
11 northern Alaska (Goetz *et al.*, 2005), and ecological changes that are affecting fisheries in
12 the Bering Sea. The temporal pattern of these responses to climatic change in Alaska, the
13 understanding of the drivers of the responses, the degree to which these responses
14 represent gradual versus threshold responses, and implications for the services provided
15 to society by ecological systems in Alaska are described below.

16 *Ecological Thresholds and Changes in Insect and Wildfire Regimes of Interior*
17 *Alaska.*—Analyses of historical insect and fire disturbance in Alaska indicate that the
18 extent and severity of these disturbances are intimately associated with longer and drier
19 summers (Juday et al. 2005; Balshi et al. 2008). Between 1970 and 2000, the
20 snow-free season increased by approximately 10 days across Alaska primarily because of
21 earlier snowmelt in the spring (Euskirchen et al. 2006, 2007). Longer summers have
22 the potential to be beneficial to the growth of plants. However, the satellite record
23 suggests that the response of plant growth to warming differs in different regions of the

1 State with growth increasing in the tundra of northern Alaska and decreasing in the boreal
2 forest of interior Alaska (Jia et al. 2003; Goetz et al. 2005). Analysis of forest
3 growth data indicates that the growth of white spruce forests in interior Alaska is
4 declining because of drought stress (Barber et al. 2002), and there is the potential that
5 continued warming could lead to forest dieback in interior Alaska (Juday et al. 2005).
6 The drought stress that has been experienced by trees in Alaska during recent decades
7 makes them particularly vulnerable to attack by insects.

8 During the 1990s, south-central Alaska experienced the largest outbreak of spruce
9 bark beetles in the world (Juday et al. 2005). This outbreak was associated with a
10 threshold response to milder winters and warmer temperatures that increased the over-
11 winter survival of the spruce bark beetle and allowed the bark beetle to complete its life
12 cycle in 1 year instead of the normal 2 years. This was superimposed on 9 years of
13 drought stress between 1989 and 1997, which resulted in spruce trees that were too
14 distressed to fight off the infestation. The forests of interior Alaska are now threatened by
15 an outbreak of spruce budworms, which generally erupt after hot, dry summers (Fleming
16 and Volney, 1995). The spruce budworm has been a major insect pest in Canadian
17 forests, where it has erupted approximately every 30 years (Kurz and Apps, 1999), but
18 was not able to reproduce in interior Alaska before 1990 (Juday et al. 2005). Areas
19 that experience the death of trees over large areas of forest are vulnerable to wildfire as
20 the dead trees are highly flammable. This is of particular concern in Alaska where
21 wildfire incidence has been increasing in recent decades.

22 The area burned in the North American boreal region has tripled from the 1960s
23 to the 1990s owing to the increased frequency of large-fire years (Kasischke and

1 Turetsky, 2006). For example, two of the three most extensive wildfire seasons in
2 Alaska's 56-year record occurred in 2004 and 2005, and half of the years with the largest
3 fires during this 50-year time period have been since 1990 (Kasischke et al. 2002,
4 2006; Kasischke and Turetsky, 2006). The increase in fire frequency in Alaska appears to
5 be primarily associated with the shift in the Pacific decadal oscillation that occurred in
6 the late 1970s as large-fire years occurred once every 6 years before the shift and
7 increased to once every 3 years after the shift (Kasischke et al. 2002). Analyses of
8 fire probability in interior Alaska indicate that fire probability increases as a step function
9 when the mean temperature in June increases above 14°C or when the August mean
10 precipitation decreases below 40 millimeters (mm) (Paul Duffy, oral commun.,
11 05/02/2008). Because the mean June temperature has been increasing in interior Alaska
12 during the last several decades, the crossing of these thresholds will likely lead to
13 substantial increases in area burned in interior Alaska, and there is the potential that the
14 large-fire years of 2004 and 2005 in Alaska may occur several times a decade instead of
15 once or twice every 50 years.

16 Analyses of the response of fire to scenarios of future climate change indicate that
17 the average area burned per year in Alaska will double by the middle of the 21st century
18 for scenarios of both moderate and high rates of fossil fuel burning (Balshiet et al.
19 2008). By the end of the 21st century, fire is projected to triple in Alaska for a scenario of
20 moderate rates of increase in fossil fuel burning and to quadruple for scenarios of high
21 rates of increase in fossil fuel burning. Such increases have the potential to release large
22 stocks of carbon stored in Alaska soils to the atmosphere, which would be a positive
23 feedback to climate warming (Balshiet et al. 2008). The projected increase in the

1 burned area also increases the fire risk to rural indigenous communities, reduces
2 subsistence opportunities, and has implications for fire policy (Chapinet al.et al. 2008).

3 *Ecological Thresholds and Changes in Wetlands of Interior Alaska.*—There has
4 been a documented decrease in the area of closed-basin lakes (*that is*, lakes without
5 stream inputs and outputs) during the latter half of the 20th century in the southern two-
6 thirds of Alaska (Kleinet al.et al. 2005; Riordanet al.et al. 2006). The decrease in lake
7 area appears to be caused by greater evaporation associated with longer and drier
8 summers and by catastrophic drainage associated with thawing of permafrost in areas
9 where the temperature of permafrost is close to melting. A decrease in the area of closed-
10 basin lakes has also been documented in Siberia in areas of “warm” permafrost (Smithet
11 al.et al. 2005).

12 Discontinuous permafrost in Alaska is warming and thawing, and extensive areas
13 of thermokarst terrain (marked subsidence of the surface resulting from thawing of ice-
14 rich permafrost) are now developing as a result of climatic change. Estimates of the
15 magnitude of the warming at the discontinuous permafrost surface are 0.5° to 1.5°C
16 (Osterkamp and Romanovsky, 1999). Thermokarst is developing in the boreal forests of
17 Alaska where ice-rich discontinuous permafrost is thawing. Thaw subsidence at the
18 thermokarst sites is typically 1 to 2 meters (m) with some sites experiencing subsidence
19 of up to 6 m (Osterkampet al.et al. 1997). Much of the discontinuous permafrost in
20 Alaska is warm and is highly susceptible to thermal degradation if regional warming
21 continues. Warming of permafrost may be causing a significant loss of open water across
22 Alaska as thawing of permafrost connects closed watersheds with groundwater
23 (Yoshikawa and Hinzman, 2003).

1 Examination of satellite imagery indicates that the loss of water can occur
2 suddenly, which suggests catastrophic drainage associated with thawing of permafrost
3 (Riordan et al. 2006). However, the reduction of open water bodies may also reflect
4 increased evaporation under a warmer and effectively drier climate as the loss of open
5 water has also been observed in permafrost-free areas (Klein et al. 2005).

6 In wetland complexes underlain by ice-rich permafrost in areas of hydrologic
7 upwelling (for example, wetland complexes abutting up against the foothills of large
8 mountain ranges), the thawing of that permafrost may result in wetland expansion as trees
9 die when their roots are regularly flooded, causing wet sedge meadows, bogs, and
10 thermokarst ponds and lakes to replace forests (Osterkamp et al. 2000). The Tanana
11 flats, which extends nearly 70 miles from the northern foothills of the Alaska Range to
12 Fairbanks, Alaska, is underlain by ice-rich permafrost that is thawing rapidly and causing
13 birch forests to be converted to minerotrophic floating mat fens (Jorgenson et al.
14 2001). It is estimated that 84% of a 260,000-hectare (ha) (642,000-acre) area of the
15 Tanana flats was underlain by permafrost a century or more ago. About one-half of this
16 permafrost has partially or totally degraded. These new ecosystems favor aquatic birds
17 and mammals, whereas the previous forest ecosystems favored land-based birds and
18 mammals.

19 During the past 50 years, it appears that warming has generally resulted in the loss
20 of open water in closed-basin lakes in wetland complexes located in areas of
21 discontinuous permafrost in the southern two-thirds of Alaska (Riordan et al. 2006).
22 The Tanana flats near Fairbanks is the only area where an increase in water area has been
23 documented (Jorgenson et al. 2001), and closed-basin lakes in the tundra region of

1 northern Alaska have shown no changes in area during the past 50 years (Riordan et al.
2 al. 2006). The loss of area of closed-basin lakes in interior Alaska may be indicative of a
3 lowering of the water table that has the potential to convert wetland ecosystems in
4 interior Alaska into upland vegetation. A substantial loss of wetlands in Alaska has
5 profound consequences for management of natural resources on national wildlife refuges
6 in Alaska, which cover about 3.1 million hectares (more than 77 million acres) and
7 comprise 81% of the National Wildlife Refuge System. These refuges provide breeding
8 habitat for millions of waterfowl and shorebirds that winter in more southerly regions of
9 North America; reduction of habitat area would present a substantial challenge for
10 waterfowl management across the National Wildlife Refuge System (Julius et al.
11 2008). Wetland areas have also been traditionally important in the subsistence lifestyles
12 of native peoples in interior Alaska as many villages are located adjacent to wetland
13 complexes that support an abundance of wildlife subsistence resources. Thus, the loss of
14 wetland area has the potential to affect the sustainability of subsistence lifestyles of
15 indigenous peoples in interior Alaska.

16 *Ecological Thresholds and Vegetation Changes in Northern Alaska.*—Shrub cover in
17 northern Alaska has increased by about 16% since 1950 (Sturmet et al. 2001; Tape et
18 al. 2006), and the treeline is expanding in most places (Lloyd and Fastie, 2003;
19 Lloyd, in press). This is consistent with satellite observations of an approximately 16%
20 increase per decade in the normalized difference vegetation index (NDVI) (Jia et al.
21 2003; Goetz et al. 2005). The increased growth of vegetation at or above the treeline
22 appears to be a response to longer and warmer growing seasons. Tundra vegetation in
23 northern Alaska may not be experiencing drought stress to the extent experienced by

1 forests in interior Alaska because the surface water in tundra regions is not able to drain
2 away through the ice-rich continuous permafrost. Experimental studies demonstrate that
3 arctic summer warming of 1°C increases shrub growth within a decade (Arft et al. 1999).
4 Satellite analyses of relationships between NDVI and summer warming (Jia et al. 2003)
5 suggest that the response of tundra vegetation is linearly related to summer
6 warmth. Thus, it appears that the response of tundra vegetation to warming is not a
7 threshold response.

8 While growth of shrubs and trees may not be threshold responses to warming, the
9 changing snow cover and vegetation in northern Alaska have the potential to result in
10 sudden changes in the absorption of heat from incoming solar radiation and the transfer
11 of that heat to warm the atmosphere. For example, the advance in snowmelt reduces
12 spring albedo, causing the ecosystem to absorb more heat and transfer it to the
13 atmosphere. The snowmelt-induced increase in heating in northern Alaska has been about
14 3.3 watts per square meter (W m^{-2}) averaged over the summer, similar in magnitude to
15 the 4.4 W m^{-2} caused by a doubling of atmospheric CO_2 over several decades (Chapin
16 et al. 2005). Thus, gradual warming has caused a rapid advance in the snowmelt date
17 and a very large increase in local heating. Although vegetation changes to date have had
18 minimal effects on atmospheric heating, conversion to shrubland would increase summer
19 heating by 8.9 W m^{-2} , with even larger changes triggered by conversion to forest.
20 Warming experiments that increase shrubs also reduce the abundance of lichens, an
21 important winter food of caribou (Cornelissen et al. 2001). Most arctic caribou herds
22 are currently declining in population, although the reasons are uncertain. In summary,
23 positive feedback associated with earlier snowmelt and shrub expansion is amplifying

1 arctic warming and may be altering food-web dynamics in ways that have important
2 cultural and nutritional implications for northern indigenous people.

3 *Ecological Thresholds and Fisheries of the Bering Sea.*—Alaska leads the United
4 States in the value of its commercial fishing catch, and most of the Nation’s salmon, crab,
5 and herring come from Alaska, and specifically from the Bering Sea. The Bering Sea is
6 one of the most productive marine ecosystems in the world, supporting some of the
7 largest oceanic populations of fish, seabirds, and marine mammals anywhere (Loughlinet
8 al.et al. 1999). The Bering Sea provides 47% of total U.S. fishery production by mass,
9 including the largest single species fishery in the United States, walleye pollock
10 (*Theragra chalcogramma*) (Criddleet al.et al. 1998). It is also an important source of
11 subsistence resources (fish, marine mammals, and seabirds) for more than 30 Alaska
12 Native communities and supports 95% of the worldwide population of northern fur seals,
13 80% of the total number of seabirds that breed in the United States, and major
14 populations of tens of thousands of Pacific walrus, steller sea lion, and several species of
15 great whales. This production is fueled by nutrients annually replenished from slope and
16 oceanic waters across the very broad [more-than-500-kilometer (km)-wide] continental
17 shelf (Stabenoet al.et al. 2001, 2006).

18 Changes in fisheries of the Bering Sea occurred in the transition of cool to warm
19 conditions in 1977, in association with a shift of the North Pacific oscillation, and were
20 followed by historically high commercial catches of salmon and pollock, as well as a
21 shift away from crab dominance on the ocean floor. In the past decade, geographic
22 displacement of marine mammal populations has been documented in the Bering Sea
23 region. The displacements of walrus and seal populations are already apparent to coastal

1 communities. The displacements of fauna in the Bering Sea has coincided with a
2 reduction of benthic prey populations, an increase in pelagic fish, an increase in air and
3 ocean temperatures, and a reduction in sea ice (Grebmeier et al. 2006). Ultimately,
4 populations of fish, seabirds, seals, walruses, and other species depend on plankton
5 blooms that are regulated by the extent and location of the ice edge in spring. As the sea
6 ice continues to decline, the location, timing, and species makeup of the blooms is
7 changing, vastly decreasing the amount of food reaching the living things on the ocean
8 floor. This radically changes the species makeup and populations of the fish and other
9 marine life forms, with significant repercussions for fisheries (Grebmeier et al. 2006;
10 Hatfield et al. 2008; Juliu et al. 2008). Thus, changes in sea ice are the major
11 driver of concern with respect to threshold changes in fisheries of the Bering Sea.

12 Seasonal sea ice extent currently divides the Bering Sea eastern shelf into two
13 biogeographic provinces, which differ in production pathways. In the subarctic
14 biogeographic province (south of the average-annual maximum sea ice extent), most
15 primary production remains within the pelagic ecosystem, and pollock is the dominant
16 tertiary consumer (Macklin and Hunt, 2004). In contrast, in the arctic biogeographic
17 province, tight coupling between pelagic primary production and the benthos benefits
18 benthic foragers, such as gray whales, walrus, and diving ducks (Grebmeier et al.
19 2006). The boundary between the two biogeographic provinces varies in location on
20 longer time scales (decadal or longer) and is expected to move northward as the region
21 becomes warmer. The average southern edge of the maximum ice extent currently lies
22 north of the Pribilof Islands (Byrd et al. 2008).

1 The Bering Sea ecosystem, however, is in a state of rapid flux owing to climate
2 change. Present data and climate projections from atmosphere-ocean models predict
3 major loss of sea ice during the next few decades (Overland and Stabeno, 2004); the
4 Bering Sea is particularly sensitive to global warming (Grebmeier et al. 2006).
5 Recent relative temperature extremes in Alaska and adjacent waters (more than 2°C)
6 represent the largest recent change on the planet (Hansen et al. 2006). However,
7 these models and data also demonstrate large natural variability. Ecosystems will *likely*
8 be affected by how the path of such warming occurs, that is, whether there will be a
9 continued slow warming trend with little interannual variability versus a warming trend
10 that incorporates wide swings in temperature and extent of sea ice.

11 Warming of the Bering Sea is expected to alter the current geographic
12 distributions and behaviors of humans, marine mammals, seabirds, and fish by
13 restructuring their habitats and food webs (Grebmeier et al. 2006). As a result of
14 warming, changes in the time and place of food production lead to dominance of top-
15 down control processes in the pelagic marine environment and the decline of benthic
16 production. Under a long-term warming scenario with early ice retreat, bottom-up control
17 mechanisms (temperature, sea ice extent and duration, ocean currents, and nutrient
18 fluxes) set the stage for the emergence and dominance of top-down control processes in
19 the pelagic marine environment and the decline of benthic production. Increased heat
20 content would increase the combined populations of the subarctic piscivores—arrowtooth
21 flounder, pollock, and cod—in proportion to expanded breeding grounds and increased
22 availability of food during critical developmental stages (Hunt and Stabeno, 2002).
23 Because arrowtooth flounder is not targeted by fishing, it is likely to become the

1 dominant component of the biomass of the three subarctic piscivores in this study and is
2 predicted to be one of the principal agents of top-down control in the Bering Sea, as
3 predator and competitor of the now-dominant, but commercially exploited, pollock and
4 cod.

5 Arrowtooth flounder is also an agent of change as a direct and indirect competitor
6 of fur seals, murre, and kittiwakes for their respective forage species (euphausiids,
7 copepods, juvenile pollock, capelin, and myctophids). Populations of fur seals, murre,
8 and kittiwakes could fluctuate in the near term depending on the locality of rookeries and
9 nesting colonies, but long-term overall trends would be downward under warming. Fur
10 seals, murre, and kittiwakes would further decline owing to competition from humpback
11 and fin whales, with fur seal declines being further accelerated by increasing killer whale
12 predation. Dislocation of feeding hot spots would likely disadvantage breeding fur seals,
13 murre, and kittiwakes as central place foragers, but would work to the advantage of
14 humpback and fin whales, further exacerbating direct and indirect competition between
15 these two groups of species. Dislocations and declines in fur seals, kittiwakes, murre,
16 pollock, and cod would stress human communities by increasing the costs of maintaining
17 a livelihood and obtaining food and by necessitating changes in the types of food taken
18 and the means of harvest.

19 The northern Bering Sea, in particular, is experiencing a rapid shift in the
20 structure and function of the formerly arctic climate regime to conditions typical of
21 marine ecosystems of the subarctic (Grebmeier et al. 2006; Hunt et al. 2002). The earlier
22 sea ice retreat results in a later, warm-water spring phytoplankton bloom, increased
23 grazing by zooplankton, and greater pelagic secondary productivity (Hunt et al. et al.

1 2002). Concurrently, benthic productivity is decreasing (Grebmeier et al. 2006). The
2 formerly ice-dominated, shallow marine ecosystem that favored highly productive
3 benthic communities also supported high densities of upper trophic level bottom-feeders,
4 such as Pacific walruses, gray whales, and seabirds, including the Ecological Society of
5 America (ESA)-listed spectacled eider.

6 The northward flowing Anadyr Current, which originates in the southern Bering
7 Sea, transports nutrient-rich water far onto the Bering Shelf and the northern Bering Sea.
8 This transport creates unusually productive shelf waters in the area north of St. Lawrence
9 Island and south of the Bering Strait, known as the Chirikov Basin (Springer et al.
10 1989; Piatt and Springer, 2003). Oceanic copepods, such as *Neocalanus cristatus* and *N.*
11 *flemingeri*, transported by the Anadyr Current, along with the large euphausiid
12 *Thysanoessa raschii* provide abundant prey for planktivores foraging near St. Lawrence
13 Island (Piatt et al. 1988). The Anadyr Current is highly variable on a seasonal and
14 annual basis, reaching its greatest velocity during July [about 1.3 Sv (13 million cubic
15 meters per second)] (Roach et al. 1995). Consequently, the primary productivity on
16 the Bering Shelf during summer months varies with the strength of northward flow
17 associated with the Anadyr Current (Springer et al. 1989; Russel et al. 1999).

18 When the Anadyr Current is weaker, planktivores presumably rely more on
19 zooplankton associated with northern Bering Shelf waters, such as the small copepod
20 *Calanus marshallae* and the large amphipod *Themisto libellula* (Coyle, Chavtur, and
21 Pinchuk, 1996; Russel et al. 1999). *Neocalanus* copepods are larger and have higher
22 energy content per prey item than the small, neritic copepod *C. marshallae* which is
23 characteristic of Bering Shelf water. The lipid content of *Neocalanus* copepods is also

1 probably higher (Obstet al.et al. 1995), making these oceanic species more energy-dense
2 than their shelf domain counterparts. When preferred *Neocalanus* copepods are not
3 available, planktivores must switch to other prey types. The progressively earlier
4 transition from winter to spring in the Bering Sea and the resulting changes in primary
5 and secondary productivity are expected to have large impacts on upper trophic-level
6 consumers (Stabeno and Overland, 2001; Grebmeier et al. 2006).

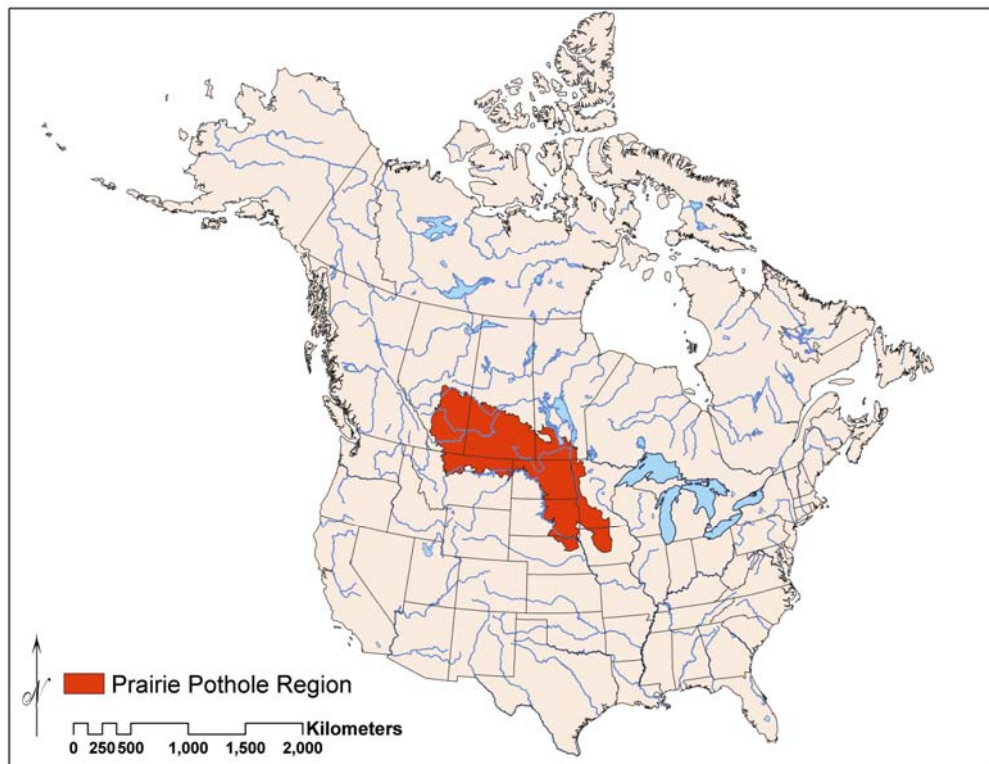
7 Projected warming of the Bering Sea is also expected to profoundly alter the
8 structure of the southeastern Bering Sea ecosystem by changing pathways and fluxes of
9 energy flow, as well as the abundance, spatial distribution, and species composition of
10 fish, seabirds, and marine mammals, thereby affecting commercial and subsistence
11 fisheries that support local, regional, and national economies (Grebmeier et al. 2006; Hunt
12 and Stabeno 2002). Climate-induced changes in physical forcing of the Bering Sea
13 modifies the partitioning of food resources at all trophic levels on the continental shelf
14 through bottom-up processes.

15

16 *Case Study 2. The Mid-Continent Prairie Pothole Region: Threshold Responses to*
17 *Climate Change*

18 The Prairie Pothole Region (PPR) of north-central North America is one of the
19 most ecologically valuable freshwater resources of the Nation (van der Valk, 1989). It
20 contains 5 million to 8 million wetlands, which supply critical habitat for continental
21 waterfowl populations and provide numerous valuable ecosystem services for the region
22 and nation. The weather extremes associated with this region are particularly important
23 for the long-term productivity of waterfowl dependent on these wetlands.

1 The PPR (fig. 3.1) exhibits a variable climate, ranging from severe droughts
2 exemplified by the 1930s when agriculture was devastated, grassland communities
3 shifted eastward, and trees died by the millions (Albertson and Weaver, 1942, 1945;
4 Woodhouse and Overpeck, 1998; Rosenzweig and Hillel, 1993) to periods of deluge,
5 such as occurred in the late 1900s when closed-basin lakes flooded, causing high
6 mortality of shoreline trees and considerable economic damage to farmland, roads, and
7 towns (Winter and Rosenberry, 1998; Johnson et al. 2005; Shapley et al. 2005).
8 The 20th-century climate of the PPR was punctuated by significant droughts. These
9 conditions have occurred over small and large areas and lasted as short as several
10 growing seasons to as long as a decade (Skaggs, 1975; Laird and Cumming, 1998;
11 Nkemdirim and Weber, 1999).



12

1 **Figure 3.1.** Location of the Prairie Pothole Region (PPR) of North America (red highlighted
2 area). (Boldsethet al.et al. 2007)

3

4 Wetlands in the PPR are likely to be strongly affected by gradual changes in
5 climate (Poiani and Johnson, 1991; Covichet al.et al. 1997). Climate drives surface
6 processes, such as the hydrologic cycle, and hydrology is the most important factor that
7 controls key wetland processes and services (Winter and Woo, 1990). A warmer and
8 drier climate, as indicated by general circulation models (GCM) for the northern Great
9 Plains (Ojima and Lackett, 2002), could affect the wetland hydroperiod, the ratio of
10 emergent plant cover to open water, the species composition, wetland permanence, and
11 primary and secondary productivity, among others (van der Valk, 1989). Winter (2000)
12 predicted that the surface area of seasonal and semipermanent wetlands in the PPR would
13 be reduced by increases in evapotranspiration and reduced summer soil moisture. With
14 increased temperatures, summer evapotranspiration would put increasing demands on
15 groundwater, resulting in earlier drying of wetlands. Thus, additional climate variability
16 of the magnitude suggested by global climate change models would profoundly affect
17 wetland water budgets and the many processes and attributes linked to these wetlands..

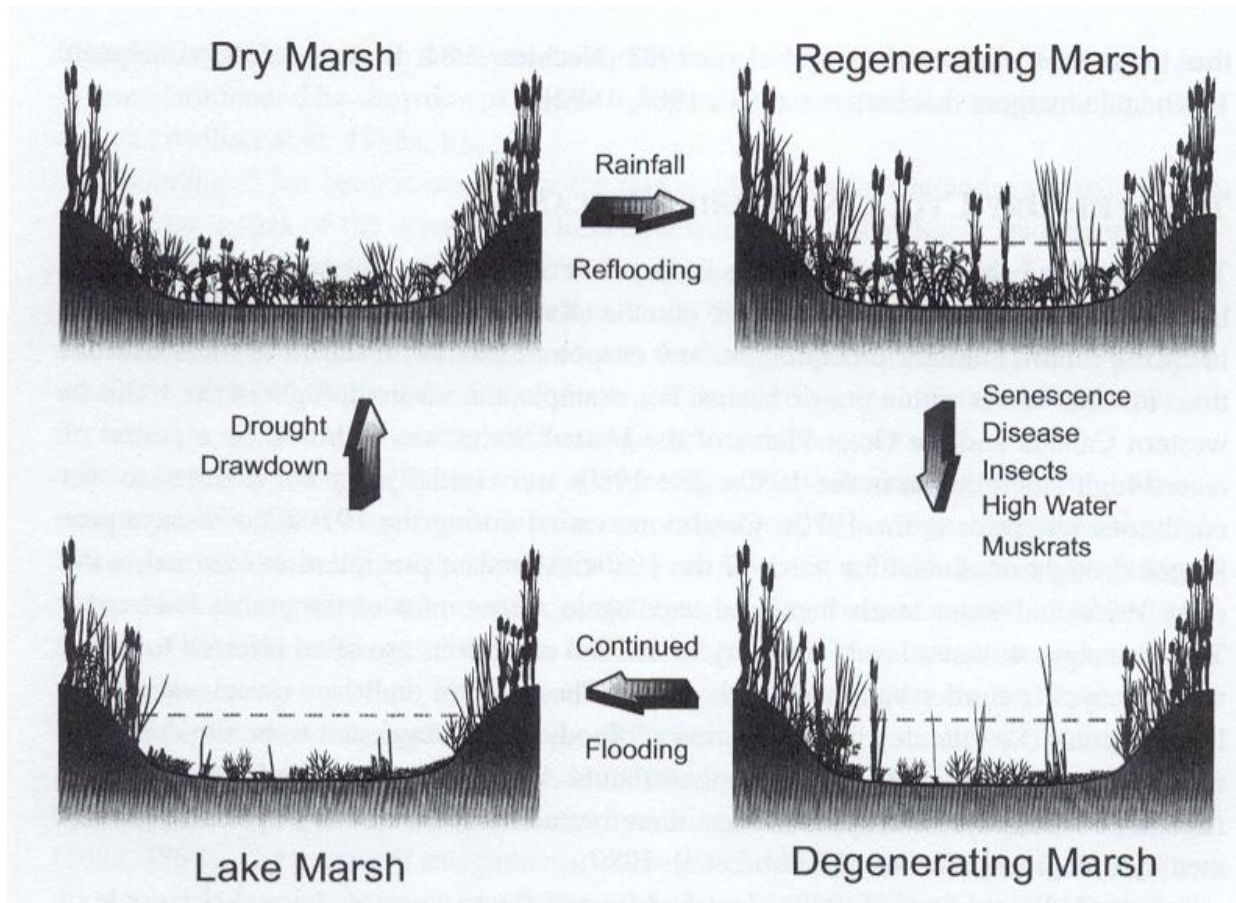
18 Changing climate can have direct effects on the trajectories of these wetland
19 ecosystems and their sustainability. Shifts in climate in this region over decadal time
20 scales could result in longer or more frequent drought periods and may lead to threshold
21 responses by the wetland systems. The interaction of extrinsic and intrinsic processes
22 reflected in such hydrologically, geologically and biologically linked systems as wetlands
23 and their surrounding watersheds could result in rapid nonlinear changes at broad spatial

1 scales that are triggered by small differences in temperature and precipitation if threshold
2 values are exceeded that may also result in these systems exhibiting hysteresis.

3 The first quantitative assessments of the possible effects of climate change on
4 PPR wetlands used the WETSIM (WETland SIMulator), which is a rule-based, spatially
5 explicit simulation model that is composed of hydrology and vegetation submodels
6 (Poiani and Johnson, 1991, 1993a, b; Poianiet al.et al.1995, 1996). Simulations using this
7 model and GCM climate forcings indicate that semipermanent wetlands would lose their
8 historic highly dynamic character by drying up more frequently and becoming
9 chronically choked with emergent cover. Shortened hydroperiods and monotonous stands
10 of emergent cover for semipermanent wetlands across the PPR would have strong
11 negative effects on the continental population of waterbirds (particularly ducks).

12 Johnsonet al.et al. (2005) used a simulation model (WETSIM) to contrast
13 historical and future wetland conditions across the PPR of North America (fig. 1). They
14 assembled 95-year climate data sets for 18 weather stations across the PPR as input to a
15 revised version of WETSIM (version 3.1), which enabled a much broader geographic
16 assessment to be conducted of the effects of past and future climate variability on wetland
17 conditions across the PPR. Their model runs reflected the high level of spatial and
18 temporal heterogeneity in wetland water levels historically across the PPR. They were
19 able to use model output to simulate the number of completions of the wetland cover
20 cycle across the PPR (fig. 3.2; Weller, 1965).

21



1

2

3 **Figure 3.2.** Wetland cover cycle (modified from Weller, 1965).

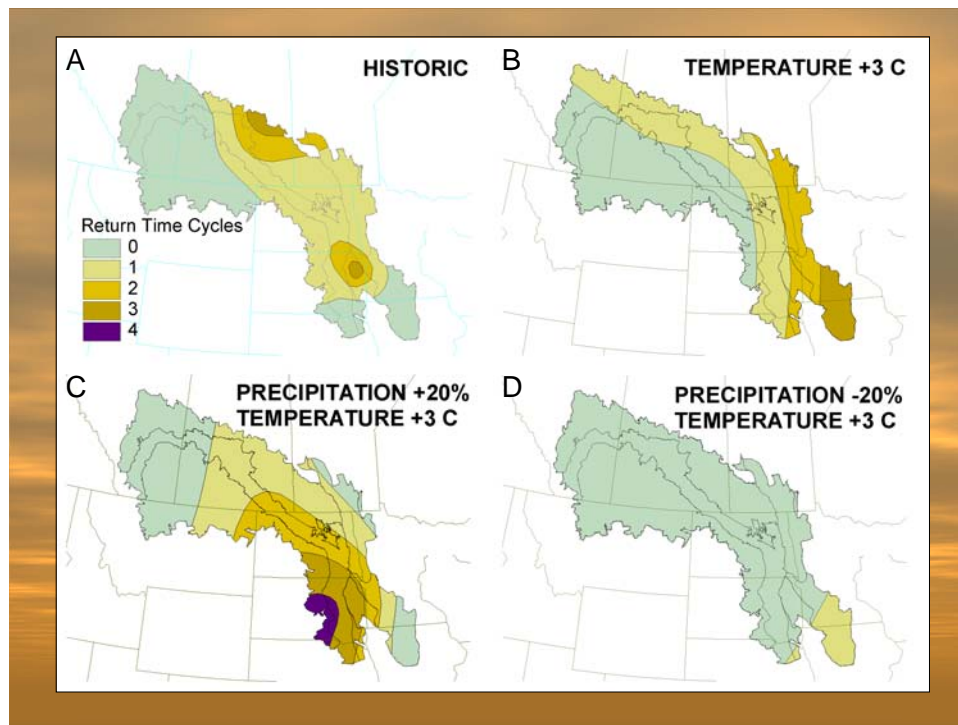
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5 The wetland cover cycle was highly sensitive to alternative future climates. The
 6 geographic pattern of return times shifted markedly with changes in temperature and
 7 precipitation. A 3°C increase in temperature and no change in precipitation resulted in a
 8 greatly diminished area and geographic shift eastward for the region of fastest return
 9 times. However, reduced precipitation and warmer air temperatures resulted in no
 10 complete cover cycle return times across the PPR except in a small area of north-central
 11 Iowa (fig. 3.3), thus representing a threshold response to climate change. Such dramatic

1 shifts in wetland conditions emphasize the sensitivity of PPR wetlands to climate
2 variability.

3 Using this information, Johnson et al. (2005) simulated the occurrence of
4 highly favorable water and cover conditions for breeding waterfowl (fig. 3.4). The most
5 productive habitat for breeding water birds would shift under an effectively drier climate
6 from the center of the PPR (the Dakotas and southeastern Saskatchewan) to the wetter
7 eastern and northern fringes (in sync with the changes in the cover cycle return results).

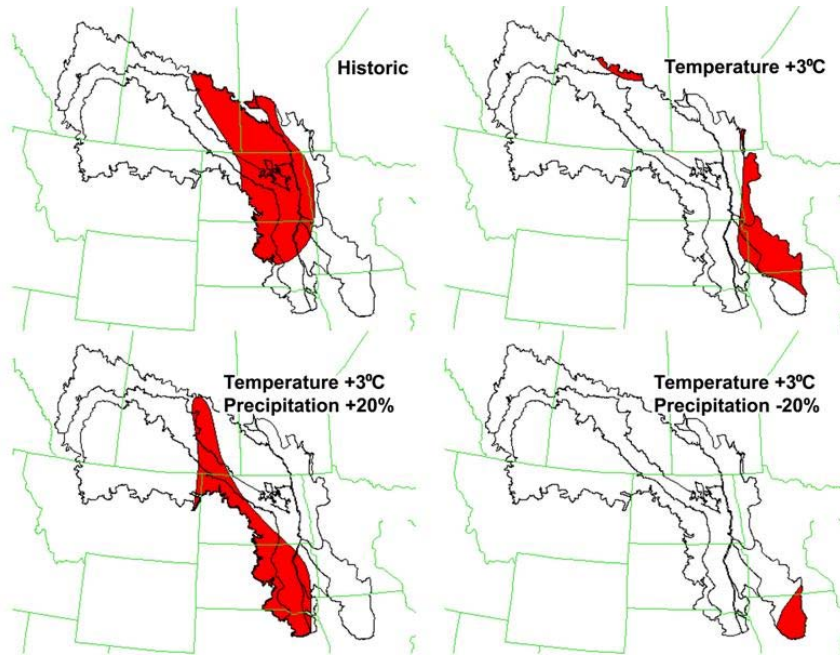
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9

10 **Figure 3.3.** Geographic patterns of the speed of the wetland cover cycle, simulated for the Prairie
11 Pothole Region (PPR) under historic (a) and alternative future (b, c, and d) climatic conditions.
12 (Johnson et al. 2005)

13



1
2

3 **Figure 3.4.** Simulated occurrence of highly favorable water and cover conditions
 4 for waterfowl breeding (occurrence of at least one return time and hemimarsch
 5 conditions at more than 30% frequency) across the Prairie Pothole Region (PPR) under
 6 historic (a) and alternative (b, c, and d) future climatic conditions. (Johnson et al. 2005)

7

8 *Case Study 3. Broad-Scale Forest Die-Back as a Threshold Response to Climate Change*
 9 *in the Southwestern United States*

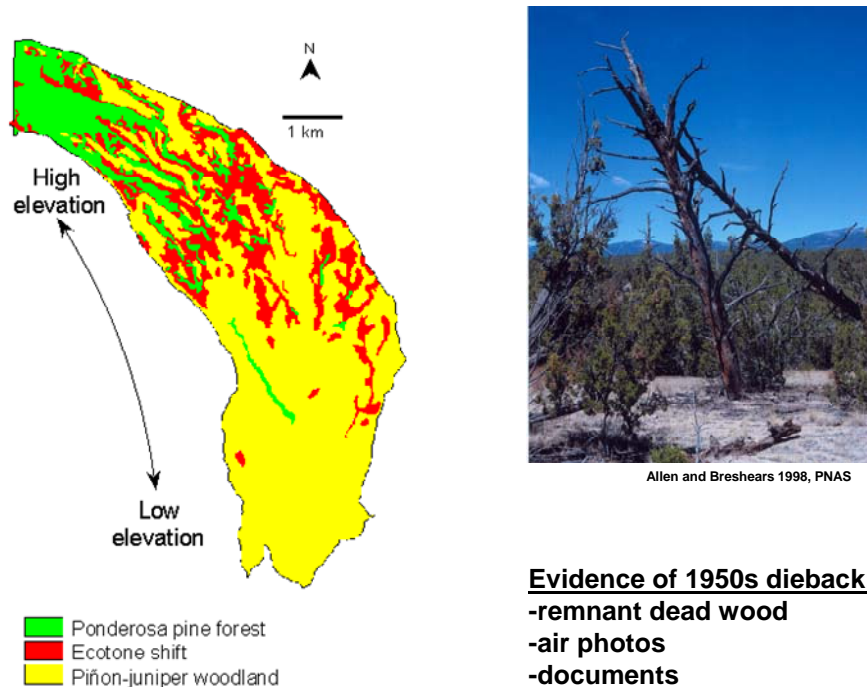
10 The ecological dynamics of semiarid forests and woodlands in the southwestern
 11 United States are observed to respond strongly to climate-driven variation in water-
 12 availability, with major pulses of woody plant establishment and mortality commonly
 13 corresponding to wet and dry periods (Swetnam and Betancourt, 1998). In particular,
 14 climate-induced water stress can trigger rapid, extensive, and dramatic forest dieback
 15 (Breshears et al. 2005), exemplifying significant ecosystem threshold responses to

1 climate. Broad-scale tree mortality can shift ecotones between vegetation types (Allen
2 and Breshears 1998) and alter regional distributions of overstory and understory
3 vegetation (Gitlin et al. 2006; Richet et al. 2008). Rapid forest dieback also has
4 nonlinear feedbacks at multiple spatial scales with other ecological disturbance processes,
5 such as fire and erosion (Allen, 2007), which, in some cases, leads to additional nonlinear
6 threshold behaviors. Massive forest mortality is an example of a threshold phenomenon
7 with substantial implications for future ecosystem dynamics and management of lands
8 undergoing such changes (Millaret et al. 2007).

9 Assessments of potential global change impacts initially focused on how
10 vegetation types matched given climatic envelopes (IPCC, 1996). Subsequent research
11 has considered how vegetation patterns might migrate in response to changing climate
12 with a focus on rates of plant establishment, has documented that forest turnover rates
13 follow global and regional patterns of productivity (significantly driven by climate)
14 (Stephenson and van Mantgem, 2005), and has increasingly moved toward dynamic
15 global vegetation models that try to incorporate more realistic disturbance dynamics
16 (Scholze et al. 2006; Purves and Pacala, 2008). Currently, climate-induced dieback
17 of woody plants is being recognized as an important vegetation response to climate
18 variation and change, with examples of forest dieback emerging from around the world
19 (Allen and Breshears, 2007). Recent research shows that water stress appears to be
20 driving increases in background tree mortality rates in western North American forests
21 (van Mantgem and Stephenson, 2007; van Mantgem et al. in review). In addition,
22 observations of extensive tree die-off—especially from semiarid ecosystems where
23 woody plants are near their physiological limits of water stress tolerance—are being

1 documented globally, for example, in Australia (Fensham and Holman, 1999), Africa
2 (Gonzalez, 2001), west Asia (Fisher, 1997), Europe (Dobertinet al.et al. 2007), South
3 America (Suarezet al.et al. 2004), and North America (Breshears et al.et al. 2005).
4 Climate-induced water stress during extended time periods can exceed the physiological
5 tolerance thresholds of individual plants and directly cause mortality through either: 1)
6 cavitation of water columns in the xylem conduits (“hydraulic failure”); or 2) forcing
7 plants to shut down photosynthesis to conserve water, leading to “carbon starvation”
8 (McDowellet al.et al. 2008; Breshears et al.et al. in press). These individual-scale
9 threshold responses to climate stress can trigger tree mortality that propagates to
10 landscape and even regional spatial scales (Allen, 2007), sometimes amplified by biotic
11 agents (like bark beetles) that can successfully attack and reproduce in weakened tree
12 populations and generate massive insect population outbreaks with positive feedbacks
13 that greatly increase broad-scale forest mortality (Kurzet al.et al. 2008).

14 Ecotones are areas where vegetation changes in response to climate are expected
15 to be most rapid and prominent (Beckageet al.et al. 2008), as highlighted by a
16 southwestern case study of drought effects on vegetation during the 1950s (fig. 3.5; Allen
17 and Breshears, 1998). Severe drought across the southwestern United States during the
18 1950s caused ponderosa pine (*Pinus ponderosa*) trees at lower, drier sites to die, resulting
19 in an upslope shift of the ponderosa pine forest and piñon-juniper woodland ecotone of as
20 much as 2 km in less than 5 years, producing a rapid and persistent change in dominant
21 vegetation cover. Similarly, within the distributional range for the piñon pine (*Pinus*
22 *edulis*), many trees at lower or drier sites also died (Swetnam and Betancourt, 1998).



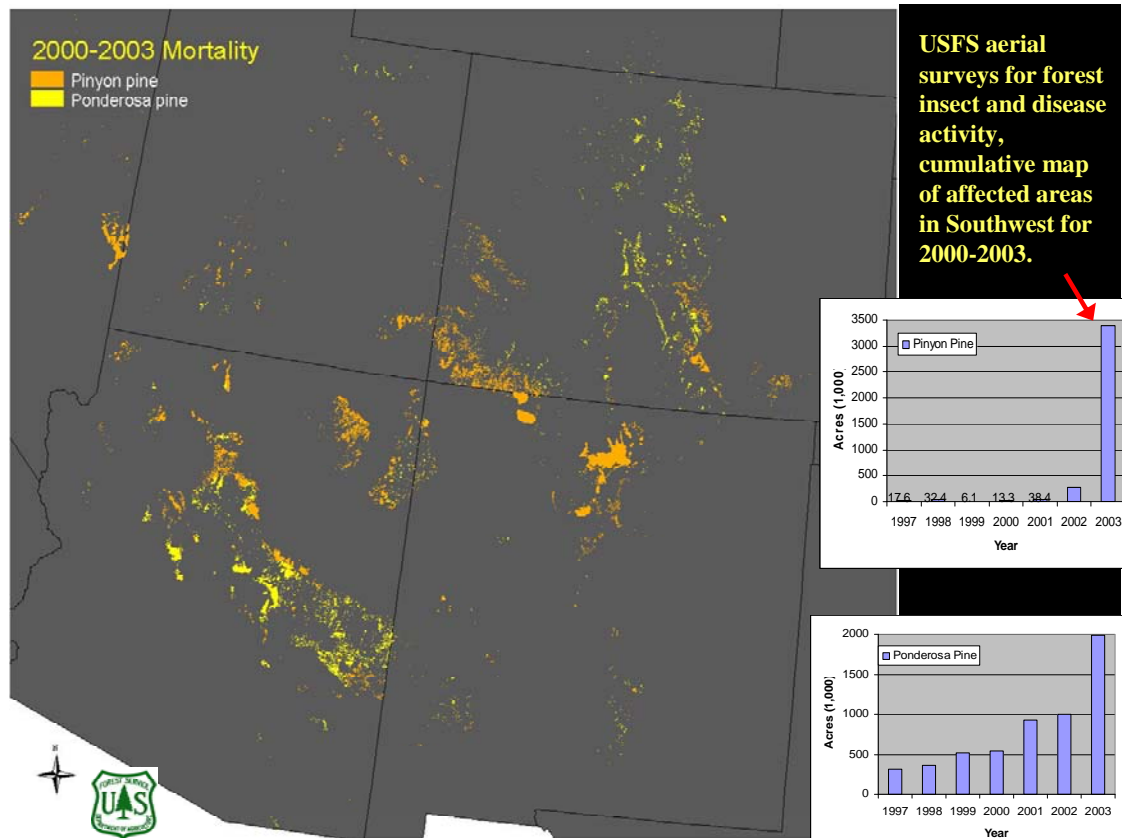
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2 **Figure 3.5.** Changes in vegetation cover between 1954 and 1963 at Frijolito Mesa, Jemez
 3 Mountains, New Mexico, showing the persistent ponderosa pine forest (365 ha), the persistent
 4 piñon-juniper woodland (1527 ha), and the ecotone shift zone (486 ha) where forest changed to
 5 woodland (from Allen and Breshears, 1998).

6

7 Although tree mortality almost certainly occurred across much of the
 8 southwestern United States in response to the 1950s drought (and probably for previous
 9 regional-scale droughts as well), few studies exist that allow scientists to test projections
 10 about the rapidity and extent of potential vegetation die-off response to drought. A recent
 11 drought beginning in the late 1990s and peaking in the early 2000s affected most of the
 12 western United States; this was the most severe drought in the Southwest since the
 13 1950s. Substantial mortality of multiple tree species has been observed throughout the
 14 Southwest during this 2000s drought (fig. 3.6; Gitlin et al. 1996; U.S. Forest Service,
 15 2006; Allen, 2007). For example, mortality of the piñon pine spanned major portions of
 16 the species' range, with substantial die-off occurring across at least 1,000,000 ha from

1 2002 to 2004 (Breshearset al.et al. 2005; U.S. Forest Service, 2006). For both droughts,
 2 much of the forest mortality was associated with bark beetle infestations, but the
 3 underlying cause of dieback appears to be water stress associated with the drought
 4 conditions.



5
 6 **Figure 3.6.** Graph of the acreage of piñon pine (*Pinus edulis*) and ponderosa pine (*Pinus*
 7 *ponderosa*) dieback from 1997-2004 in the Four Corners states of Arizona, New Mexico,
 8 Colorado, and Utah; map showing cumulative area from 2000 to 2004. Based upon annual aerial
 9 forest insect and disease activity inventories by the U.S. Forest Service.

10 The precipitation deficit that triggered the recent regional-scale die-off of the
 11 piñon pine across the Southwest was not as severe (dry) as the previous regional drought
 12 of the 1950s, but the recent 2000s drought was hotter than the 1950s drought by several
 13 metrics, including mean, maximum, minimum, and summer (June-July) mean
 14 temperature (Breshearset al.et al. 2005). Although historic data from the 1950s is

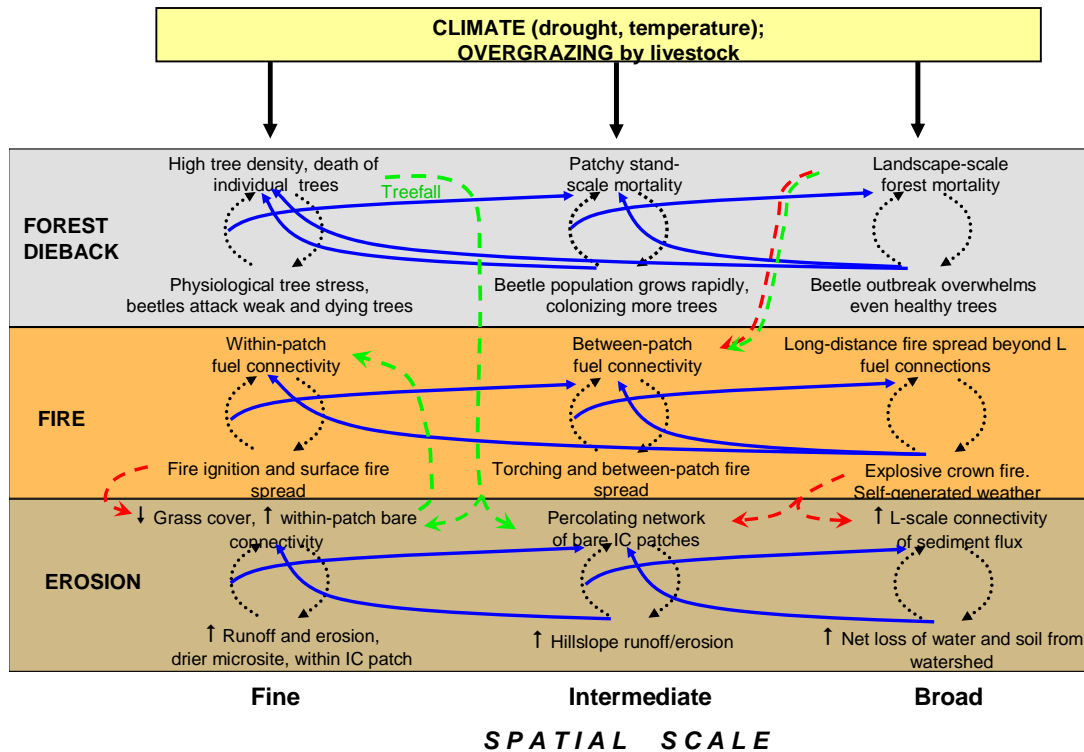
1 limited, available data suggest that piñon pine mortality in response to the recent drought
2 has been more extensive, affected greater proportions of more age classes, and occurred
3 at higher elevation and wetter sites than in the previous 1950s drought. Hence, the
4 warmer temperatures associated with the 2000s drought may have driven greater plant
5 water stress through increased evapotranspirational demand, and resulted in more-
6 extensive tree die-off. Because global change is projected to result in droughts under
7 warmer conditions—referred to as *global-change type drought*, the severe piñon pine
8 dieback from the recent drought may be a harbinger of vegetation response to future
9 global-change type droughts (Breshears et al. 2005).

10 In addition to the die-off of dominant overstory tree species, high levels of
11 dieback also were observed in other southwestern U.S. species and lifeforms in response
12 to the warm regional drought in the 2000s (Gitlin et al. 2006; Allen, 2007). These
13 include species where bark beetles are unimportant or nonexistent, including one-seed
14 juniper (*Juniperus monosperma*)—a co-dominant with piñon pine for much of its range;
15 shrubs such as wavy-leaf oak (*Quercus undulate*) and mountain mahogany (*Cercocarpus*
16 *montanus*); and blue grama (*Bouteloua gracilis*), the dominant herbaceous species in
17 many of these woodland systems.

18 In addition to direct climate-induced mortality, severe protracted drought also can
19 cause substantial reductions in the productivity and soil surface cover of herbaceous
20 plants, which in turn affects numerous other ecological processes. In particular,
21 reductions in herbaceous ground cover can trigger a nonlinear increase in soil erosion
22 once a threshold of decreased herbaceous cover has been crossed, through increased
23 connectivity of bare soil patches (fig. 3.7; Davenport et al. 1998; Wilcox et al.

1 2003; Ludwig et al. 2005; Mayoret et al. in press). On the other hand, dieback of
 2 woody canopies tends to cause an immediate successional shift toward greater cover of
 3 understory vegetation if moisture conditions are adequate (for example, Richet et al.
 4 2008), which propagates a different set of effects.

5



6

7 **Figure 3.7.** Diagram representing interactions across spatial scales for three different disturbance
 8 processes (forest dieback, fire, and erosion) in northern New Mexico landscapes (from Allen
 9 2007). Dashed black arrows represent pattern-process feedbacks within three different spatial-
 10 scale domains, with one example of pattern and process shown for each domain for each
 11 disturbance. Solid black arrows indicate the overarching direct effects of widespread
 12 environmental drivers or disturbances (such as climate and overgrazing) on patterns and
 13 processes at all scales. Blue arrows indicate the point at which altered feedbacks at finer spatial
 14 scales induce changes in feedbacks at broader scales (for example, fine-scale changes cascade to
 15 broader scales), and also where changes at broader scales overwhelm pattern-process
 16 relationships at finer scales. Red dashed arrows illustrate some examples of amplifying (positive
 17 feedback) interactions between disturbance processes within and between spatial scales; green
 18 dashed arrows illustrate dampening (negative feedback) interactions between disturbance
 19 processes. Abbreviations: L = landscape; IC = intercanopy (interspaces between tree canopies).

1

2 Overall, the dieback of overstory vegetation affects numerous key ecosystem
3 processes, which are tied to site-specific distributions of incoming energy and water
4 (Zouet al.et al. 2007), and has multiple cascading ecological effects. Widespread tree
5 mortality may propagate additional pervasive changes in various ecosystem patterns and
6 processes. Breshears (2007) summarizes the important ecological role of woody plant
7 mosaics in semiarid ecosystems:

8 *A large portion of the terrestrial biosphere can be viewed as lying within a*
9 *continuum of increasing coverage by woody plants (shrubs and trees), ranging from*
10 *grasslands with no woody plants to forests with nearly complete closure and coverage by*
11 *woody plants (Breshears & Barnes, 1999; Breshears, 2006). The characteristics of*
12 *woody plants determine fundamental descriptors of vegetation types including grassland,*
13 *shrubland, savanna, woodland, and forest. Because woody plants fundamentally affect*
14 *many key aspects of energy, water and biogeochemical patterns and processes, changes*
15 *in woody plant cover are of particular concern (Breshears, 2006).*

16 Climate-driven, rapid forest dieback has feedbacks with other ecological
17 disturbance processes, such as fire and erosion, in some cases leading to further nonlinear
18 ecosystem threshold behaviors (fig. 3.7). Warming and drying climate conditions are
19 driving higher-severity fire activity at broader scales in the southwestern United States
20 directly (Swetnam & Betancourt, 1998; Westerling et al. 2006), and probably also
21 indirectly where forest dieback changes fuel conditions (fig. 3.7: Bigler et al. 2005).
22 High-severity stand-replacing fires within woodlands and forests can almost instantly
23 cause large reductions in tree canopies and soil surface covers, thereby also triggering

1 dramatically increased rates of runoff and soil erosion for several years post-fire until
2 vegetation regrowth restores adequate land surface cover (Veenhuis, 2002; Moody and
3 Martin, in press). Forest dieback, fire, and erosion also have significant effects on
4 ecosystem carbon pools (Breshears and Allen, 2002; Kurz et al. 2008). The
5 combined interactive effects of climate-driven ecological disturbance processes
6 (vegetation dieback, fire, and erosion) are highlighted by the major changes in woodland
7 and forest ecosystems that have occurred in northern New Mexico during the past 60
8 years (fig. 3.8; Allen, 2007). Climate-induced forest dieback, fire, and accelerated
9 erosion already may be causing permanent “type conversion” changes to some
10 southwestern ecosystems. Even without factoring in ongoing/predicted climate changes,
11 it will be at least several decades to centuries before reestablishment of pre-disturbance
12 tree canopy covers will occur on many semiarid woodland and forest sites in this region
13 (Allen and Breshears, 1998; Savage and Mast, 2005).



1

2 **Figure 3.8** Increased herbaceous cover has developed since recent piñon pine forest dieback in
3 the Jemez Mountains of New Mexico and may promote surface fire regimes and changes in
4 runoff and erosion patterns. July 2004.

5

6 Examples of drought-induced tree die-off in semiarid forests and woodlands
7 highlight the rapidity and extensiveness with which climate stress can trigger pervasive
8 and persistent ecosystem changes. Climate change has the potential to drive multiple
9 nonlinear or threshold-like processes that can interact in complex ways, including tree
10 mortality, altered fire regimes, energy and water budget changes, and soil erosion
11 thresholds (Allen, 2007), making ecological predictions difficult (McKenzie and Allen,
12 2007). For example, the projections of state-of-the-art dynamic global vegetation models
13 “are currently highly uncertain, making vegetation dynamics one of the largest sources of
14 uncertainty in Earth system models” (Purves and Pacala, 2008). Additional research,

1 including research on threshold responses, is needed to improve projections of the
2 nonlinear ecological effects of expected climate changes, such as broad-scale forest
3 dieback, associated ecosystem dynamics, and effects on carbon budgets and other
4 ecosystem goods and services (Breshears and Allen, 2002; Millennium Ecosystem
5 Assessment, 2005; Millaret al.et al. 2007).

6

7 *Case Study 4. Thresholds in Climate Change for Coral-Reef Ecosystem Functioning*

8 Corals are perpetually subjected to environmental changes in time and space. As
9 adult colonies, corals are sessile and so are subjected to changes in the environmental
10 factors through time in one location. As larvae, corals are motile, and each must select a
11 location from a complex and variable array of available sites. Corals are resilient to
12 changes in both space and time through acclimatization, adaptation, local environmental
13 ameliorations, initial community composition, and the morphological characteristics of
14 the reef. It is reasonable to assume that most corals will not go extinct with global climate
15 change because of their abilities to acclimatize, to adapt, and to broadcast their larvae
16 geographically. The threshold or tipping point for coral-reef ecosystems is the point along
17 the environmental gradient at which the ecological or biological processes change from
18 negative feedback for net accretion to positive feedback or reef erosion. Systems consist
19 of mixtures of positive and negative feedbacks, with positive feedbacks tending to alter
20 the nature of the system, and negative feedbacks tending to minimize these changes
21 (Chapinet al.et al. 1996). Once the feedback process starts and net accretion decreases to
22 a point of erosion of the reef, there is no return to the functioning coral-reef ecosystem.

1 The following natural and anthropogenic stressors and coral reef responses to them may
2 include (Birkeland 2004):

- 3 • Inverse density dependence (or Allee effect) Algal abundance at levels
4 beyond the capacity of herbivores to keep in balance;
- 5 • Predators of corals at a rate higher than the rate of recovery and coral
6 population replenishment;
- 7 • Bioerosion of corals;
- 8 • The prevalence of crustose coralline algae, which weakens binding of the
9 substratum, is decreased and thereby decreases successful coral
10 recruitment; and
- 11 • Invasives—establishment of introduced species, which modify the habitat
12 in ways that favor the survival and dominance of the introduced species is
13 displacing natural species.

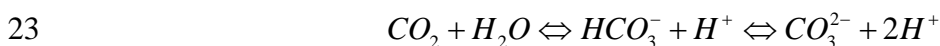
14 Such local processes as these stressors and the feedback mechanisms of corals to
15 these stressors have determined the substantial degradation of coral reefs over the past 3
16 decades in the tropical western Atlantic Ocean (Gardner et al. 2003) and in the Indo-
17 Pacific Ocean (Bruno and Selig, 2007). It is *likely* that the crossing of thresholds in coral
18 ecosystems began nearly 3 decades ago with no evidence the rate of degradation is
19 decreasing.

20 Although anthropogenic modification of local ecological processes has been the
21 dominant force in coral-reef degradation (Birkeland, 2004) and tipping points have been
22 crossed decades ago in many areas (Gardner et al. 2003; Bruno and Selig, 2007),
23 global changes in climate and oceanic characteristics are now becoming more apparent.

1 Global processes that are affecting coral reefs, which are related to the increased
2 concentration of atmospheric CO₂, are sea level rise, the decline in pH of seawater, and
3 the increase in seawater temperature.

4 *Rise and Fall of Sea Level.*—Coral reef ecosystems have experienced rise and fall
5 of sea levels several times in geological history with associated effects on reef
6 functioning (defined as constructing reefs upwardly). Reef accretion has stopped for
7 periods of time in excess of 10 million years, the threshold for the cessation of reef
8 upward growth being the time of decreasing sea level. It is hard to determine the effect
9 of climate change alone on whether corals will keep pace with sea level rise, increasing
10 water temperatures, and change in ocean pH. Whether coral reefs keep up with sea level
11 rise depends on a multitude of local environmental factors and the degree to which these
12 factors stress the corals themselves. The rate of sea level rise alone does not provide a
13 predictable tipping point for reef deposition that can be generalized over a region
14 (Hallock et al. 1993, Garrison et al. 2003).

15 *Decrease in Seawater pH.*—The concentration of CO₂ in the atmosphere is generally
16 expected to reach two times the preindustrial (late 18th century) levels by 2065
17 (Houghton et al. 1996). As CO₂ concentration increases in the atmosphere, the
18 surface seawaters take up more CO₂. The increased uptake of atmospheric CO₂ by the
19 surface waters of the ocean leads to a decrease in pH of surface waters, an increase in the
20 proportion of bicarbonate ions (HCO_3^-), and a decrease in the proportion of carbonate
21 ions (CO_3^{2-})(Feely et al. 2008). . The overall effect is on the rate of precipitation of
22 coral skeleton.



1 The oceans have already taken up an additional one-third to one-half of
2 industrial-age emissions of CO₂, and the concentrations of carbonate ions in the oceans
3 have decreased from 11% (preindustrial), to 9% (now) and are projected to decrease to
4 7% when carbonate concentrations are double the preindustrial concentrations, perhaps in
5 3 to 5 decades (ISRS, 2007).

6 Kleypas and others (1999) determined that doubled atmospheric CO₂ will lead to
7 a 14% to 30% decrease in reef calcification rates. This was estimated to be a general
8 tipping point from net carbonate accretion to net carbonate loss by Kleypas and others
9 (2001). Net reef accretion is potentially reduced to zero when increased CO₂ in the
10 atmosphere reaches about 500 to 600 ppm. On the other hand, CO₂ is less soluble in
11 seawater at higher temperatures. While increased concentrations of atmospheric CO₂ may
12 be accelerating the uptake of CO₂ by surface seawater, global warming may be slightly
13 damping the uptake. But of more substantial influence in accelerating the tipping point of
14 net reef accretion are the synergistic biological effects on corals of reduced growth in the
15 face of natural and anthropogenic stressors.

16 Sabine and others (2004) showed that uptake of anthropogenic CO₂ by subtropical
17 Atlantic waters has been greater than by Pacific waters. The north Atlantic stores 23% of
18 the total anthropogenic (fossil-fuel and cement-manufacturing emissions) CO₂ taken up
19 by the world oceans, even though the north Atlantic occupies only 15% of the world's
20 total ocean area. Pacific waters are less receptive to the uptake of CO₂ and therefore are
21 buffered from a decrease in pH because of higher concentrations of dissolved inorganic
22 carbon. As seawater becomes warmer coral reef net accretion will probably become

1 slightly more restricted in latitude (Kleypaset al.et al. 1999, 2001) because of the changes
2 in chemistry from CO₂ uptake in the world's oceans.

3 *Seawater Warming.*—The thresholds in tolerance of corals to an increase in water
4 temperature and its duration before “bleaching” (expelling the symbiotic zooxanthellae)
5 is predicted by the degree heating week (DHW) record, 12-week accumulations measured
6 as °C weeks. The DHW product is an accumulation of hotspot values over the bleaching
7 threshold [1°C over the maximum monthly mean (MMM)]. The threshold values of
8 DHW vary from site to site because the MMM varies from site to site; thus, corals are
9 likely adapted to their own threshold temperatures at each site. Furthermore, the past
10 history of events in the physical environment and local characteristics of the physical
11 environment can modify the actual location of the threshold or tipping point (Smith and
12 Birkeland 2007). Based on our knowledge of tolerances and the gaps in the literature on
13 thresholds identified in developing this SAP, corals are *likely* to reach a threshold with an
14 increase in sea water temperatures.

15 *Mechanisms of Reef Resilience That Alter Thresholds.*— The resilience of corals
16 to environmental changes is largely determined by their capacity to acclimatize (adjust
17 physiologically and behaviorally). The thresholds of resilience of corals to environmental
18 factors, such as water temperature and ultraviolet (UV) radiation, are altered by changes
19 in symbiotic interactions. Reef-building corals are dependent on symbiotic dinoflagellate
20 algae (zooxanthellae) in their endodermal cells for their nutrition and proficiency in
21 deposition of skeleton. There are a number of clades or types of zooxanthellae, and the
22 physiological and ecological attributes of zooxanthellae vary among clades. The
23 symbiotic relationship breaks down under stressful conditions of extra warm seawater or

1 strong UV radiation. Under these conditions, corals sometimes expel much of the
2 zooxanthellae of clade C and allow the buildup of clade D, with which the coral growth
3 rate is slower but survival under stressful conditions may be greater. As with
4 morphological adjustments, the symbiotic adjustments of corals may be determined by a
5 balance between the stresses imposed by the physical environment and by ecological
6 interactions with other species (Bruno and Selig 2007). In addition to adjustments in
7 morphology and symbiotic relationships, acclimatization can occur through biochemical
8 conditioning. Increased water temperature triggers a substantial increase in biochemical
9 activity in corals, Intense biochemical activities resulting from changes in water
10 temperature may indicate a processes of acclimatization that might increase the distance
11 to the threshold for mortality of the coral from seawater temperature (Smith and
12 Birkeland 2007).

13 Whether changes in morphology, symbiotic relationships, physiological
14 conditioning, or production of biochemicals are the mechanisms to shift the threshold for
15 survival from climate change, acclimatization costs the coral in terms of energy and
16 materials that would otherwise be available for growth and successful competition.
17 Acclimatization can be approached by robustness or plasticity. The mound-shaped
18 species of *Porites* (such as *P. lobata*) are robust and live in a wide range of habitats. They
19 are the last to drop out of the coral community near a river mouth or in bays with
20 increasing turbidity. Species of *Acropora* dominated the reef front at the municipal sewer
21 outfall for Koror, Palau, until predation on corals by the crown-of-thorns starfish and
22 bleaching by the large-scale seawater warming of 1997–98 killed the *Acropora* spp. but
23 not the *Porites* spp. (Richmond et al. 2002). *Porites* can maintain itself rather constantly

1 despite fluctuations in the external physical environment, but at a metabolic cost (fig.
2 3.9).

3 The relatively rapidly growing *Pocillopora eydouxi* display plasticity and can
4 differ substantially among habitats in rates of growth, colony morphology, and types of
5 zooxanthellae hosted. *Pocillopora* are generally more vulnerable to the physical
6 environment and so their growth rates vary among habitats and they are more likely to
7 bleach [expel zooxanthellae and/or photosynthetic pigments] with higher than usual water
8 temperatures and with more intense UV radiation.



9
10 **Figure 3.9.** Branching corals overgrowing mound-shaped corals.

11 *Factors that Shift the Thresholds.*—Corals are most vulnerable to infrequent or
12 very frequent environmental changes. As explained in the previous section, corals can
13 acclimatize (physiological or behavioral response) or adapt (genetic response) to
14 environmental changes of intermediate frequency. If the phenomena, such as

1 extraordinarily warm seawater, are infrequent enough to be unpredictable, then the corals
2 will not be able to acclimatize or adapt. However, if the events are too frequent, the
3 corals will not have time to recover between events.

4 The factor of duration relates to the different effects of acute and chronic
5 disturbances on the resilience of coral communities. The threshold seawater temperature
6 associated with global climate change is determined in part by the duration of the warm
7 water event. In 1997–98, an increased average surface seawater temperature of 1.0° to
8 1.5°C (to about 30° or 31°C) over a period of several weeks caused extensive mortality of
9 corals in the Indian Ocean, the southwestern Pacific Ocean, and the western Atlantic
10 Ocean (Bruno and Selig 2007). In contrast, daily fluctuations of 6°C to 6.5°C (to about
11 34° or 35.5°C) in reef flat pools in American Samoa are endured in good health by about
12 80 species of corals.

13 The threshold seawater temperature that severely affects a coral will be higher in
14 areas of constant or even intermittent high water motion and the threshold of temperature
15 tolerance will be lower in areas of low water motion (Smith and Birkeland, 2007).
16 Thresholds in levels of tolerable input of nutrients or sediment will be low in backwaters
17 and relatively much higher in areas of strong current. In contrast, it will take substantially
18 longer for the ecosystem to solidify rubble into a stable substratum for reef recovery in
19 areas of strong water motion than in areas of low water motion. The threshold of
20 tolerance of corals to infection by disease is sometimes lowered by stress from other
21 environmental factors and by abrasion of surface tissue by predators or other objects
22 (Garrison et al. 2003). The physical and biological environments are a complex system of

1 factors that potentially act synergistically to shift the threshold of the specific factor
2 associated with climate change.

3 *Levels of Thresholds.*—Thresholds should be considered at two levels: the first at
4 which the population is killed or the ecosystem becomes dysfunctional, and the second at
5 which the population or the ecosystem is prevented from becoming reestablished. An
6 acute disturbance to a coral reef is a distinct event. A chronic disturbance is an ongoing
7 process. The coral-reef communities of American Samoa have been severely affected by
8 large-scale acute disturbances, such as outbreaks of the coral-eating crown-of-thorns
9 starfish *Acanthaster planci* (1938, 1978), hurricanes (1981, 1987, 1990, 1991, 2004,
10 2005), and bleaching in response to seawater warming (1994, 2002, 2003). When allowed
11 a 15-year interval between disturbances, the coral communities have recovered
12 (Birkeland et al. 2008). This is in contrast to the western Atlantic where there has
13 been a continual degradation of coral reef systems for a half a century (Gardner et al.
14 2003). The relatively small area of the tropical western Atlantic allows widescale events
15 on continents to affect the whole region (Hallock et al. 1993; Garrison et al.
16 2003). The nutrients (Hallock et al. 1993), pollutants (Garrison et al. 2003), and
17 diseases (Lessios et al. 1984) can disperse across the entire region. A recent paper by
18 Bruno and Selig (2007) reported that 3,168 square kilometers of reef has been dying each
19 year rather uniformly throughout the Indo-Pacific Ocean. Reefs are appearing to be
20 losing their resilience globally.

21 American Samoan reefs have managed to maintain resilience by receiving
22 disturbances only as acute events and being largely isolated from nearby large
23 landmasses. Overfishing, however, has been chronic, and the fish communities have not

1 been as resilient as the corals (Zelleret al.et al. 2006 a, b). Some localized and well-
2 defined areas experience chronic stresses, such as sedimentation at the mouths of rivers
3 or in the backs of bays, and have not been recovering for decades.

4

5

1 **Chapter 4—Examples of Threshold Change in Ecosystems**

2 *4.1 Background*

3 The existence of ecological thresholds has long been apparent to people who
4 depend on natural resources. Fisheries collapses, for instance, have been noted for
5 centuries. However, ongoing climate change has given this issue greater urgency because
6 more ecosystems may be getting pushed toward response thresholds simultaneously, and
7 based on gaps in the literature identified through the development process for this SAP,
8 little is known regarding where the tipping points are. Summarized below are examples
9 of where ecological thresholds have been crossed; they represent different geographic
10 areas, ecosystem types, and drivers of change. These reflect the new stressor of climate
11 change and how it leads to new ecosystem responses. For example, the temperature
12 increases documented for many areas can likely cause an ecosystem changeover when
13 normal droughts are experienced because the additional evapotranspirative demand of
14 higher temperatures exceeds the adaptive capacity of trees, leading to the massive forest
15 dieback described in Case Study 3.

16 *4.2 Evidence of Thresholds from the Past*

17 Thresholds appear to have been crossed in the past, leading to ecosystem changes
18 that persist today. A recent example of threshold behavior is the encroachment of woody
19 plants into perennial grasslands that has occurred throughout arid and semiarid regions of
20 the world for at least the past several centuries. This broad-scale land cover conversion
21 and associated soil degradation (*i.e.*, desertification) has local to global consequences for
22 ecosystem services, such as reduced air and water quality (Schlesinger et al. 1990;

1 Reynolds and Stafford Smith, 2002). Multiple interacting processes and threshold
2 behavior are involved in these dynamics (Rietkerk and van de Koppel, 1997).

3 Cross-scale linkages among local soil and grass degradation, landscape
4 connectivity of erosion processes, and land cover-weather feedbacks have been invoked
5 to explain threshold behavior in space and time that occur during desertification (Peterset
6 al.et al. 2006). Four stages and three thresholds have been identified as the spatial extent
7 of desertified land increases through time (Peterset al.et al. 2004). Following introduction
8 of woody plant seeds into a grass-dominated system (Stage 1), local spread often occurs
9 as a result of feedback mechanisms between plants and soil properties interacting with
10 wind and water erosion to produce fertile plant islands surrounded by bare areas that
11 move the system across a threshold into Stage 2 (Schlesingeret al.et al. 1990). This rate of
12 spread may be slower than other stages as a result of interactions between plant life
13 history characteristics that occur infrequently, such as recruitment, and the low
14 precipitation and high temperatures that characterize dry regions. As the size and density
15 of woody plants increase through time, contagious processes among patches, primarily
16 wind and water erosion that connect bare soil patches, become the dominant factors
17 governing the rate of desertification. As a result, a nonlinear increase in woody plant
18 cover occurs and a second threshold is crossed as the system enters Stage 3. Through
19 time, sufficient land area can be converted from grassland (low bare area, low albedo) to
20 woodland (high bare area, high albedo) so that regional atmospheric conditions, in
21 particular wind speed, temperature, and precipitation, are affected. At this point, a third
22 threshold is crossed where land-atmosphere interactions with feedbacks to vegetation
23 control system dynamics (Stage 4) (Pielkeet al.et al. 1997). Feedbacks to broad-scale

1 vegetation patterns have been documented in the Sahara region of Africa (Claussenet
2 al.et al. 1999).

3 *4.3 Evidence of Sensitivity to Current Stressors*

4 *4.3.1 Temperature Increase*

5 The effects of increasing temperatures as an effect of climate change are not
6 independent of the effects of other important environmental stressors, and thus need to be
7 assessed in the context of multiple, interacting stressors. AR4 WG II (2007) reports with
8 very high confidence that the increased warming effect of climate change is strongly
9 affecting natural biological systems in both marine and fresh water systems. The
10 chemical and physical characteristics of lakes experience major effects owing to changes
11 in temperature, especially changes in nutrient dynamics. Increased temperatures in lake
12 systems will affect the distributions, growth, and survival of fish and many other aquatic
13 organisms. Tied with increased temperatures is a change in precipitation, which can cause
14 substantial physical and chemical changes in lakes and streams, with large consequences
15 for aquatic biota. In marine systems, increased temperature from climate change is
16 affecting coastal resources and habitats because of sea level rise that is caused by thermal
17 expansion of the oceans and the melting of ice cover. The rate of sea level rise is
18 expected to accelerate because of global warming. Salt marshes must increase their
19 vertical elevation at rates that keep pace with sea level rise or risk transformation to a
20 lower position along the marsh gradient. In transgressing systems, where there is a
21 landward movement of the marsh system, structure and composition of marsh
22 communities is expected to change when the rate of sea level rise exceeds the rate of
23 vertical accretion. Transition from one type of marsh to another (for example, high

1 marsh to low marsh) at a given point has been described as ecosystem state change
2 (Milleret al.et al. 2001).

3 The effects of temperature increases on terrestrial systems are further emphasized
4 in the IPCC Assessment Report for Working Group II (2007)(AR4WGII) report with
5 very high confidence where it is stated that the overwhelming majority of studies of
6 regional climate effects on terrestrial species reveal consistent responses to warming
7 trends, including poleward and elevational range shifts of flora and fauna. Responses of
8 terrestrial species to warming across the Northern Hemisphere are well documented by
9 changes in the timing of growth stages (that is, phenological changes), especially the
10 earlier onset of spring events, migration, and lengthening of the growing season. Changes
11 in abundance of certain species, including limited evidence of a few local disappearances,
12 and changes in community composition over the last few decades have been attributed to
13 climate change. A further indication of effects of increased temperatures is revealed in
14 earlier snowmelt and stream runoff, which affects both aquatic and terrestrial ecosystems
15 and species. Sensitivity of target organisms to climate change depends on several aspects
16 of the biology of a species or the ecological composition and functioning of a system. For
17 example, species that are physiologically sensitive to changes in temperature or moisture;
18 species that occupy climate-sensitive habitats such as shallow wetlands, perennial
19 streams, and alpine areas; and species with limited dispersal abilities will all be more
20 sensitive to climate change. (SAP 4.4, 2008) SAP 4.3 (2008) states that projected
21 increases in temperature and a lengthening of the growing season will likely extend
22 forage production into late fall and early spring, thereby decreasing the need for winter-
23 season forage reserves; that a shift in optimal temperatures for photosynthesis might be

1 expected under elevated CO₂; and that climate-change-induced shifts in plant species are
2 already underway in rangelands. There is a need to better understand the complexities of
3 ecosystems and the drivers of change within them and to be able to identify the
4 thresholds of these changes in a changing climate.

6 *4.3.2 Moisture Availability*

7 Moisture is so critical to all life forms that its availability has the potential
8 to transform ecosystems abruptly through threshold crossings. Case Study 2
9 demonstrates the role that prolonged drought and water stress had in a threshold-triggered
10 massive forest-dieback with consequences for erosion and other state changes that will
11 make a return to the pre-threshold forest unlikely. Similarly, changes in available
12 summer moisture have lead to a significant rise in the frequency and severity of wildland
13 fire in the Northern Rocky Mountains (Westerling et al. 2006). Diminished
14 snowpacks that melt earlier in the spring have affected the timing and extent of seasonal
15 wetlands where amphibians breed. A threshold may occur wherein the reduced
16 amphibian population cannot accommodate the necessary shift in the timing of breeding
17 or cannot survive multiple dry years, causing local extinction (Corn 2003).

18 *4.3.3 Climate Interactions*

19 As important as the increases in temperatures and changes in moisture
20 availability are for causing ecosystems to go through thresholds, it is the interactions that
21 are key to driving the change. In general, plants in undisturbed ecosystems are at their
22 moisture-limited capacity for net primary productivity. Therefore, increased temperatures
23 *and* droughtiness will combine to produce severe stress on plant growth whereas

1 increased temperatures and increased moisture availability will lessen the stress or may
 2 promote plant productivity, leading to an ecosystem with increased resilience. Because
 3 evapotranspirative demands on vegetation increase with temperature, thresholds are more
 4 likely to occur whenever moisture availability does not simultaneously increase with
 5 warming temperatures. The exception is ecosystems that are primarily limited by
 6 temperature, such as arctic and alpine ecosystems. In these latter cases, ample moisture
 7 means that vegetation can respond without evapotranspirative limits but that threshold
 8 changes can still occur as competitive relationships are altered between plant species
 9 (Hansell et al. 1998). The shrubbification of the arctic, detailed in Case Study 1, is an
 10 example. Case Study 2 makes the importance of interactions clear because trees in the
 11 southwestern United States had survived similar droughts in the past but this time
 12 temperatures had increased and the interaction of both climatic stressors pushed the
 13 ecosystem into threshold change.

14

15 Temperature

		Current	Higher
Moisture	Lower	Drought	Severe drought
Availability	Current	No change	Evapotranspirative stress
	Higher	Enhanced growth	Enhanced growth with potential threshold Shifts

16

17 *4.3.4 Climatic Variability Increases*

18 The climate drivers that produce threshold ecosystem responses may be complex
 19 and involve the interaction of variability in phenology and weather episodes. The “2007

1 spring freeze” in the eastern United States is an example. A very warm late winter/early
2 spring period in much of the southeastern United States in 2007 led to budbreak and
3 development of forest canopy 2 to 3 weeks earlier than usual. A very cold Arctic air
4 mass spread across much of the eastern United States in early April (an event not unusual
5 for that time of year), dropping the low daily temperatures well below freezing for
6 several days. The freeze killed newly formed leaves, shoots, and developing flowers and
7 fruits and resulted in a sharp drop in vegetation greenness (NDVI) across a large swath of
8 the southeast. The severity of impact was species specific, but at one site affected by this
9 episode there was a significant reduction in forest photosynthetic activity for at least
10 several weeks after this event, and the leaf-area index was depressed throughout the
11 summer (Guet al.et al. 2008). While our understanding of the long-term effects of this
12 episode are unclear, they may *likely* include significant changes in the forest composition
13 due to mortality and/or increased susceptibility to pests of the more susceptible species if
14 similar episodes occur in the future (IPCC 2007).

15 *4.3.5 Other Human Stressors and Climate Change*

16 The interaction of human stresses on ecosystems (for example, land use change)
17 and climate change may be most evident for lotic ecosystems and may produce threshold
18 responses that each stress alone would not produce. Flow variability over time and space
19 is a fundamental characteristic of lotic ecosystems. It is this temporal and spatial flow
20 variability that defines and regulates biotic composition and key ecosystem processes in
21 streams and rivers (Poffet al.et al. 1997; Palmeret al.et al. 2007). Climate change will
22 alter flow regimes and generate changes to biotic communities in many of these
23 ecosystems, although it is not clear that these flow alterations will produce threshold-type

1 responses in these systems that have evolved in response to high flow variability.
2 However, more severe or prolonged droughts in the western U.S. resulting from human-
3 induced climate change will interact with growing water demands to potentially produce
4 hydrologic regime shifts in many drainage basins (Barnett et al., 2008).

5 Recent empirical evidence suggests that severe droughts can produce more
6 dramatic and long lasting effects (for example, loss of biodiversity) on the biological
7 communities of streams and river ecosystems than do other changes in the flow regime,
8 such as floods (Boulton et al. 1992; Lake, 2004). Studies of drought effects on
9 macroinvertebrates in Australian streams where drought is a common and widespread
10 phenomenon suggest that there may be a significant lag effect that prevents recruitment
11 after drought conditions end (Boulton, 2003). Historical evidence exists of large shifts in
12 river fish communities in response to decades-to-century-scale droughts in the Colorado
13 River basin at the end of the Pleistocene (Douglaset al. et al. 2003), but recent findings
14 indicate large uncertainties in long-term effects of drought on fish (Matthews and Marsh-
15 Matthews, 2003).

16 Many of the expected changes to flow regimes from climate change are similar to
17 those that result from urbanization and other human alterations of drainages. Among
18 these are increased flashiness of hydrographs and longer periods of low or intermittent
19 flow, higher water temperatures, and simplified biotic assemblages (Paul and Meyer,
20 2001; Royet al. et al. 2003; Allan, 2004; Nelson and Palmer, 2007). The increases in
21 urbanization that have occurred and are likely to continue in many regions of the United
22 States will very likely exacerbate climate change effects.

1 The strongest evidence for potential threshold effects in rivers and streams
2 appears to be the result of combined impacts of high or increasing human water
3 withdrawals and the likelihood of more frequent or longer droughts under a warming
4 climate. Defining a water stress index equivalent to total human water use divided by
5 river discharge, Vorosmarty and others (2000) showed that the combination of projected
6 population and climate change results in substantial increases in water stress over large
7 areas of the eastern and southwestern United States. In an analysis of sustainable water
8 use in the United States, the Electric Power Research Institute (EPRI) (2003) reported
9 that total freshwater withdrawal exceeded 30% of available precipitation over much of
10 the semiarid and arid regions of the United States and over large areas of Florida and
11 other metropolitan areas in the east. High rates of human water use reduce flow and
12 extend low flow periods, restricting and degrading habitat for river and stream biota.
13 Using two scenarios from the 2001 IPCC report, Xenopoulos and others (2005) reported
14 that the combination of climate change and increased water withdrawal may result in loss
15 of up to 75% of the local fish biodiversity in global river basins.

16 There are several examples of potential large-scale threshold responses to the
17 combined effects of human water management and climate-induced drought. In the
18 Columbia River basin of the Pacific northwest, multiple stressors, including population
19 growth; conflicts between hydropower, agriculture, and recreation interests; and
20 ineffective water management institutions and structures, have increased the vulnerability
21 of water resources (Payne et al., 2004; Miles et al. 2007) already vulnerable as a result of
22 reduced winter snowpack (Barnett et al., 2005), which generates much of the summer
23 flow, and sustained or repetitive droughts projected by climate change models that would

1 drive water supplies to extreme low levels. Because salmon populations are under
2 considerable stress because of dams, water withdrawals, and other human actions,
3 reduced summer flow under a warmer climate may exceed population sustainability
4 thresholds (Neitzel et al.,1991).

5 The Colorado River supplies much of the water needs of a large area of the
6 western United States and northern Mexico. The lower portions of the river have become
7 highly vulnerable to drought due to increase in demand from population increases. A
8 long-term drought beginning about 2000 has lowered water levels considerably in Lakes
9 Powell and Mead and many climate models project future conditions that will eventually
10 lead to the drying up of Lake Powell and reduced flow in the Colorado River by more
11 than 20%. Water allocations for maintaining the ecological integrity of natural
12 communities could drop below thresholds that ensure their viability as scarce water is
13 prioritized for human communities (Pulwarty and Kenney, 2008).

14 Even in the humid southeastern United States, the combined effects of increased
15 water withdrawals and climate change may exceed thresholds in ecosystem response. The
16 Chattahoochee-Apalachicola River basin in Alabama, Florida, and Georgia is both an
17 important water source for agricultural, industrial, and municipal uses and an important
18 fishery. More than 75% of the fish species inhabiting this river system depend on access
19 to floodplain and tributary areas to forage and spawn, and there are flow thresholds below
20 which fish cannot move into these critical areas (Light et al. 1998). Analysis of
21 projected future water withdrawals and climate change for the Chattahoochee-
22 Apalachicola River basin indicates that by 2050, minimum flows will drop below these
23 minimum flow thresholds for at least 3 months in summer in some areas (Gibson et al.

1 al. 2005). Further exacerbating this situation will be the increased percentage of flow that
2 is wastewater effluent with lower minimum flows in this rapidly urbanizing basin, which
3 will increase biological oxygen demand and reduce dissolved oxygen concentrations
4 potentially below threshold levels required by some species of fish (Gibson et al.
5 2005).

6 The drying up of streams and wetlands represents thresholds that involve
7 contraction or elimination of entire aquatic ecosystems. Prairie rivers, streams, and
8 wetlands of the Great Plains may be particularly vulnerable to these types of thresholds
9 because of the combined effects of water withdrawals for agricultural and municipal uses
10 and projected climate changes that will result in longer periods of drought (Johnson et al.,
11 2005). For example, since the late 1970s, the Arkansas River and many of its tributaries
12 in Kansas have had long periods of dry channels because of extensive surface and
13 groundwater use in its drainage basin (Dodd et al. 2004). The drying up of
14 headwater streams and even some larger streams and rivers for extended periods may
15 become common in wetter areas of the United States as well, particularly as a result of
16 the combined effects of increased water withdrawal and climate change.

17 Riparian ecosystems are also vulnerable to drought-related thresholds, particularly
18 in the more arid regions of the United States. Riparian forests dominated by cottonwood
19 are being replaced by drought-tolerant shrubs along some rivers in the western United
20 States. Increased surface and groundwater withdrawals combined with drought have
21 resulted in the replacement of riparian forests of native cottonwood (*Populus fremontii*)
22 and willow (*Salix gooddingii*) by an invasive shrub (*Tamarix ramosissima*), resulting in
23 reduced animal species richness, diversity, and abundance over extensive areas along the

1 San Pedro River in Arizona (Lite and Stromberg, 2005). Surface flow and the depth to
2 groundwater appear to be the primary controls on riparian vegetation, with loss of native
3 riparian communities when rivers and streams drop below flow permanence thresholds of
4 50% to 75% (Stromberget al.et al. 2005, 2007).

5 *4.3.6 Ecosystem Vulnerability and Climate Change*

6 Ecosystems are very likely to differ significantly in their potential for climate
7 change to impact them to the point that thresholds are crossed and substantial alterations
8 occur. Given the magnitude and pervasiveness of climate change, it is surprising how
9 little is known regarding the sensitivity of different ecosystems to any single aspect of
10 climate change (such as increased temperatures), and even less is known about the
11 impacts of multiple climate change factors. This lack of basic understanding represents a
12 critical knowledge gap and research challenge, one that is further complicated by the fact
13 that climate change is only one component of global change and that multiple alterations
14 to climate, biogeochemical cycles, and biodiversity are occurring in tandem.

15 General hypotheses, however, can be posed and predictions made about some of
16 the ecosystem attributes that may be important in generating differential ecosystem
17 vulnerability to climate change, including the likelihood that important thresholds of
18 response are crossed. For example, most ecosystems have a single or just a few dominant
19 species that mediate ecological processes, control the majority of the resources (including
20 space), and/or have disproportionate impacts on species interactions. Thus, if climate
21 change favors a new dominant species, the prediction is that it will likely be the rate at
22 which the extant species can be replaced and the traits of these new species that will
23 determine the likelihood that the ecosystem will be altered significantly to result in

1 threshold behavior in state or function. For example, ecosystems dominated by long-lived
2 species (for example, trees) with slow population turnover would be expected to be
3 relatively slow to respond to climate change whereas those ecosystems dominated by
4 short-lived species (for example, annual plants) are expected to be more vulnerable to
5 experiencing substantial change if the new dominant species replacing the old have very
6 different species traits.

7 Ecosystems can differ dramatically in the sizes of key carbon and nutrient pools,
8 as well as rates of biogeochemical transformations and turnover. These attributes may
9 also determine the rate and magnitude of ecosystem response to climate change if climate
10 forcings influence these biogeochemical attributes. For example, ecosystems with large
11 nutrient pools and/or slow turnover rates are expected to respond minimally to climate
12 change-induced alterations in nutrients. In contrast, ecosystems with limited nutrient
13 pools and rapid biogeochemical cycling are expected to be more vulnerable to climate
14 change that results in critical thresholds being crossed. The general hydrologic balance of
15 ecosystems would similarly impact ecosystem sensitivity to any climate change that
16 affects water availability. In general, those ecosystems with a precipitation-to-potential
17 evapotranspiration ratio near or below 1:1 will be predicted to be more vulnerable to
18 change than ecosystems where this ratio is greater than 1:1.

19 Levels of biodiversity (functional traits and species) within an ecosystem may
20 also be important in influencing sensitivity to climate change (Grebmeier 2006). The
21 number and traits of species may buffer ecosystems from change and influence the extent
22 to which immigration of new species will occur. For example, depending on how well
23 species in an ecosystem functionally complement each other and the ability of species to

1 compensate for the change resulting from the loss of the dominant species, the
2 replacement of a dominant species by another species could result in no change or large
3 changes in ecosystem state. Similarly, invading species may result in the rapid crossing
4 of thresholds or may have little or no impact depending on the traits of these species
5 relative to the traits of native species.

6 Finally, interactions with the natural disturbance regime inherent in an ecosystem,
7 other climate change factors, and other global changes, such as habitat fragmentation and
8 species invasions, will more than likely influence whether or not ecosystems cross
9 response thresholds and experience substantial amounts of change in their structure and
10 function. For example, ecosystems that are historically prone to fire may experience more
11 frequent fires with climate change, making them more susceptible to invasions by exotic
12 species as resources become available post-fire.

1

2 **Chapter 5—What Can Be Done?**

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

10 *5.1 Integration of Management and Research*

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

19 *5.1.1 Need for Conceptual Models*

20 Most frameworks for nonlinear ecosystem behavior are hierarchical so a small
21 number of structuring processes control ecosystem dynamics; each process operates at its
22 own temporal and spatial scale (O’Neill *et al.*, 1986). Finer scales provide the
23 mechanistic understanding for behavior at a particular scale, and broader scales provide

1 the constraints or boundaries on that behavior. Functional relationships between pattern
2 and process are consistent within each domain of scale so that linear extrapolation is
3 possible within a domain (Wiens, 1989). Thresholds occur when pattern-and-process
4 relationships change rapidly with a small or large change in a pattern or environmental
5 driver (Bestelmeyer, 2006; Groffman *et al.*, 2006), although both external stochastic
6 events and internal dynamics can drive systems across thresholds (Scheffer *et al.*, 2001).
7 Crossing a threshold can result in a regime shift where there is a change in the direction
8 of the system and the creation of an alternative stable state (Allen and Breshears, 1998;
9 Davenport *et al.*, 1998; Walker and Meyers, 2004). Under some conditions, thresholds
10 may be recognized when changes in the rate of fine-scale processes within a defined area
11 propagate to produce broad-scale responses (Gunderson and Holling, 2002; Redman and
12 Kinzig, 2003). In these cases, fine-scale processes interact with processes at broader
13 scales to determine system dynamics. A series of cascading thresholds can be recognized
14 where crossing one pattern-and-process threshold induces the crossing of additional
15 thresholds as processes interact (Kinzig *et al.*, 2006).

16 *5.1.2 Scaling*

17 Recent theories and ideas about system behavior have used hierarchy theory as a
18 basis for describing interactions among processes at different scales. Such theories
19 include complex systems (Milne, 1998; Allen and Holling, 2002), self-organization
20 (Rietkerk *et al.*, 2004), panarchy (Gunderson and Holling, 2002), and resilience (Holling,
21 1992; Walker *et al.*, 2006). Cross-scale interactions (CSIs) (processes at one spatial or
22 temporal scale interacting with processes at another scale that often result in nonlinear
23 dynamics with thresholds) are an integral part of all of these ideas (Carpenter and Turner,

1 2000; Gunderson and Holling, 2002; Peters *et al.*, 2004). These interactions generate
2 emergent behavior that can not be predicted based on observations at single or multiple,
3 independent scales (Michener *et al.*, 2001). Cross-scale interactions can be important for
4 extrapolating information about fine-scale processes to broad-scales or for down-scaling
5 the effects of broad-scale drivers on fine-scale patterns (Ludwig *et al.*, 2000; Diffenbaugh
6 *et al.*, 2005). The relative importance of fine- or broad-scale pattern-and-process
7 relationships can vary through time and compete as the dominant factors controlling
8 system dynamics (*e.g.*, Rodó *et al.*, 2002; King *et al.*, 2004; Yao *et al.*, 2006).

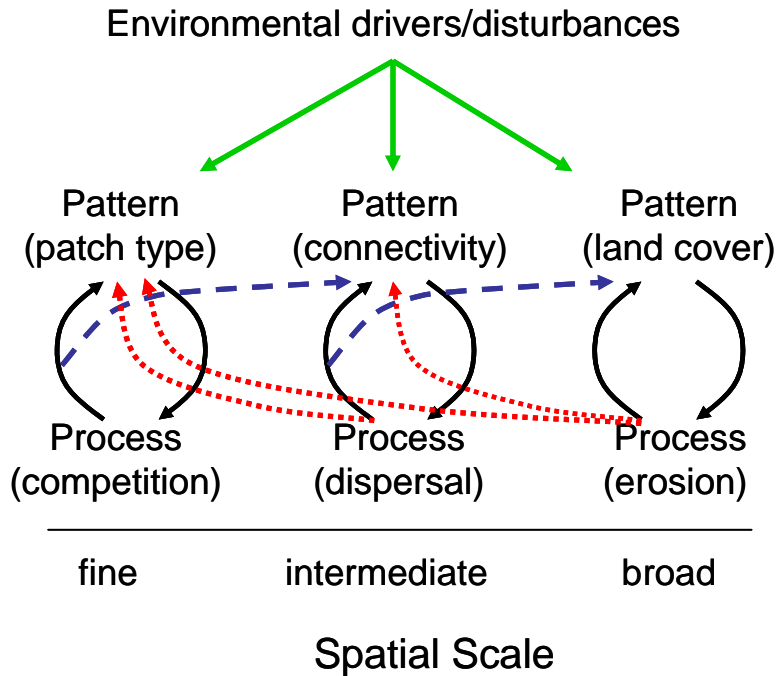
9 Because CSI-driven dynamics are believed to occur in a variety of systems,
10 including lotic invertebrate communities in freshwater streams (Palmer *et al.*, 1996) and
11 lakes (Stoffels *et al.*, 2005), mouse populations in forests (Tallmon *et al.*, 2003), soil
12 microbial communities (Smithwick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

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

1 stable. Changes in external drivers or disturbances can alter pattern-and-process
2 relationships in two ways.

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

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



1
2 **Figure 5.1.** Diagram representing cross-scale interactions. Solid arrows represent pattern-and-
3 process feedbacks within three different scale domains with one example of pattern and process
4 shown for each domain. Green arrows indicate the direct effects of environmental drivers or
5 disturbances on patterns or processes at different scales (*e.g.*, patch disturbance versus climate).
6 Blue arrows indicate the point at which altered feedbacks at finer scales induce changes in
7 feedbacks at broader scales (*e.g.*, fine-scale changes cascade to broader scales). Red arrows
8 indicate when changes at broader scales overwhelm pattern-and-process relationships at finer
9 scales.

10 *5.1.3 Applying Models from Other Disciplines*

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

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

15 *5.2 Adaptive Management to Increase Resilience*

16 The process of selecting, implementing, monitoring, assessing, and adjusting
17 management actions is called adaptive management or, in the context of this report,
18 adaptive ecosystem management (AEM) (Holling 1978; Walters 1986; Prato 2004,
19 2007a). AEM can be done passively or actively. If passive AEM is used, the decision to
20 adjust management actions or not depends on whether the indicators or multiple attributes
21 of the outcomes of management actions suggest that the ecosystem is becoming more
22 resilient or more variable and might cross a threshold. If active AEM is used, the
23 decision of whether or not to adjust management actions is determined by testing

1 hypotheses about how the ecosystem state is responding to management actions. Active
2 AEM treats management actions as experiments. Unlike passive adaptive management,
3 active AEM yields statistically reliable information about ecosystem responses to
4 management actions although it is more expensive and difficult to apply than passive
5 AEM and requires sufficient monitoring (Lee 1993, Wilhere 2002).

6 To increase ecosystem resilience, a number of approaches have been put forth for
7 use in adaptive management. These include avoiding landscape fragmentation and its
8 converse, restoring connectivity; ensuring that refugia are protected so that recolonization
9 of species is possible; focusing protection on keystone species where applicable; reducing
10 other stressors such as pollution; removing introduced invasive species; and reducing
11 extraction of ecosystem services for humans (for example, ensuring water flows for
12 aquatic ecosystems under stress) (Scott and Lemieux 2005, Groffman et al. 2006). For
13 each ecosystem, AEM potentially provides quantitative documentation as to the relative
14 efficacy of the different approaches to improving resilience (Keeley 2006; Millar et al.
15 2007; Parker et al. 2007).

16 *5.2.1 Role of Monitoring*

17 Because climate change effects are likely to interact with patterns and processes
18 across spatial and temporal scales, it is clear the monitoring strategies must be integrated
19 across scales. First and foremost, the Earth's surface must be hierarchically stratified [for
20 example, using the U.S. Department of Agriculture (USDA)-National Resources
21 Conservation Service (NRCS) Major Land Resource Area/Ecological Site Description
22 System and U.S. Forest Service ecoregions), and conceptual or simulation models of
23 possible impacts must be specified for each stratum (Herrick *et al.*, 2006). The models

1 are used to develop scenarios and to identify key properties and processes that are likely
2 to be associated with abrupt changes. Second, simultaneous multiple-scale monitoring
3 should be implemented at up to three spatial scales based on these scenarios and the
4 recognition of pattern-and-process coupling developed in the models (Bestelmeyer,
5 2006), which may feature cross-scale interactions (Peters *et al.*, 2004).

6 Remote sensing platforms can be used to monitor some broad-scale spatial
7 patterns, including significant shifts in plant community composition, vegetation
8 production, changes in plant mortality, bare ground and soil and water surface
9 temperatures, and water clarity. These platforms may also be used to detect rates of
10 change in some contagious processes, such as the spread of readily observable invasive
11 species. Changes in variance across space and time derived from such measures may be a
12 primary indicator of incipient nonlinear change (Carpenter and Brock, 2004). These
13 measures should be coupled with ground-based measures at mesoscale to patch scales.
14 Mesoscale monitoring often requires widely distributed observations across a landscape
15 (or ocean) acquired with rapid methodologies including sensor networks. Such widely
16 distributed monitoring is necessary because incipient changes may materialize in
17 locations that are difficult to predict in advance (such as with tidal wave warning
18 systems). In other cases, however, more targeted monitoring is necessary to detect
19 mesoscale discontinuities in smaller areas that are likely to first register broad-scale
20 change, such as at ecotone boundaries (Neilson, 1993). Finally, patch-scale monitoring
21 can feature methodologies that focus on pattern-and-process linkages that scale up to
22 produce systemwide threshold changes, such as when vegetation patches degrade and
23 bare patches coalesce to result in desertification (Rietkerk *et al.*, 2004; Ludwig *et al.*,

1 2005). The involvement of land users is particularly important at this scale because
2 recognition of processes that degrade resilience may be used to mitigate climate-driven
3 thresholds by way of local management decisions. Consequently, technically-
4 sophisticated approaches should be balanced with techniques suitable for the public at
5 large (for example, Carpenter *et al.*, 1999; Pyke *et al.*, 2002).

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

13 Nutrient export via streamflow is a sensitive metric for identifying changes in
14 ecosystem structure and function at the watershed scale that may be difficult to detect on
15 complex and spatially heterogeneous systems. For example, nitrate concentration in
16 streams has been used as a sensitive indicator of forest nitrogen saturation (Stoddard,
17 1994; Swank and Vose, 1997; Lovett *et al.*, 2000; Aber *et al.*, 2003), effects of insect pest
18 outbreaks (Eshleman *et al.*, 1998), and effects of short-term climate perturbations
19 (Mitchell *et al.*, 1996; Aber *et al.*, 2002). Stream chemistry monitoring, particularly at
20 gauges sites where discharge is also monitored, can provide sensitive signals of changes
21 in ecosystem biogeochemical cycles.

22 5.2.2 Role of Experiments

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

13 Quantitative approaches also show promise in identifying key processes related to
14 threshold behavior. Statistical analyses based on nonstationarity (Rodó *et al.*, 2002) and
15 nonlinear time series analysis (Pascual *et al.*, 2000) are useful for identifying key
16 processes at different scales. Spatial analyses that combine traditional data layers for fine-
17 and broad-scale patterns with data layers that use surrogates for transfer processes at
18 intermediate scales (for *example.*, seed dispersal) can isolate individual processes and
19 combinations of processes that influence dynamics in both space and time (for example,
20 Yao *et al.*, 2006). Simulation models that use fine-scale models to inform a broad-scale
21 model can be used to examine the relative importance of processes and drivers at
22 different scales to system dynamics as well as interactions of processes and drivers
23 (Moorcroft *et al.*, 2001; Urban, 2005). Coupled biological and physical models that

1 include population processes and connectivity among populations as well as broad-scale
2 drivers have been used to show the conditions when connectivity is important, and to
3 identify the locations that are more susceptible or resilient to management decisions
4 (Cowen *et al.*, 2006).

5 *5.3 Management by Coping*

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

18 *5.3.1 Reducing Multiple Stressors*

19 The key to reducing stressors is to identify the factors that influence resilience. In
20 many cases management practices that increase resilience can be designed from existing
21 knowledge; in other cases, however, it is not clear what management practices will
22 enhance resilience (Millar et al., 2007). For example, connectivity in a fragmented
23 landscape can be restored by creating corridors for species movement between suitable

1 habitat patches (Gustafson, 1998). Alternatively, inadvertent connectivity that has been
2 established and utilized by invasive species can be removed to reduce stress on the native
3 populations remaining.

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

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

22 5.3.2 Triage

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

17

18 5.3.3 System-Level Planning and Policy

19 Expanding management to regional levels is also key because climate change may
20 be pushing ecosystems to regional synchrony. An example is that wildland fire is
21 synchronously increasing throughout the western United States and could lead to major
22 recruitment events for species such as lodgepole pine or trigger beetle outbreaks at
23 unprecedented scales. These recruitment events could lead to supercohorts that develop

1 with succession following subcontinental scale disturbance. There is little management
2 precedent for these types of outcomes that are threshold events on a continental scale
3 even if they are common on local scales.

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

11 *5.3.4 Capacity Building and Awareness*

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

22 Adaptation can take many forms. Scenario planning provides descriptions of
23 plausible future conditions. Scenario planning, done at the local level, makes

1 stakeholders aware of the scope of uncertainty, facilitates tolerance for change, and
2 motivates the desire to build capacity to better handle threshold changes. Multiscenario
3 approaches used with ecosystem modeling can also be used to develop a range of
4 possible post-threshold conditions to better inform strategic decisionmaking and planning
5 for natural resource managers (Lemieux and Scott 2005). Impact assessments on specific
6 resources (for example, individual species population viability) can be expanded to
7 examine the underlying viability of protected areas designed to maintain ecosystems
8 (Scott et al. 2000). These assessments can prepare managers by broadening the scope of
9 planning and ensuring that institutional action plans remain flexible.

10

11 *5.4 Summary*

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

22 The gaps identified include the need to increase the resilience of ecosystems and
23 reduce multiple stressors to avoid threshold crossing. Both of these challenges are

1 difficult to plan for but also are consistent with managing ecosystems under conditions of
2 uncertainty such as climate change. After a threshold occurs, viable options are to
3 increase coping mechanisms, adaptive capacity, and stakeholder tolerance. The
4 publication of SAP 4.2 will bring the state of scientific understanding to the forefront of
5 the natural resource management paradigm, identifying a need for greater scientific
6 research on thresholds and ecosystem response to adequately manage natural resources
7 for the future.
8

1 **Chapter 6—Summary and Recommendations**

2 In this document, much of what is understood about thresholds of ecological
3 change is reviewed and summarized. This is a nascent field of inquiry and even the
4 definition of thresholds remains somewhat fluid. Chapter 2 provides a clarification and
5 should help focus future research on this topic.

6 *Summary*

7 The existence of thresholds in the tolerance of ecosystems to climate change
8 should be a key concern of scientists, Federal land managers and other natural resource
9 professionals responsible for the state of national natural resources and the ecological
10 services they provide. Sudden, large-scale changes in ecosystems may present new
11 challenges to resource managers because the capacity to predict, manage and adapt to
12 threshold crossings is currently limited. One goal of resource management is to minimize
13 variance in ecological goods and services but thresholds, as described in this document in
14 Chapter 3, can greatly increase variance. There are numerous other implications of
15 ecosystems crossing response thresholds because the current regulatory and legal
16 frameworks do not account for threshold behavior of systems at present.

17 *Recommendations*

18 Given the knowledge that ecological thresholds exist and the lack of tools to
19 know just where those thresholds are, scientists need to provide better predictive
20 capabilities and managers must make adjustments to increase their capacity to cope with
21 surprises. If climate change is pushing more ecosystems toward thresholds, what can be
22 done at the national level? The SAP 4.2 committee identified potential actions below.

1 These are organized by actions or approaches that can be taken before, during, and after
2 thresholds of ecological change are crossed.

3 *Before*

4 *Develop Better Threshold Knowledge.*—While conceptually robust and widely
5 acknowledged, further advancement and agreement on thresholds of change in
6 ecosystems is limited by the small number of empirical studies addressing this topic.
7 Further advancement will be dependent on rigorous statistical testing for reliable
8 identification of thresholds across different systems and should be a national priority
9 because of the potential for substantive surprises in the management of our natural
10 resources.

11 *Monitor Multiple Drivers.*—Consideration should be given to monitoring
12 indicators of ecosystem stress rather than solely the resources and ecological services of
13 management interest. Monitoring the effects on vegetation in coastal wetlands due to
14 increased salinity and/or inundation from sea level rise may be able to predict what
15 degree of stress vegetation can endure before it goes beyond the ability to recover
16 (Burkett *et al.*, 2005). Monitoring soil conditions in areas that are susceptible to
17 nonnative species invasions may provide information on when invasive species may
18 appear in a stressed ecosystem and push it to its threshold. Another variation on this
19 theme is to monitor variability rather than mean values of an ecological service. If the
20 amplitude of variability is increasing, this trend is likely an indication of system
21 instability before a threshold is crossed.

22 *Collate and Integrate Information Better at Different Scales.*— Greater
23 efficiency and use of information is likely to result from coordinating and pooling

1 information from adjoining jurisdictions and different agencies. For example, trends may
2 not be significant or noticeable at small scales but are clear at larger scales. These and
3 other observations argue for much better integration and coordination of monitoring
4 information, not necessarily more monitoring. Although there is a considerable
5 investment in making monitoring “smarter” initially, the payoff is clear in being able to
6 detect early indicators of ecosystem change that may result in crossing thresholds.

7 *Reduce Other Stressors.*—The trigger points for abrupt change in ecosystems that
8 are responding to climate change are rarely known because human civilizations have not
9 witnessed climate change of this magnitude. However, an approach that is likely to
10 reduce the threat of crossing thresholds is to reduce other stressors on ecosystems (Scott
11 and Lemieux, 2005). These other stressors might include air and water pollution,
12 regional landscape fragmentation, and control of invasive plants. To help reduce
13 stressors, decisions could be made to allow larger or more extensive buffers when
14 considering carrying capacity of habitats, minimum habitat sizes for species of interest, or
15 use of ecological services such as water.

16 *During*

17 *Manage Threshold Shifts.*—There may be constraints to reducing or reversing
18 climate change-induced stresses to components of an ecosystem. If a threshold seems
19 likely to occur but the uncertainties remain high as to when it will occur, contingency
20 plans should be created. These can be implemented when the threshold shift begins to
21 occur or can be carried out in advance if the threshold is clear. An example is a riverine
22 system that experiences an upward trend in water temperature due to climate change and
23 for which no options exist for mitigating the rising temperatures. Fish species that cannot

1 tolerate water temperatures above a threshold would have to be moved to another river
2 system or replaced with genotypes or species tolerant of warmer water.

3 *Project Impacts to Water Supply, Biodiversity, and Resource Extraction.*—There
4 are many efforts to project climate change (*e.g.*, GCMs) and ecosystem responses to
5 climate change (*e.g.*, mapped atmosphere-plant-soil systems) using simulating modeling
6 and other tools. These models generally project ecosystem trends and shifts, but do not
7 explicitly consider the possibility of thresholds within the system dynamics of the
8 modeling. A concerted effort must be made to understand, model, and project ecosystem
9 responses to climate change with explicit acknowledgment of thresholds. An example is
10 the bark beetle outbreak occurring in western forests where one threshold was passed
11 when warmer winters allowed two life cycles of beetle reproduction per year rather than
12 one and where a second threshold may be passed by the expansion of the forests
13 northward to connect with boreal forests that provide a corridor eastward. Such a scenario
14 would lead to continental scale beetle infestation (Logan *et al.*, 1998).

15 *Recognize Need for Subcontinental Decisionmaking.*— The scale of some
16 threshold crossings, such as the bark beetle example above, is likely to require
17 coordinated decisions on larger scales than in the past.

18 *Instigate Institutional Change To Increase Adaptive Capacity.*— The capacity for
19 synthesis will be critical for identifying potential thresholds in ecosystem processes on
20 multiple scales. Institutional changes that promote greater interdisciplinary and
21 interagency scientific and information exchange are likely to increase adaptive capacity
22 in general. The institutional changes are especially needed to implement comprehensive
23 monitoring to detect and document responses to thresholds in ecosystems.

1 *Identify Recommendations for Monitoring and Research.*— This effort can
2 evaluate the need for specific calls for urgently needed research to address thresholds.
3 The ubiquity of threshold problems across so many fields suggests the possibility of
4 finding common principles at work. The cross-cutting nature of the problem of large-
5 scale system change suggests an unusual opportunity to leverage effort from other fields
6 and apply it to investigating systemic risk of crossing thresholds. Ecological and
7 economic systems share common elements as complex adaptive systems. To the extent
8 that the analogy holds, these two disciplines have potential for mutual leverage. Beyond
9 the specific analogy between ecology and economics, certain dynamic behaviors and
10 structural (topological network) constraints are common to broad classes of systems.
11 Leverage can also occur by sharing methods across disciplines. Diverse fields such as
12 engineering risk analysis, epidemiology, and ecology employ similar methods and
13 research styles. The aim is not to replace conventional approaches, but to explore
14 complementary approaches. Exploiting commonalities is one way that leverage is
15 achieved.

16 *After*

17 Although many of the management responses to thresholds should continue after
18 thresholds have been crossed (e.g. monitoring, building ecosystem resilience), human
19 society will largely be faced with adjusting to different ecosystems. These adaptations
20 may be expensive, requiring significant new infrastructure. Capacity building, scenario
21 planning, and adaptive management must all be applied to quickly improve the ability of
22 management to cope with a different ecosystem and for stakeholders to adjust their
23 expectations of ecosystem services.

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Despite the incomplete understanding of thresholds of ecological change and the relative inability to predict when and where they will occur, there have been enough occurrences with significant consequences to warrant consideration of thresholds in natural resource planning and management. This document has summarized much of what is known about thresholds and has suggested approaches to improve our understanding of thresholds, to reduce the chances of threshold crossing, and to enhance the ability to cope with thresholds that have occurred. Given the magnitude of climate change effects on ecosystems, the added factor of sudden, threshold changes complicates societal responses and underscores the importance of continued integration of research and management to develop appropriate strategies for coping with thresholds.

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1

2

1 **Appendix A—Glossary**

2 **adaptive capacity**

3 the capacity of organisms, both individuals and groups, to respond to and change in the
4 state of the system (Folke *et al.*, 2003; Walker *et al.*, 2004; Adger *et al.*, 2005); depends
5 on initial diversity and the capacity of component organisms to adjust and change

6 **degradation**

7 deterioration of a system to a less desirable state as a result of failure to actively adapt or
8 transform

9 **ecosystem**

10 all the organisms, including people, in an area and the nonbiological materials, such as
11 water and soil minerals, with which they interact

12 **ecosystem services**

13 benefits that people derive from ecosystems, including supporting, provisioning,
14 regulating, and cultural services

15 **exogenous factor**

16 factor external to the system being managed and which therefore is not incorporated into
17 the management framework

18 **exposure**

19 nature and degree to which the system experiences environmental or sociopolitical stress

20 **mitigation**

21 reduction in the exposure of a system to a stress or hazard

22 **negative feedbacks**

1 **interaction** in which the effects of two interacting components on one another have
2 opposite signs; generally buffer against changes in the system; an important mechanism
3 enhancing resilience

4 **positive feedback**

5 interaction in which the effects of two interacting components on one another have the
6 same sign (both positive or both negative); tend to amplify changes in the system, leading
7 to threshold changes in the system

8 **resilience**

9 capacity of a socioecological system to absorb a spectrum of shocks or perturbations and
10 continue to develop with similar fundamental function, structure, identity, and feedbacks,
11 *i.e.*, to remain within a given stability domain (Holling, 1973; Gunderson and Holling,
12 2002; Walker *et al.*, 2004; Folke, 2006a); includes adaptive capacity but also depends on
13 legacies (*e.g.*, seed banks) and strong negative feedbacks that might balance positive
14 feedbacks that might destabilize the system

15 **socioecological system**

16 system in which human activities depend on resources and services provided by
17 ecosystems and ecosystem organization is influenced, to varying degrees, by human
18 activities

19 **steady state**

20 condition of a system in which there is no net change in system structure or functioning
21 over the time scale of study

22 **sustainability**

- 1 use of the environment and resources to meet the needs of the present without
- 2 compromising the ability of future generations to meet their own needs
- 3 **threshold**
- 4 an abrupt persistent change in system structure or functioning in response to small
- 5 changes in an ecosystem driver
- 6 **vulnerability**
- 7 the degree to which a system is likely to experience harm due to exposure to a specified
- 8 hazard or stress (Turner *et al.*, 2003; Adger, 2006)