Chapter 4—Examples of Threshold Change in Ecosystems

4.1 Background

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

4.2 Evidence of Thresholds from the Past

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

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

Cross-scale linkages among local soil and grass degradation, landscape connectivity of erosion processes, and land cover-weather feedbacks have been invoked to explain threshold behavior in space and time that occur during desertification (Peterset al.et al. 2006). Four stages and three thresholds have been identified as the spatial extent of desertified land increases through time (Peterset al.et al. 2004). Following introduction of woody plant seeds into a grass-dominated system (Stage 1), local spread often occurs as a result of feedback mechanisms between plants and soil properties interacting with wind and water erosion to produce fertile plant islands surrounded by bare areas that move the system across a threshold into Stage 2 (Schlesingeret al.et al. 1990). This rate of spread may be slower than other stages as a result of interactions between plant life history characteristics that occur infrequently, such as recruitment, and the low precipitation and high temperatures that characterize dry regions. As the size and density of woody plants increase through time, contagious processes among patches, primarily wind and water erosion that connect bare soil patches, become the dominant factors governing the rate of desertification. As a result, a nonlinear increase in woody plant cover occurs and a second threshold is crossed as the system enters Stage 3. Through time, sufficient land area can be converted from grassland (low bare area, low albedo) to woodland (high bare area, high albedo) so that regional atmospheric conditions, in particular wind speed, temperature, and precipitation, are affected. At this point, a third threshold is crossed where land-atmosphere interactions with feedbacks to vegetation control system dynamics (Stage 4) (Pielkeet al.et al. 1997). Feedbacks to broad-scale vegetation patterns have been documented in the Sahara region of Africa (Claussenet al.et al. 1999).

4.3 Evidence of Sensitivity to Current Stressors

4.3.1 Temperature Increase

The effects of increasing temperatures as an effect of climate change are not independent of the effects of other important environmental stressors, and thus need to be assessed in the context of multiple, interacting stressors. AR4 WG II (2007) reports with very high confidence that the increased warming effect of climate change is strongly affecting natural biological systems in both marine and fresh water systems. The chemical and physical characteristics of lakes experience major effects owing to changes in temperature, especially changes in nutrient dynamics. Increased temperatures in lake systems will affect the distributions, growth, and survival of fish and many other aquatic organisms. Tied with increased temperatures is a change in precipitation, which can cause substantial physical and chemical changes in lakes and streams, with large consequences for aquatic biota. In marine systems, increased temperature from climate change is affecting coastal resources and habitats because of sea level rise that is caused by thermal expansion of the oceans and the melting of ice cover. The rate of sea level rise is expected to accelerate because of global warming. Salt marshes must increase their vertical elevation at rates that keep pace with sea level rise or risk transformation to a lower position along the marsh gradient. In transgressing systems, where there is a landward movement of the marsh system, structure and composition of marsh communities is expected to change when the rate of sea level rise exceeds the rate of vertical accretion. Transition from one type of marsh to another (for example, high marsh to low marsh) at a given point has been described as ecosystem state change (Milleret al.et al. 2001).

The effects of temperature increases on terrestrial systems are further emphasized in the IPCC Assessment Report for Working Group II (2007)(AR4WGII) report with very high confidence where it is stated that the overwhelming majority of studies of regional climate effects on terrestrial species reveal consistent responses to warming trends, including poleward and elevational range shifts of flora and fauna. Responses of terrestrial species to warming across the Northern Hemisphere are well documented by changes in the timing of growth stages (that is, phenological changes), especially the earlier onset of spring events, migration, and lengthening of the growing season. Changes in abundance of certain species, including limited evidence of a few local disappearances, and changes in community composition over the last few decades have been attributed to climate change. A further indication of effects of increased temperatures is revealed in earlier snowmelt and stream runoff, which affects both aquatic and terrestrial ecosystems and species. Sensitivity of target organisms to climate change depends on several aspects of the biology of a species or the ecological composition and functioning of a system. For example, species that are physiologically sensitive to changes in temperature or moisture; species that occupy climate-sensitive habitats such as shallow wetlands, perennial streams, and alpine areas; and species with limited dispersal abilities will all be more sensitive to climate change. (SAP 4.4, 2008) SAP 4.3 (2008) states that projected increases in temperature and a lengthening of the growing season will likely extend forage production into late fall and early spring, thereby decreasing the need for winter-season forage reserves; that a shift in optimal temperatures for photosynthesis might be expected under elevated CO_2; and that climate-change-induced shifts in plant species are already underway in rangelands. There is a need to better understand the complexities of ecosystems and the drivers of change within them and to be able to identify the thresholds of these changes in a changing climate.

4.3.2 Moisture Availability

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

4.3.3 Climate Interactions

As important as the increases in temperatures and changes in moisture availability are for causing ecosystems to go through thresholds, it is the interactions that are key to driving the change. In general, plants in undisturbed ecosystems are at their moisture-limited capacity for net primary productivity. Therefore, increased temperatures *and* droughtiness will combine to produce severe stress on plant growth whereas increased temperatures and increased moisture availability will lessen the stress or may promote plant productivity, leading to an ecosystem with increased resilience. Because evapotranspirative demands on vegetation increase with temperature, thresholds are more likely to occur whenever moisture availability does not simultaneously increase with warming temperatures. The exception is ecosystems that are primarily limited by temperature, such as arctic and alpine ecosystems. In these latter cases, ample moisture means that vegetation can respond without evapotranspirative limits but that threshold changes can still occur as competitive relationships are altered between plant species (Hansell et al. 1998). The shrubbification of the arctic, detailed in Case Study 1, is an example. Case Study 2 makes the importance of interactions clear because trees in the southwestern United States had survived similar droughts in the past but this time temperatures had increased and the interaction of both climatic stressors pushed the ecosystem into threshold change.

Temperature

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

4.3.4 Climatic Variability Increases

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

4.3.5 Other Human Stressors and Climate Change

The interaction of human stresses on ecosystems (for example, land use change) and climate change may be most evident for lotic ecosystems and may produce threshold responses that each stress alone would not produce. Flow variability over time and space is a fundamental characteristic of lotic ecosystems. It is this temporal and spatial flow variability that defines and regulates biotic composition and key ecosystem processes in streams and rivers (Poffet al.et al. 1997; Palmeret al.et al. 2007). Climate change will alter flow regimes and generate changes to biotic communities in many of these ecosystems, although it is not clear that these flow alterations will produce threshold-type responses in these systems that have evolved in response to high flow variability. However, more severe or prolonged droughts in the western U.S. resulting from human-induced climate change will interact with growing water demands to potentially produce hydrologic regime shifts in many drainage basins (Barnett et al., 2008).

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

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

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

There are several examples of potential large-scale threshold responses to the combined effects of human water management and climate-induced drought. In the Columbia River basin of the Pacific northwest, multiple stressors, including population growth; conflicts between hydropower, agriculture, and recreation interests; and ineffective water management institutions and structures, have increased the vulnerability of water resources (Payne et al., 2004; Miles et al. 2007) already vulnerable as a result of reduced winter snowpack (Barnett et al., 2005), which generates much of the summer flow, and sustained or repetitive droughts projected by climate change models that would drive water supplies to extreme low levels. Because salmon populations are under considerable stress because of dams, water withdrawals, and other human actions, reduced summer flow under a warmer climate may exceed population sustainability thresholds (Neitzel et al.,1991).

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

Even in the humid southeastern United States, the combined effects of increased water withdrawals and climate change may exceed thresholds in ecosystem response. The Chattahoochee-Apalachicola River basin in Alabama, Florida, and Georgia is both an important water source for agricultural, industrial, and municipal uses and an important fishery. More than 75% of the fish species inhabiting this river system depend on access to floodplain and tributary areas to forage and spawn, and there are flow thresholds below which fish cannot move into these critical areas (Lightet al.et al. 1998). Analysis of projected future water withdrawals and climate change for the Chattahoochee-Apalachicola River basin indicates that by 2050, minimum flows will drop below these minimum flow thresholds for at least 3 months in summer in some areas (Gibsonet al.et al. 2005). Further exacerbating this situation will be the increased percentage of flow that is wastewater effluent with lower minimum flows in this rapidly urbanizing basin, which will increase biological oxygen demand and reduce dissolved oxygen concentrations potentially below threshold levels required by some species of fish (Gibsonet al.et al. 2005).

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

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

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

4.3.6 Ecosystem Vulnerability and Climate Change

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

General hypotheses, however, can be posed and predictions made about some of the ecosystem attributes that may be important in generating differential ecosystem vulnerability to climate change, including the likelihood that important thresholds of response are crossed. For example, most ecosystems have a single or just a few dominant species that mediate ecological processes, control the majority of the resources (including space), and/or have disproportionate impacts on species interactions. Thus, if climate change favors a new dominant species, the prediction is that it will likely be the rate at which the extant species can be replaced and the traits of these new species that will determine the likelihood that the ecosystem will be altered significantly to result in threshold behavior in state or function. For example, ecosystems dominated by long-lived species (for example, trees) with slow population turnover would be expected to be relatively slow to respond to climate change whereas those ecosystems dominated by short-lived species (for example, annual plants) are expected to be more vulnerable to experiencing substantial change if the new dominant species replacing the old have very different species traits.

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

Levels of biodiversity (functional traits and species) within an ecosystem may also be important in influencing sensitivity to climate change (Grebmeier 2006). The number and traits of species may buffer ecosystems from change and influence the extent to which immigration of new species will occur. For example, depending on how well species in an ecosystem functionally complement each other and the ability of species to compensate for the change resulting from the loss of the dominant species, the replacement of a dominant species by another species could result in no change or large changes in ecosystem state. Similarly, invading species may result in the rapid crossing of thresholds or may have little or no impact depending on the traits of these species relative to the traits of native species.

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