Ecological Tipping Points:

Subtle alterations may signal the approach to drastic transformations of ecosystems affected by global climate change

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Abstract

The steady change in the global climate is pushing many ecosystems toward thresholds of rapid irreversible transformation. The approach to such ecological tipping points is illustrated by recent changes in arctic tundra vegetation, increases in freshwater inputs to arctic seas, increasing frequency of coral-reef bleaching, and widespread desertification of arid lands. Ecological tipping points are difficult to predict because their approach may be accompanied by slow, subtle changes, in contrast to the rapid, drastic changes that occur when a tipping point is reached. The capacity to forecast tipping points would be enhanced by the establishment of the National Ecological Observatory Network (NEON), which would provide a comprehensive, coordinated infrastructure for observing ecological change throughout the United States. Early warning of tipping points would increase the chances of effective responses to these environmental threats.

Keywords: global climate change, tundra, ocean circulation, coral reefs, desertification

Arctic tundra, tropical coral reefs, and arid grasslands are very different and widely separated ecosystems but they are all linked by the Earth’s changing climate systems and they are all edging closer to ecological tipping points. When tipping points are reached, ecological change accelerates due non-linear responses, positive feedbacks, or synergy among multiple stressors. Beyond the tipping points, ecosystems are propelled toward irreversible transformations that often toward diminish their capacity to provide valuable ecosystem services.

Ecological tipping points and the possibility of forecasting ecological changes using the proposed National Ecological Observatory Network (NEON) were the subjects of the November
2006 annual symposium and congressional briefing of the Association of Ecosystem Research Centers (AERC). This paper synthesizes the presentations at these meetings.

Tundra Transformations

Warming trends in the arctic have already begun to convert open tundra to forest and shrub land. These changes are expected to cause feedbacks on the climate system that will accelerate the increase in arctic land surface temperatures. The Arctic has been warming at a rate of up to 0.4ºC per decade over the last several decades (ACIA 2004, Chapin et al. 2005). Over the past 200 years, periods of cooling have alternated with periods of warming, but the most recent trend is part of a more pronounced warming since the Little Ice Age temperature minimum, reached during the early to mid 1800s (Overpeck et al. 1997). Warming since the Little Ice Age has had multiple effects on the vegetation of the Arctic. Communities or species whose distribution is directly or indirectly limited by temperature have begun to expand into habitat that was previously too cold, while vegetation density at the marginal edges and growth rates of marginal individuals has increased in many locations.

Climate change effects are evident at forest edges or tree lines. An expanding tree line leaves a “fingerprint” on the landscape that allows the dynamics of tree-line change to be reconstructed from tree rings. Historical tree-line sites are occupied by old trees while progressively younger populations occur in more recently established areas. Tree line advance is evidenced by a decline in tree age closer to the forest edge together with an absence of dead trees. The ages of the trees at the expanding front can be used to determine the timing of the expansion. This fingerprint of expanding tree lines has been found at white spruce tree-line sites throughout Alaska (figure 1, Suarez et al. 1999, Lloyd et al. 2002, Lloyd and Fastie 2003) and at some Canadian tree-line sites (MacDonald et al. 2000). Although the timing of the expansion is
variable among sites (Lloyd 2005), it seems to have been approximately simultaneous with the onset of post-Little Ice Age warming.

At the same time that spruce trees moved into tundra ecosystems, tall shrub species have expanded within the tundra. After boreal forest, the next “warmest” vegetation type is shrub tundra, which lacks trees, but is dominated by various species of shrub (including birches, alder, and willows) that can be several meters high. Shrub tundra tends to be fairly patchy on the landscape. Its distribution is more likely a result of the indirect effects of temperature on soil conditions rather than the direct effects of temperature. The expansion of shrub tundra has been documented from comparisons of aerial photos of 155 Alaska tundra sites taken in the 1950s with photos of the same sites taken in 2000 (Sturm et al. 2001, Tape et al. 2006). The photo pairs show that individual shrubs had grown larger, shrub density had increased, and shrubs had expanded into areas previously occupied only by low tundra (figure 2). The expansion of shrubs was evident in the vast majority of photo pairs suggesting that shrub expansion was a widespread phenomenon affecting large areas of the Arctic. The timing of the expansion is more difficult to estimate than that of spruce trees, but population models suggest that shrub expansion began in the late 1800s (Sturm et al. 2001, Tape et al. 2006).

Tree and shrub expansion is not merely a symptom of a warming climate but also promotes further warming of the land surface and thus constitutes an ecological tipping point. One of the most important climate feedbacks from expansion of woody vegetation involves the alteration of surface energy exchange. Tree and shrub covers are less reflective (have lower albedo) than the open tundra surface in the summer. In the winter, the difference in albedo is even more dramatic because the tree canopies (and some shrub canopies) extend above the highly reflective snow cover. Differences in albedo lead to differences in the net shortwave solar
heating. Forest, woodland, and tall shrub vegetation types, which protrude above the snow, may increase solar heating by 20-260% compared to tundra, with greater differences at lower latitudes, which receive more winter sunlight (Chapin et al. 2000, Sturm et al. 2005a, b). The effect of vegetation change on climate is small so far, with the extra heating due to albedo changes probably contributing less than 3% of the total summer warming trend in Alaska (Chapin et al. 2005). However, as the spread of trees and shrubs continues, the albedo effect will increase. If trees were to expand to cover all of northern Alaska (an unlikely, if instructive, scenario), the albedo effect would make a greater contribution to regional warming then the effect of a doubling of CO$_2$ (Chapin et al. 2005).

A further feedback contributing to the tipping point effect involves shrubs, snow, and soils (Sturm et al. 2005b). Shrubs trap more snow and thus develop deeper winter snowpack than does low herb tundra. Deeper snowpack provides more thermal insulation to the soil, leading to significantly higher soil temperatures underneath the shrubs. Warmer soils promote enhanced microbial activity, which in turn leads to increased nutrient availability. Warmer soils and increased nutrients in turn promote further shrub growth. The expansion of shrubs thus leads, through this mechanism, to further expansion of shrubs. The effect of the initial perturbation is thus magnified within the ecosystem, and may move the ecosystem quickly past this tipping point to a new, woodier state.

Initially a response to global warming, the spread of trees and shrubs throughout the arctic tundra may become self-sustaining due to the feedbacks on heat balance and soil conditions. The expansion of these species is likely to lead to a complete transformation of the plant and associated animal communities of the arctic and an acceleration of the regional warming trend.
The long reach of the ocean conveyer belt

As arctic lands approach a tipping point so does the ocean. The warming of the arctic is melting glaciers and sea ice. This together with increasing precipitation in high latitudes is increasing the delivery of freshwater to the northern North Atlantic Ocean, which could rapidly alter ocean circulation, according to some recent models (Rahmstorf 2000).

Presently, the world’s oceans circulate along looping surface-water and deep-water flow paths that connect to form a sort of conveyer belt (Broecker 1991). A major engine for this circulation is the formation of North Atlantic Deep Water (NADW) that occurs when cooling surface waters become dense enough to sink from the surface to the deep ocean. If surface waters in areas of NADW formation become too fresh to sink, the circulation engine may stall (Rahmstorf 1995, Broecker 1997, Clark et al. 2002, Rahmstorf 2002).

Altering ocean circulation could have far reaching consequences for climate, because ocean currents redistribute heat around the world. For example, the HADCM3 model (version 3 of the Hadley Centre coupled atmosphere-ocean general circulation model) showed that a shutdown of NADW formation would cause widespread cooling in the northern hemisphere and warming in the southern hemisphere (Rahmstorf 2002, figure 3). The effects on surface air temperature would be strongest over the Atlantic, with decreases of up to 6°C in the northern North Atlantic, and increases of up to 2°C in the South Atlantic (figure 3). Most of the Earth’s land surfaces would experience decreases in surface air temperature of 1-2°C (figure 3).

Estimates of the sustained excess freshwater input that would be required to trigger a shut down of NADW formation range from ~2000 to 5000 km³/y. Until recently, such excess inputs were considered only a distant possibility. However, melting of ice stocks on land and sea, increases in river discharge, and changing precipitation patterns at high northern latitudes
indicate that we may be closer than we thought (Peterson et al. 2006). Excess fresh water contributions from these sources averaged $\sim$1650 km$^3$/y during the 1990s (table 1). The largest single source of excess fresh water, accounting for nearly half of the total, was the melting of sea ice, which contains less salt than seawater due to exclusion of salts during freezing. Increases in net precipitation (precipitation minus evaporation) onto the ocean surface accounted for approximately one third of the total excess in fresh water. The remainder came from increases in river discharge to the Arctic Ocean and melting of glaciers (including the Greenland ice sheet). Looking backward, it is apparent that changes in the freshwater sources leading to sustained excess inputs during the 1990s began around 1965-1970 (Peterson et al. 2006). This is not only evident in records of the inputs themselves but also in records of freshwater storage in the northern North Atlantic Ocean (Peterson et al. 2006).

The existence of a tipping point with respect to NADW formation and the potential effects that a shut down of NADW formation would have on climate are, of course, very uncertain. Many models predict a gradual slowing of NADW formation in the future with concomitant gradual effects on climate (Cubasch et al. 2001). In any case, the observed changes in freshwater sources and ocean storage discussed above lend some immediacy to the debate. Understanding the timing and rate of future changes in NADW formation is important because effects of changing ocean circulation on regional climate would be superimposed upon direct effects of global warming. Cooling as a consequence changes in ocean circulation might offset global warming effects in the North Atlantic region. On the other hand, the warming in the South Atlantic as a consequence of changes in ocean circulation would be in addition to the direct global warming effect. If NADW formation were to shut down within the next few decades, the Northern Hemisphere might become significantly colder than it is now. This would
facilitate accumulation of ice in the Arctic and potentially stimulate NADW formation anew. However, a common feature of models showing rapid cessation of NADW formation in response to freshwater forcing is that the values required to shut down and to restart NADW formation are vastly different. Whereas the tipping point for shut down may be sustained excess freshwater input of \( \sim 1900 \text{ km}^3/\text{y} \), restarting NADW formation after a shut down may take a sustained deficit in freshwater inputs of \( \sim 6000 \text{ km}^3/\text{y} \) (Rahmstorf 1995).

The fate of coral reefs

Ocean circulation connects processes in the arctic seas with those in the tropics, where coral reef ecosystems face transformations as complete as those in taking place in the arctic tundra. Two trends are pushing coral reefs toward tipping points: rising seawater temperatures and increasing flux of atmospheric carbon dioxide (CO\(_2\)) into sea water. If the trends continue, the coral reefs of shallow tropical seas may die within a few decades.

Tropical reef-forming corals depend on endosymbiotic algae (zooxanthellae) to grow and survive. The loss of most of the zooxanthellae normally found within the coral tissue (coral bleaching), has occurred with increasing frequency on coral reefs throughout the world in the last 20 years, mostly during periods when strong El Nino conditions prevail in the Pacific, typically every 3-7 years (Coles and Brown 2003). Coral bleaching results primarily from elevated seawater temperatures under high light conditions. The high temperature causes a breakdown of the photosynthetic machinery in the zooxanthellae, diverting light energy from fixation of CO\(_2\) to the production of toxic oxygen radicals that interfere with normal cellular processes. The zooxanthellae, that are no longer capable of photosynthesis, are then either ejected, digested, or just disintegrate within the host; no one knows for sure.
If the conditions that cause the bleaching are sustained long enough, the coral host will die. Projections of rising ocean temperature due to global warming suggest that within 30 years summer temperatures may be at levels that will cause annual bleaching (figure 4, Hoegh-Guldberg 2004). It is widely thought that bleaching with this frequency would push corals to a tipping point that would be lethal in the long term (Hoegh-Guldberg 2004).

Corals and zooxanthellae may be capable of acclimating to elevated temperatures, resulting in bleaching resistant coral populations (Baker et al. 2004, Berkelmans and van Oppen 2006). The mechanisms by which a coral or zooxanthellae becomes more thermally tolerant include inducible heat-shock proteins, production of oxidative enzymes that deactivate harmful oxygen radicals, fluorescent pigments that reflect and dissipate light energy, and adaptive shifts in zooxanthellae populations to strains with more thermally tolerant physiology. However, as discussed below, rising temperature is not the only threat to coral reefs posed by the rising level of atmospheric CO₂.

About 48% of the anthropogenic CO₂ released to the atmosphere since the start of the Industrial Revolution has been absorbed by the oceans (Sabine et al. 2004). As more anthropogenic CO₂ is absorbed, the pH and the carbonate concentration of seawater decrease. The decrease in carbonate concentration causes a decrease in the saturation state of aragonite, the calcium carbonate mineral that is the foundation of coral exoskeletons. As the saturation state of aragonite falls so does the ability of corals to form new exoskeleton material for growth.

Aragonite saturation state can be expressed as Ω, the product of the carbonate and calcium concentrations divided by the aragonite solubility product. Aragonite tends to precipitate at Ω>1 and dissolve at Ω<1. Aragonite saturation in seawater varies with latitude, with Ω peaking at close to 4 near the equator and decreasing to less than 3.2 at latitudes above
Coral reefs are only found in waters with $\Omega > 3.2$ (Kleypas et al. 1999, figure 5). This may be close to the tipping point of coral reef growth. As atmospheric CO$_2$ continues to rise, the ocean area of coral reef sustainability will shrink. By 2060, $\Omega$ is projected to drop below 3.5 in all major reef areas of the world, including Australia’s Great Barrier Reef (Guinotte et al. 2003).

Recent research has focused on relating aragonite saturation state ($\Omega$) to coral growth. Corals held in laboratory mesocosms showed an immediate but reversible 45-80% reduction in skeletal growth when CO$_2$ concentrations in the water was raised from 400 ppm to 800 ppm (Langdon and Atkinson 2005). Data for 12 species of corals showed that skeletal growth rate decreases linearly with decreasing $\Omega$, with growth rate approaching zero as $\Omega$ approaches 1 (Langdon and Atkinson 2005). Corals in Biosphere 2 maintained low growth rates with no sign of acclimation when $\Omega$ was held at 1.6 ± 0.3 for two and a half years (Langdon et al. 2000).

A minimum growth rate is needed to sustain coral reefs because their growth must exceed erosion enough to keep pace with rising sea level. Physical processes can contribute to erosion but the dominant processes are biological. Bioerosion is caused by bivalves, sponges, polychaete worms, and endolithic fungi and algae that burrow into coral rock, dissolving and weakening the underlying structure of the reef. Combining estimates of bioerosion and coral growth as a function of aragonite saturation state, it is estimated that net reef accretion may not be sustainable if $\Omega$ drops below 3.2, as expected when atmospheric CO$_2$ exceeds 500 ppm (Langdon unpub.).

Thus, tropical coral reefs are approaching two tipping points: a 2°C rise in temperature that would eliminate their essential symbiotic algae, and atmospheric CO$_2$ concentrations of 500 ppm that would decrease skeletal growth to a rate below that of bioerosion. Moreover, the effects of temperature and CO$_2$ may be synergistic because the symbiotic algae are thought to
provide much of the energy that supports calcification. At projected rates of temperature and CO$_2$ increase, coral reefs will pass the two tipping points in 50-100 years. The subsequent breakdown of coral reef ecosystems would eliminate reef-dependent fisheries and expose reef-protected coastlines, including sea grass and mangrove ecosystems, to the full force of storm waves.

**Tipping toward desert**

Low and mid latitude terrestrial ecosystems are also approaching tipping points. Dryland ecosystems, which make up 41% of the land surface and are inhabited by over two billion people, are particularly susceptible to degradation and change. Up to 20% of drylands are suffering from some degree of desertification caused by climate change and various human activities such as cash-cropping, fuel wood cutting, irrigation, and overgrazing. The environmental impacts of desertification include soil nutrient depletion, salinization, lowered water tables, vegetation change, erosion, and over exploitation of resources. The impacts of desertification on human populations can be devastating.

Climate change is increasing the risk of desertification in drylands throughout the world. While precipitation is increasing in high latitudes, contributing to the freshening of the northern North Atlantic a possible shutdown of ocean circulation, rainfall is projected to decrease by 10-20% in northern and southern Africa by the end of the 21$^{st}$ century (figure 6, de Wit and Stankiewicz 2006). This decrease in rainfall is predicted to have threshold effects on density of perennial rivers and streams, with a critical tipping point at 400-500 mm annual rainfall, below which there would be little surface drainage (figure 7, de Wit and Stankiewicz 2006). In most drylands, predicted increases in temperature are not expected to be offset by increases in rainfall. Thus, drylands will become more arid and more likely to experience desertification.
Recent models suggest that desertification involves non-linear pattern-process relationships and can be characterized by thresholds (Peters et al. 2004). One of the processes associated with the early stages of desertification is the change from grass-dominated to shrub-dominated systems with increased bare ground. This transition can be viewed as a switch between two alternate stable states triggered by declines in precipitation below a threshold (figure 8, Tausch et al. 1993).

Thresholds in transitions from grasslands to shrublands are influenced by soil characteristics. For example, the probability of grass persistence increases as the percentage of clay increases from 10 – 30% in surface soils (figure 9, Bestelmeyer et al. 2006a). At a regional scale, sandy soils are more likely to lose grass cover than gravelly soils, which in turn is more likely to lose grass cover than lithic soils (figure 10, Bestelmeyer et al. 2006b). In some cases, grass cover is degraded by deposition of soil carried from adjacent land by runoff or wind (Bestelmeyer et al. 2006b). In this way, degradation on adjacent lands may spread to well-managed lands under some conditions.

Various aspects of desertification thresholds can be defined. These include: pattern thresholds such as grass connectivity, shrub density, and habitat fragmentation; process thresholds such as erosion rate, fire frequency, and plant dispersal rate; and degradation thresholds such as soil depth, and nutrient availability (Bestelmeyer 2006). These types of thresholds interact. For example, pattern thresholds can regulate process rates and critical levels of soil degradation, as shown by the increase in soil loss with decrease in vegetation cover (Davenport et al. 1998). Measures of the three interacting types of thresholds, if done at appropriate spatial and temporal scales (Brown and Havstad 2004), can form the basis for detecting the onset of transitions soon enough for management interventions to prevent or
reverse ecosystem degradation. Thus, human actions potentially interact with these biophysical variables.

An often overlooked factor in examining tipping points in general is that societies may change in ways to lessen or exacerbate the risk of the tipping point. Because so many humans live in drylands, socio-economic systems are tightly coupled to desertification. For example, in the western U.S., the various Homestead Acts from 1862 through 1916 set the stage for land degradation by allotting settlers areas that were too small to support grazing livestock. This situation encouraged overgrazing of open ranges. As a response, the Taylor Grazing Act of 1934 set grazing allotments to encourage stewardship of rangelands. This solidified grazing as the primary land use and had mixed effects on rangeland conservation (Wilkinson 1992). In West Africa, social resilience was found to mitigate the effects of desertification. The Senegalese people living in arid lands responded to desertification by reducing herd size, diversifying livestock and crop types, or migrating to urban areas (Bradley and Grainger 2004). Effective responses to desertification will require socio-economic and policy interventions, but pacing such interventions to prevent irreversible ecological change remains a significant challenge and depends on timely forecasts of tipping points.

**NEON: A continental-scale instrument to forecast ecological change**

Ecological change happens across broad scales, over long-time frames, at uneven rates. Therefore, detecting and understanding ecological change will require large-scale, long-term, and coordinated vigilance. The National Ecological Observatory Network (NEON) is being designed to provide such vigilance in U.S. ecosystems. Its mission is to discover and understand the fundamental ecological principals that govern the responses of the biosphere and to provide the capacity to forecast future states of ecological systems.
NEON will be a continental-scale research instrument with geographically distributed infrastructure using a networked communications system to link lab and field instrumentation. It will provide a foundation from which to address many of the major questions in ecology: How will ecosystems and their components respond to natural- and human-induced changes? What will be the pace and pattern of these responses? How do the internal responses and feedbacks of ecosystem processes and components interact with changes in climate, land use, and invasive species? How do these feedbacks vary with ecological context and spatial and temporal scales?

The planned geographic distribution of NEON is based on an analysis of climate and other variables that divides the United States into 20 domains (figure 11). Within each domain there will be specific sites of intensive observation. The infrastructure at each site will include fundamental instrument units consisting of interacting suites of sensors (figure 12). Sensor platforms will likely include BioMesoNet towers equipped to measure ultra-violet, infrared, and photosynthetically active radiation, barometric pressure, and atmospheric precipitation, as well as profiles of temperature, wind speed and direction, and water vapor, CO₂, and other gases. Other linked sensors will measure profiles of temperature and moisture in the soil as well as depth to the water table (figure 13). From these measurements, fluxes of heat, water, and CO₂ could be calculated. This information could be used to monitor and forecast environmental changes such as the increasing heat flux in the Alaskan tundra and the desertification of rangelands in the Southwestern U. S.

The fundamental instrument units within each NEON domain will be supplemented by many other sensor arrays and platforms. These might include dispersed wireless sensor networks, sensors suspended in tree canopies or from canopy cranes, belowground chambers for observation of roots and soil, buoy- or raft-mounted sensors in lakes, and mobile sensor
platforms mounted on vehicles or aircraft. Remote sensing from aircraft and satellites would provide more evenly dispersed information that would be integrated with data from sensors distributed over the ground surface. Airborne observations would include high-fidelity imaging spectroscopy for vegetation indices, leaf area index, canopy characteristics, and diversity. Airborne wave-form LIDAR would be used for measuring vegetation height, ground topography, biomass, and life form diversity. All these data would be highly relevant to investigating ecological tipping points in a variety of ecosystem types.

In addition to the capacity for collecting and processing a vast array of physical data, NEON will be designed to track mobile organisms as bio-sentinels. Small mobile organisms are the first sentinels that will react to environmental change. Small organisms are also the main agents transporting diseases across landscapes. Many invasive organisms are small and mobile. None of these organisms can currently be tracked over long distances. The ability to track individual organisms across continental scales is fundamental to many of the major questions addressed by NEON. These include questions about migrations of insects, birds, bats, and fishes. NEON could install local receiver networks to understand movements within habitats, and monitor movement between habitats and regions via aerial tracking using commercial and small aircraft.

NEON is conceived as a launch pad for ecological studies including investigations of the effects of fire, grazing, increasing CO$_2$, invasive species, hanta virus, urbanization, climate change, and hydrologic change. It would provide research tools with spatial coverage and capabilities unlike anything currently available to ecologists. Importantly, NEON should permit us to predict ecological thresholds, in a sense providing a capacity to predict the unpredictable, as we plan our future environments.
Conclusions

The examples presented here illustrate the significance of ecological tipping points and their relevance to the consequences of global change. Tundra vegetation is reaching a tipping point as the spread of trees and shrubs is stimulated by warming trends and in turn enhances warming by decreasing the reflectance of solar radiation. Warming trends are also increasing freshwater inputs to the northern North Atlantic. If freshwater inputs exceed a tipping point, then ocean circulation in the Northern Hemisphere could suddenly shutdown, profoundly altering heat distribution over the Earth. Increasing sea surface temperatures may exceed the threshold for survival of reef-building corals, while increasing atmospheric CO$_2$ may slow coral skeleton growth below the threshold needed to sustain reef structure. Global warming is decreasing the net precipitation to most arid lands, pushing them closer to tipping points for loss of vegetation and soil.

Forecasting the approach of ecological tipping points is challenging because environmental changes may be subtle and gradual until the tipping point is reached, after which the rate of change accelerates. There is an urgent need for timely forecasts of tipping points because change beyond a tipping point can cause irreversible losses of valuable ecosystem services. The establishment of NEON would increase the capacity for early detection and forecast of ecological changes in the United States.

Acknowledgements

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References Cited


Table 1. Excess freshwater contributions from major sources to the Arctic Ocean, Hudson Bay/Baffin Bay/waters surrounding the Canadian Archipelago (HBCA), Nordic Seas, and Atlantic Subpolar Basin during the 1990s. Values for river discharge and net precipitation are relative to a 1936-1955 baseline. Values for small glaciers/ice caps, the Greenland ice sheet, and sea ice are relative to a water balance of zero (no net change in volume). The small glaciers/ice caps category includes net melt from the pan-arctic watershed, arctic and subarctic islands, and ice caps around but not connected the Greenland ice sheet. The sea ice category focuses specifically on stocks in the Arctic Ocean. The negative value for rivers flowing into Hudson Bay reflects a deficit. See Peterson et al. (2006) for details.

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<th>Sources</th>
<th>Freshwater excess (km$^3$/y)</th>
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<tr>
<td>Greenland ice sheet</td>
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<td>Rivers, Arctic Ocean</td>
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<td>Rivers, Hudson Bay</td>
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**Figure legends**

Figure 1. Date of tree line advance at 10 tree-line sites in Alaska. The date indicated is the decade in which a population (defined as > 5 trees/ha) of white spruce (*Picea glauca*) established above the previous tree limit. Data from Suarez et al. (1999), Lloyd and Fastie (2003) and Lloyd et al. (2003). Figure was originally published in Lloyd (2005).

Figure 2. Aerial photos from the Chandler River, 50 miles south of the village of Umiat in northern Alaska, reveal widespread expansion of tall shrubs in the arctic tundra. In the upper photo, taken in 1949, shrubs are the darker areas of vegetation, located primarily along drainages and other sheltered areas. In the lower photo, taken in 2001, shrubs have expanded in area, and density has increased within locations that had shrubs in 1949. Photos were originally published in Sturm et al. (2001).

Figure 3. Surface temperature changes predicted if formation of NADW ceases (Rahmstorf 2002).

Figure 4. Projected amounts of warming superimposed on sea-surface temperature variability observed at three reef sites (Hoegh-Guldberg 1999). A horizontal line denotes the bleaching threshold temperature for each particular reef. Data show that by the 2030-2050, and even sooner in Phuket, Thailand, temperatures will exceed the bleaching threshold every summer, which would probably kill the corals.
Figure 5. Aragonite saturation state ($\Omega$) versus latitude for coral reefs (open circles) and for communities with coral colonies but no reef structure (filled circles) (Kleypas et al. 1999). Today, coral reefs give way to corals without reefs where $\Omega$ drops below 3.2-3.4. The highest $\Omega$ values are now around 4 (upper dashed line) but, by 2065, the uptake of fossil fuel CO$_2$ is expected to lower the maximum $\Omega$ to 3.4 (lower dashed line), a tipping point below which corals may be unable to build their skeletons fast enough to keep up with rising sea-level and the natural bioerosion processes that constantly tear down the reef structure.

Figure 6. Precipitation in Africa at the end of the 20$^{th}$ century (left) and change in precipitation projected for the end of the 21$^{st}$ century (right) (de Wit and Stankiewicz 2006).

Figure 7. The effect of a 10% drop in rainfall on the perennial drainage density of surface water at different levels of annual rainfall (de Wit and Stankiewicz 2006). Thresholds for large decreases in surface drainage occur when annual rainfall is 400-500 mm and 1000-1100 mm.

Figure 8. The relative successional potential for transitions between herbaceous and woody perennial vegetation as a function of effective precipitation (Tausch et al. 1993). The most stable state is represented by the lowest trough. The relative stability shifts from herbaceous vegetation at high precipitation (A) to woody vegetation at low precipitation (E).

Figure 9. Dynamics of native perennial grasses over a 60 year period in an arid environment as a function of % clay in the 10-20 cm zone within the soil profile (adapted from Bestelmeyer et al. 2006a).
Figure 10. Dynamics of native perennial grasses over a 33 year period in an arid environment as a function of geomorphic unit location within a landscape (adapted from Bestelmeyer et al. 2006b).

Figure 11. The 20 NEON domains as delineated by an algorithm that includes a variety of climate and soil variables.

Figure 12. The hierarchical arrangement of NEON observatories. Within each of the 20 domains (Fig. 1), research sites would be chosen to collect information appropriate to address scientific questions related to environmental issues of national importance. Sites for instrumentation would be chosen to have appropriate vegetation and aquatic characteristics.

Figure 13. A conceptualization of a NEON observation site. Numerous devices would automatically measure attributes of the environment at high frequencies but many data would be collected by humans in the field.
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Figure 2. Aerial photos from the Chandler River, 50 miles south of the village of Umiat in northern Alaska, reveal widespread expansion of tall shrubs in the arctic tundra. In the upper photo, taken in 1949, shrubs are the darker areas of vegetation, located primarily along drainages and other sheltered areas. In the lower photo, taken in 2001, shrubs have expanded in area, and density has increased within locations that had shrubs in 1949. Photos were originally published in Sturm et al. (2001).
Figure 3. Surface temperature changes predicted if formation of NADW ceases (Rahmstorf 2002).
Figure 4. Projected amounts of warming superimposed on sea-surface temperature variability observed at three reef sites (Hoegh-Guldberg 1999). A horizontal line denotes the bleaching threshold temperature for each particular reef. Data show that by the 2030-2050, and even sooner in Phuket, Thailand, temperatures will exceed the bleaching threshold every summer, which would probably kill the corals.
Figure 5. Aragonite saturation state (Ω) versus latitude for coral reefs (open circles) and for communities with coral colonies but no reef structure (filled circles) (Kleypas et al. 1999). Today, coral reefs give way to corals without reefs where Ω drops below 3.2-3.4. The highest Ω values are now around 4 (upper dashed line) but, by 2065, the uptake of fossil fuel CO₂ is expected to lower the maximum Ω to 3.4 (lower dashed line), a tipping point below which corals may be unable to build their skeletons fast enough to keep up with rising sea-level and the natural bioerosion processes that constantly tear down the reef structure.
Figure 6. Precipitation in Africa at the end of the 20th century (left) and change in precipitation projected for the end of the 21st century (right) (de Wit and Stankiewicz 2006).
Figure 7. The effect of a 10% drop in rainfall on the perennial drainage density of surface water at different levels of annual rainfall (de Wit and Stankiewicz 2006). Thresholds for large decreases in surface drainage occur when annual rainfall is 400-500 mm and 1000-1100 mm.
Figure 8. The relative successional potential for transitions between herbaceous and woody perennial vegetation as a function of effective precipitation (Tausch et al. 1993). The most stable state is represented by the lowest trough. The relative stability shifts from herbaceous vegetation at high precipitation (A) to woody vegetation at low precipitation (E).
Figure 9. Dynamics of native perennial grasses over a 60 year period in an arid environment as a function of % clay in the 10-20 cm zone within the soil profile (adapted from Bestelmeyer et al. 2006a).
Figure 10. Dynamics of native perennial grasses over a 33 year period in an arid environment as a function of geomorphic unit location within a landscape (adapted from Bestelmeyer et al. 2006b).
Figure 11. The 20 NEON domains as delineated by an algorithm that includes a variety of climate and soil variables.
Figure 12. The hierarchical arrangement of NEON observatories. Within each of the 20 domains (figure 11), research sites would be chosen to collect information appropriate to address scientific questions related to environmental issues of national importance. Sites for instrumentation would be chosen to have appropriate vegetation and aquatic characteristics.
Figure 13. A conceptualization of a NEON observation site. Numerous devices would automatically measure attributes of the environment at high frequencies but many data would be collected by humans in the field.