by L.H. Pardo, T. Blett, C.M. Clark, and L.H. Geiser

Impacts of Nitrogen Pollution on Terrestrial Ecosystems in the United States

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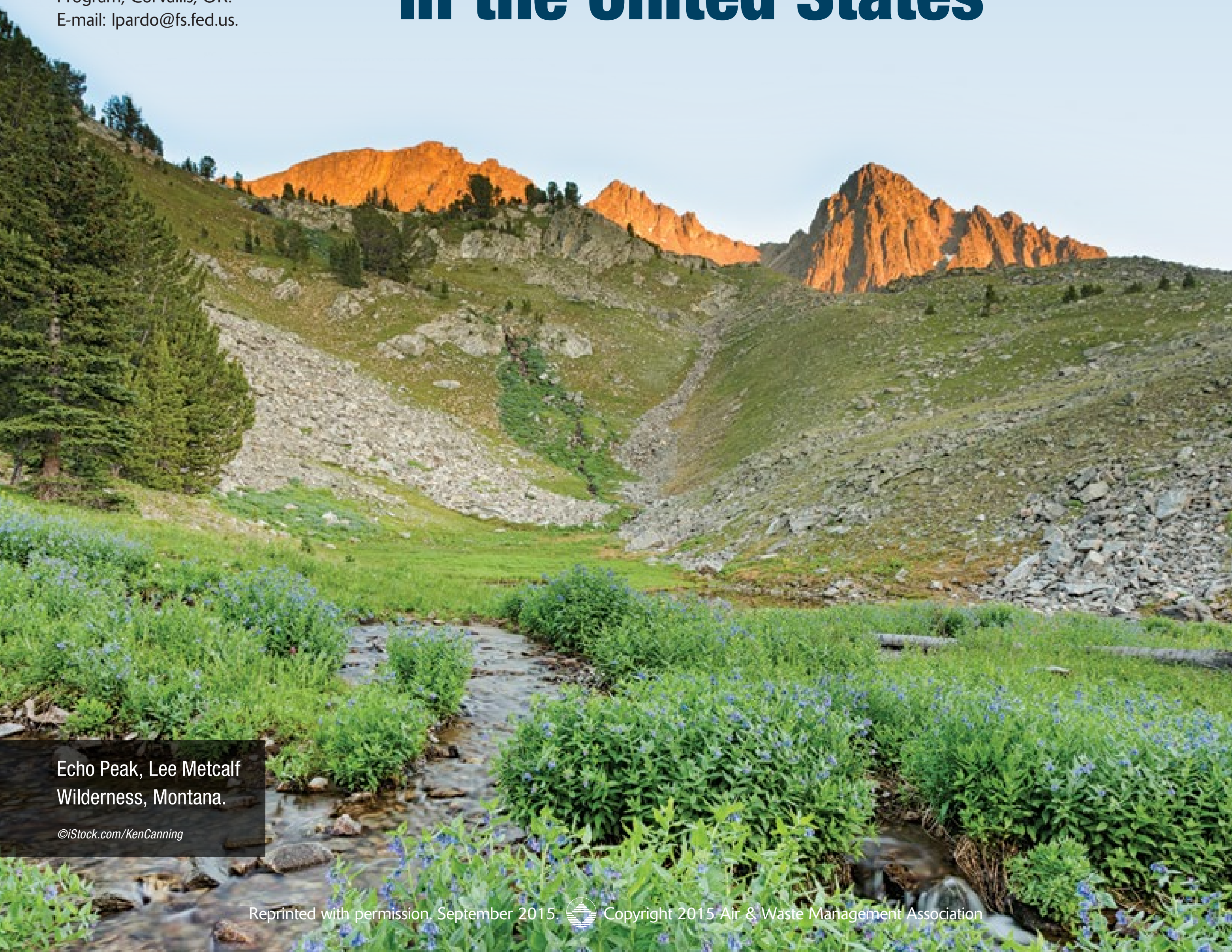

Echo Peak, Lee Metcalf Wilderness, Montana.

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Terrestrial ecosystems provide important resources for many human uses, however, these resources are threatened by nitrogen from air pollution. Identifying reductions in air pollution that will protect ecosystems is the main focus of the mitigation strategies currently being developed in the United States.

Nitrogen Pollution Effects on Ecosystems

Nitrogen (N) has historically been the nutrient that most often limits plant growth in the United States. However, human activity since the Industrial Revolution has resulted in increased emission and hence deposition of N.[1] Initial increases in N deposition can act as a fertilizer for some plant species, increasing growth, which may be beneficial for some systems, but over time or as deposition continues to increase, added N often has detrimental effects. Since N is a scarce resource, it is typically cycled from one organism or pool to another with minimal losses from the ecosystem.

Elevated N deposition disrupts the normally tight N cycle of natural ecosystems resulting in changes in how the ecosystem behaves. For example, nitrate in soil that leaches into ground and surface waters may affect water quality downstream and may also acidify lakes and streams to the extent that many species of fish cannot survive. Excess N deposition can also alter the physical structure of the ecosystem, for example, favoring fast-growing invasive species over native species, which can increase the plant material available to fuel wildfires and lead to increased frequency of fires, posing a risk to human structures and wildlife habitat.[2]

Terrestrial ecosystems provide resources for human use and consumption, including, among many others: timber, recreation, abundant clean air and water, food for animals and humans, medicine, habitat for wildlife, ecosystem physical stability and resilience to climate change, as well as nonmaterial benefits, such as the opportunity for humans to experience, learn from, and appreciate natural landscapes and diverse flora and fauna. There are several pathways by which N deposition may reduce the benefit that society receives from terrestrial ecosystems (see Table 1).

Most biota in terrestrial ecosystems receive N inputs directly by root uptake of plant-available N in soils and via deposition. In contrast, epiphytic lichens and mosses—those growing on trees—receive N only from atmospheric sources and tend to respond directly to small increases in atmospheric N deposition compared to plants and fungi growing in soils; soils have varying N sources, microbe-and mineral-mediated chemistries, and storage capacities. Thus, epiphytic lichens and bryophytes are often the most sensitive terrestrial biota and can be used as indicators of N deposition impacts on an ecosystem. In addition to impacts on individual plants, N deposition can drive changes in entire communities and adversely affect ecosystems, by shifting plant composition in habitats important to threatened and endangered species, favoring invasive plant species, increasing fire frequency and intensity, impacting ecosystem health, and decreasing biodiversity.

The N cycle is complex, because N has many forms and is utilized in many different ways by organisms; adding N to ecosystems has both beneficial and detrimental effects. Often, one small alteration within an ecosystem can lead to a cascade of responses that ultimately significantly changes some aspect or use of the system (see "Consequences of N Pollution on Ecosystems").[3]

Tools for Assessing Risk and Condition

A widely used approach[9] to assess ecosystem risk is to determine the critical load—the level of deposition below which no harmful ecological effect occurs over the long term, according to present knowledge. We compare this critical load to the actual deposition level using "exceedance" to evaluate *where* risk is higher or *when*, historically, risk was elevated. Exceedance is the difference between the actual deposition and the critical load; thus, exceedance >0 signifies a system at risk for detrimental impacts of N deposition. The critical load approach is an ecosystem assessment tool with great potential to simplify complex scientific information and communicate effectively with the policy community and the public.

Critical loads have been used for decades in Europe[9] and are now becoming an important tool for resource managers and policy-makers in the United States.[10] Their use is now mandated by the U.S. Forest Service in managing national forests[11] and critical loads are increasingly used by the National Park Service in assessing the condition of resources on national park lands.[12] The U.S. Environmental Protection Agency (EPA) is reviewing the use of critical loads to help determine areas where air pollution may be impacting ecosystems as part of a five-year review of the secondary National Ambient Air Quality Standards for nitrogen and sulfur oxides.

Management and Mitigation Strategies

The management approaches currently being used or considered fall into two categories: (1) removing N-tolerant invasive plants and replacing them with native plants, and (2) amending the soil to protect the health or competitive advantage of native plants. Elevated N deposition may promote herbaceous plant invasions in many habitats, with the potential to reduce native biodiversity, altering communities and ecosystems in the United States.[13] For example, N deposition of ~10-11 kg N ha^{-1} yr^{-1}, a level common over much of the United States, was associated with strong increases in the proportion of invasive species and their cover for most communities evaluated, including a variety of different habitats.[13]

To mitigate N impacts in some park ecosystems (including dunes, forests, coastal systems, and old fields) the National Park Service removes invasive N–responsive weedy species by burning, hand pulling, herbicide application, or mowing. Another example of habitat restoration, on state lands in California, is the effort to restore the threatened Bay Checkerspot butterfly by using cattle grazing and mowing to remove non-native grasses (see Example 2 and Figure 8).[14] The goal of all these types of projects is to enhance habitat suitability by limiting human disturbance, replanting native species, and controlling invasive species with treatments specifically prescribed for each site.

Carbon (C) or nutrient additions may also serve to restore soils such that they may better support native plant species. While some research projects have explored the use of soil C amendments to immobilize soil N in order to allow species adapted to low N conditions to compete successfully for N resources, land managers do not generally embrace this technique as it can require costly C inputs which are most effective when tilled into the soil—which would cause further unacceptable disturbance of natural systems. Other soil amendments may include restoring specific soil nutrients lost via acidification, to alleviate plant nutrient imbalances (i.e., to increase levels of plant nutrients to above deficiency thresholds for nutrients such as calcium (Ca), phosphorus (P), etc.). Nutrient additions have been conducted as pilot studies by the Forest Service in the southeastern United States.

Nitrogen and sulfur (S) deposition have been declining since the U.S. Clean Air Act Amendments of 1990, and are expected to continue to do so, especially in the eastern United States, under current regulations. While many areas now in exceedance of current critical load are expected

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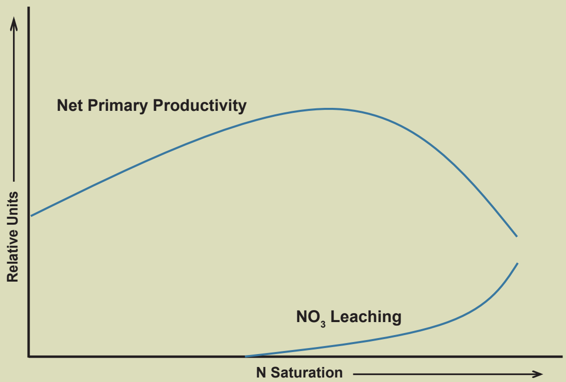
Table 1. Examples of types of responses to elevated N deposition.

	BIOGEOCHEMICAL CYCLING	TISSUE CHEMISTRY
Response	N saturation is the condition in which available N (deposition + N produced microbially within the system) exceeds biotic demand. N saturation often results in elevated leaching of nitrate (NO_3^-) to ground or surface water.	Some forms of N deposition can be directly toxic to some species of plants. Indirect effects of N deposition include elevated tissue N leading to increased herbivory.
Examples	 Figure 1. As N deposition increases, ecosystem production initially increases up to a threshold deposition value after which it decreases. Nitrate leaching begins to increase when growth, and hence uptake, of N begin to decrease.[15]	 *Heather Throop* Figure 2. Increased N inputs exacerbated the damage caused to *Quercus* spp. by an outbreak of *Anisota* spp. on Long Island.
Societal impact	Elevated nitrate (NO_3^-) concentrations in ground water can indicate soil acidification and mobilization of toxic aluminum. In surface water, this aluminum can harm fish populations. These biogeochemical changes may be the beginning of a cascade of effects leading to the other responses listed in this table.	Pest infestation can rapidly and dramatically alter the structure of an ecosystem.

GROWTH, MORTALITY, HEALTH

1. Detrimental impacts of N deposition on trees include declines in growth and the number of surviving seedlings, and increases in mortality. The type and magnitude of response varies by species.
2. In sensitive ecosystems (e.g., high elevation, shallow, poor soils), N deposition can cause high mortality in a short period of time (i.e., a decade).
3. Nutrient imbalances caused by plant uptake of excess N and depletion of soil calcium pool can make trees susceptible to secondary stressors such as winter injury.

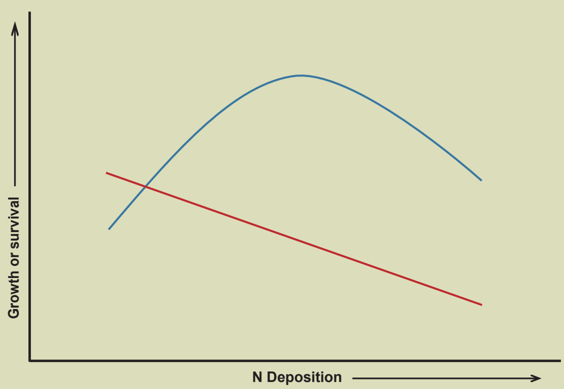
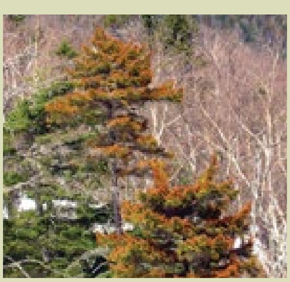


Figure 3. Six of 24 tree species showed negative responses in growth or survivorship to N deposition in the northeastern United States.[16] Two patterns were observed and are shown above: increase followed by decrease or decrease across the whole deposition range.



Paul Schaberg, USDA Forest Service

Figure 4. Winter freezing injury of red spruce needles can lead to crown deterioration and tree mortality. Additions of N can contribute to foliar calcium deficiencies that predispose trees to winter injury.

Johnny Boggs, USDA Forest Service

Figure 5. N addition of about 1.5x ambient deposition in southern Vermont led to heavy mortality after 25 years in red spruce plots at a sensitive site with very shallow soils.[17]

Declines in forest health can impact timber, paper, and nontimber (e.g., maple syrup) production, as well as recreation.

SHIFTS IN COMMUNITY COMPOSITION

N deposition can alter community composition by shifting the competitive advantage toward those species which tolerate or need a high N environment. Shifts in community composition can be observed most rapidly in lichens, herbaceous plants, and some shrub ecosystems. Shifts in community composition could occur among plants that are native to that ecosystem or result from an increase in the abundance of an invasive species.

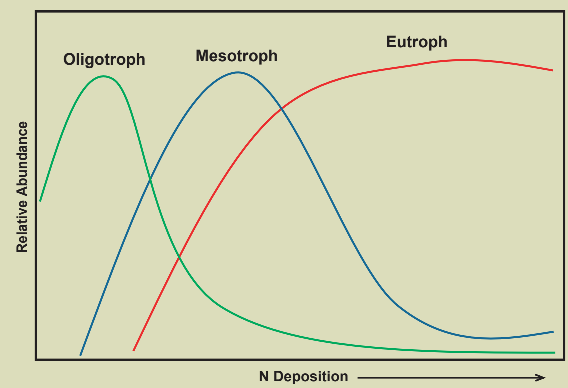
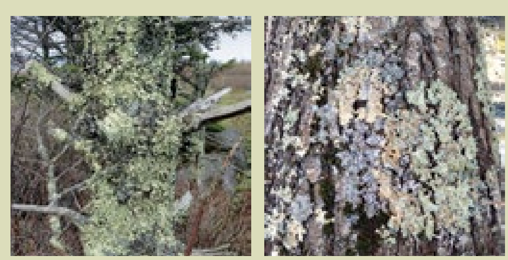


Figure 6. N-sensitive lichen species (oligotrophs) are most abundant when N deposition is low and decline as N deposition increases; moderately N tolerant species (mesotrophs) are most abundant at moderate N deposition levels; and N-tolerant species (eutrophs) are most abundant at high N deposition.



Karen Dillman

Figure 7. One of the southeastern United States' most air pollution tolerant lichens, *Flavoparmelia caperata*, was healthy on Mt Rogers (above left) but in poor condition at Grayson Highlands (above right) and along the Blue Ridge Parkway.

Shifts in community composition can affect fire risk, habitat for threatened and endangered species, and can disrupt food chains.

Figure 8. Grazing, which removes excess N in biomass, helps restore Bay checkerspot butterfly habitat. Invasive annual grasses can be seen on the left side of the fence. Native forbs flower on the right, grazed side of the fence.

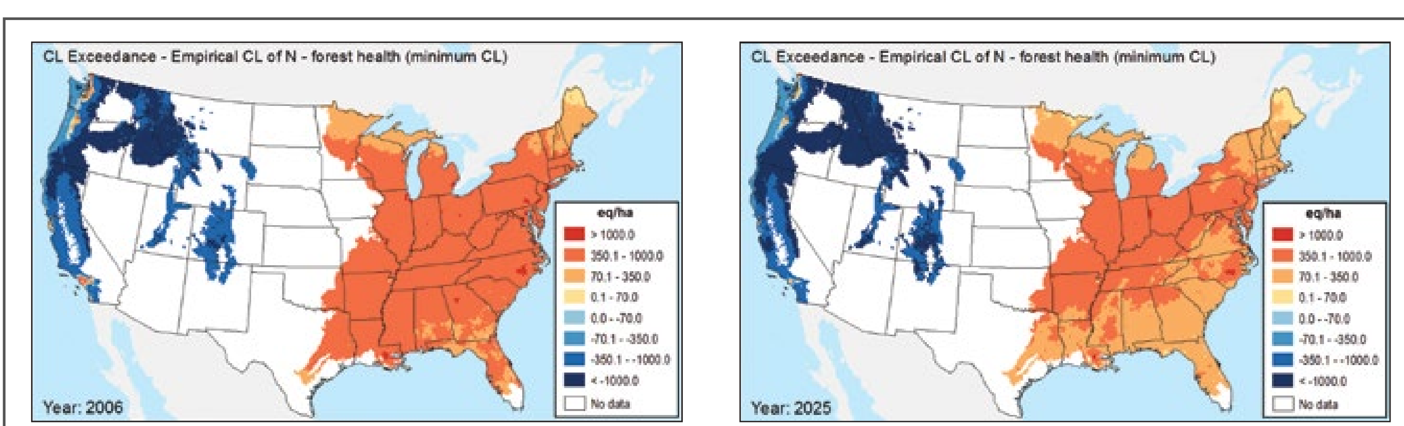
Stuart Weiss

to no longer to be in exceedance by 2025 (see Figure 9), critical load estimates are expected to be set even lower as more regionally specific estimates of critical loads are developed. Thus, while recovery of ecosystem condition is possible, it is also possible that exceedances may persist for decades.

Critical Load Assessments

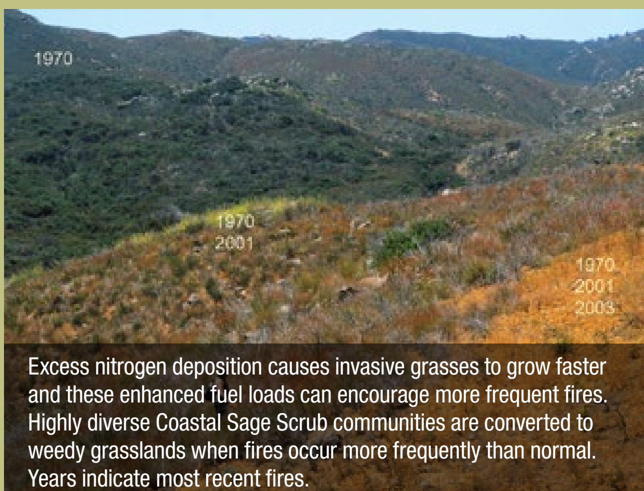
The management strategies discussed above could affect only a small portion of the lands potentially impacted by N deposition. Thus, focusing on the reduction of emissions to decrease deposition to below the critical load is, currently, the approach aimed at protecting the greatest proportion of affected lands in the United States. In the coming year, national-scale assessments of N impacts on lichens, herbaceous plants, and trees will allow estimation of critical loads at multiple scales from site to landscape to the continental United States. These assessments include environmental factors,

Figure 9. The area in exceedance of the empirical CL of N is projected to decrease from 2006 to 2025 as N deposition is projected to decrease.



Consequences of N Pollution on Ecosystems

Example 1: Increasing ecosystem susceptibility to secondary stressors or catastrophic events



Excess nitrogen deposition causes invasive grasses to grow faster and these enhanced fuel loads can encourage more frequent fires. Highly diverse Coastal Sage Scrub communities are converted to weedy grasslands when fires occur more frequently than normal. Years indicate most recent fires.

Richard W. Halsey, The California Stuart Weiss Chaparral Institute

In California, coastal sage scrub ecosystems are subjected to high N deposition levels of up to 20 kg ha^{-1} yr^{-1}, favoring invasive annual grasses over native perennial bunch grasses and shrubs. Enhanced grass biomass and cover then provide additional fuels and connect previously discontinuous cover so that wildfire can spread, leading to increased fire frequency and burn area size. Increased fire frequency prevents re-establishment of the shrub community, leading to rapid conversion to grassland and further increasing fire frequency.[4,5]

In Vermont, depletion of soil base cations caused, in part, by N deposition inputs predisposed paper birch trees to ice storm damage.[6] Trees growing on base cation-depleted soils—those with low plant-available calcium and elevated toxic aluminum—did not recover crown vigor and growth rates after the stress caused by the ice storm. Ice storms are predicted to increase in the Northeast as part of the changing climate, so this type of damage is an increasing risk.

Example 2: Habitat loss can endanger species

Serpentine grasslands in California have a distinct flora associated with natural low nutrient conditions. Excess N deposition inputs have allowed invasive grasses to colonize and subsequently decrease the abundance of a native plant required by the endangered Bay Checkerspot butterfly (for egg-laying and nutrition) to levels unable to sustain a healthy population.[7,8]

Bay Checkerspot butterfly

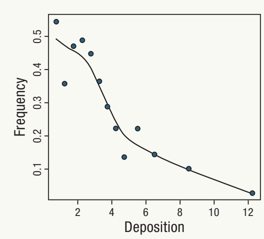
Stuart Weiss

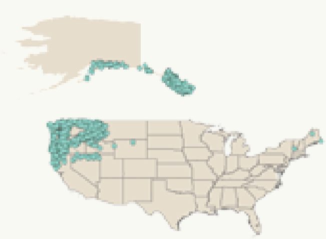
Example 3: Disruption of the food chain can have consequences

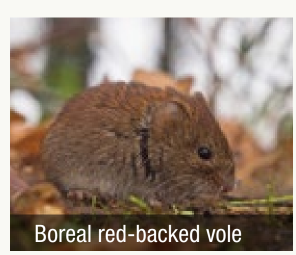
Loss of sensitive lichens has implications for ecosystem services

Moose grazing

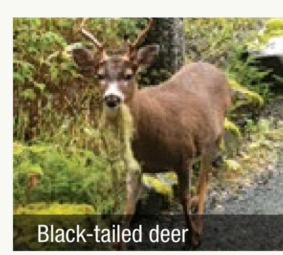
Old Man's Beard







Boreal red-backed vole



Black-tailed deer

Moose: US Fish and Wildlife Service; Lichen: Stephen Sharnoff; Deer: Karen Dillman; Vole: iStockphoto

Loss of sensitive lichens can impact entire forest ecosystems by eliminating a food source at the base of the food chain. Old Man's Beard is one of the most common lichen species in the western United States, but it is rare in the eastern United States, likely because it responds negatively to any increase in N deposition. The Old Man's Beard is important ▶

winter forage for voles, caribou, deer, and moose which are, in turn, valued by hunters, wildlife viewers, and recreationists.

Example 4: Alterations in ecosystems can represent tipping points from stable to unstable conditions

Recent experiments have demonstrated that losses of species from N inputs can lead to reductions in ecosystem stability.[18,19] With species losses, communities become more homogenous and dependent on the functioning of fewer species. As climate or other conditions change, favoring or suppressing those few remaining species, there are fewer compensatory effects in the community, and the community as a whole becomes more volatile to changes in environmental conditions.[20] This "boom and bust" community cycle can be induced by elevated N inputs, with a 30% reduction in richness associated with an 8% reduction in stability.[19] ■

such as temperature and precipitation, which will facilitate assessment of potential impacts of climate change in combination with N deposition. These analyses also demonstrate the interconnectedness of organisms within an ecosystem and the potential for alteration of a component of the ecosystem to diminish the benefits to society provided by ecosystems. **em**

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