Case Studies

Estimating and mitigating the impacts of climate change and air pollution on alpine plant communities in national parks

By Ellen Porter, Harald Sverdrup, and Timothy J. Sullivan

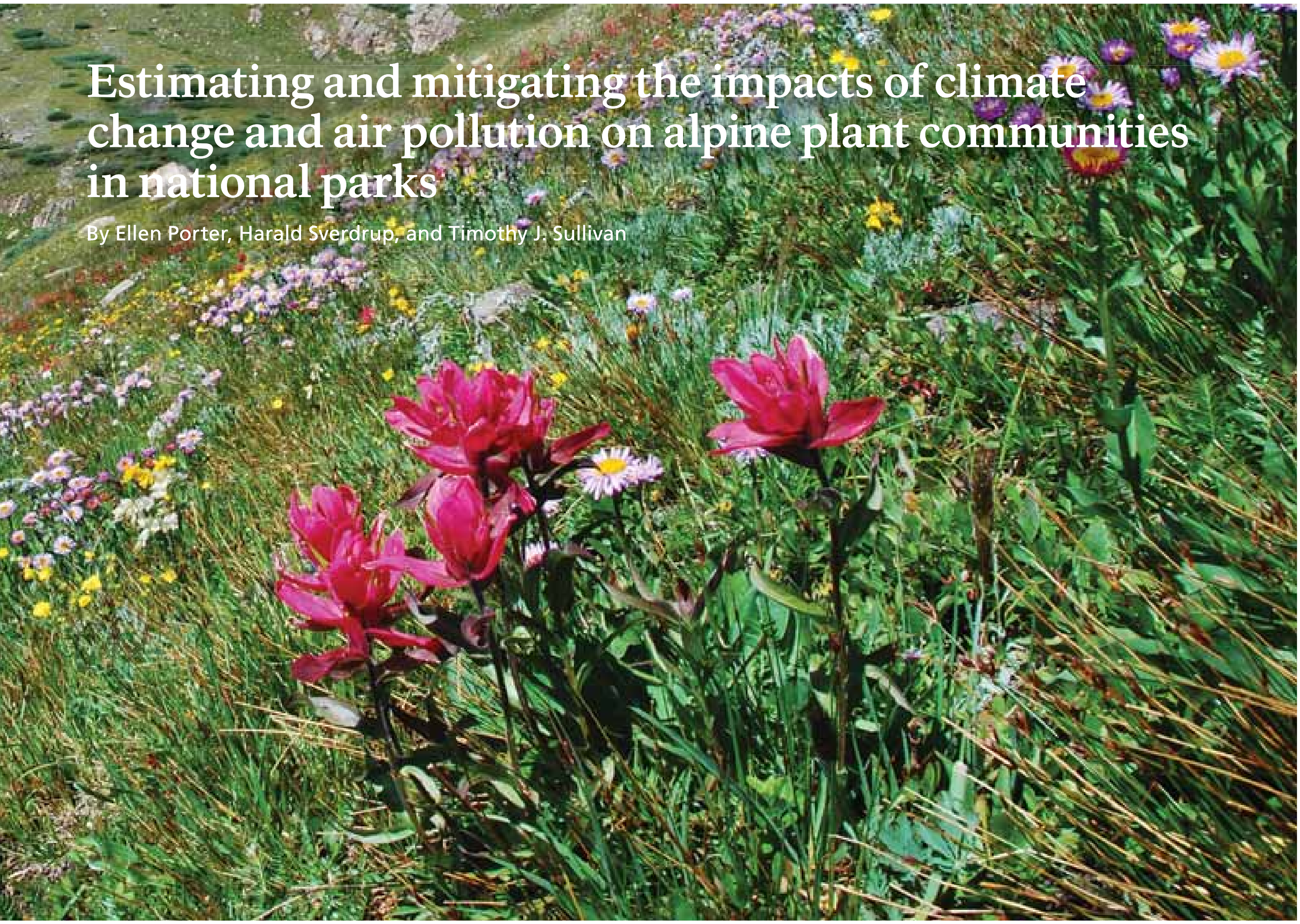

Figure 1. Alpine meadows and hillsides may look very different in the future as climate change and nitrogen from air pollution cause changes in plant communities.

IMAGINE AN ALPINE MEADOW AT THE HEIGHT OF wildflower season: a tapestry of blue columbines, yellow buttercups, crimson paintbrush, white phlox, and pink bitterroot contrasting with the deep blue sky of the Rocky Mountains (fig. 1). This explosion of color continues to inspire hikers to brave the high winds, low temperatures, and thin air in the high regions of our western national parks during the brief summers that are experienced at those elevations. We know that a changing climate is likely to affect this display (Bowman 2000). A longer growing season and changes in rain and snowfall will alter the alpine environment. Some plants will be displaced and others lost entirely, while some will thrive under new conditions. These changes will occur in addition to those already under way because of air pollution.

Air pollutants containing nitrogen are altering plant communities in many areas of the world because of nitrogen's fertilizing effect (Bobbink et al. 2010). Vehicles, power plants, industry, and agriculture all emit nitrogen that deposits into ecosystems with rain and snow, fertilizing some plants at the expense of others. Alpine plant communities are particularly at risk, having evolved under low-nitrogen conditions (Bowman 2000). When additional nitrogen from air pollution is available, plants with the ability to quickly assimilate it, including some invasive and nonnative species, gain a competitive advantage (Clark et al. 2007). Current levels of nitrogen pollution are sufficient to induce changes in alpine plant communities in and near Rocky Mountain National Park, Colorado (Bowman et al. 2006). But can we anticipate the even greater changes that are likely to occur as nitrogen pollution interacts with climate change? The Air Resources Division of the National Park Service (NPS) has recently collaborated with U.S. and European scientists to apply the innovative environmental effects model ForSAFE-VEG to help estimate future conditions and answer such questions.

Abstract

Two of the major stressors affecting plant communities in remote locations are climate change and excess nitrogen input from atmospheric pollution. Both stressors are causing profound changes in ecosystems, and there are strong interactions between plant responses to nitrogen pollution and responses to climate change. Certain native plant communities, notably those found in alpine, desert, and wetland areas, are expected to be very sensitive to both climate change and nitrogen addition. Many plant species in these areas have strict habitat requirements, and as climate change and nitrogen alter physical, hydrological, and chemical conditions, these species are displaced or marginalized. Plant communities located in "edge" or transition zones (e.g., tree line) are expected to be particularly vulnerable. While climate change is disturbing moisture and temperature regimes, nitrogen deposition from air pollution is causing unnatural fertilization (eutrophication) of ecosystems. This enrichment may favor certain species, often invasive weeds, over native plants. Species better able to use nitrogen crowd out native plants adapted to low-nitrogen conditions, making plant communities even more vulnerable to differences in temperature and precipitation expected as a result of climate change. In a workshop held in 2008, National Park Service (NPS) and university alpine plant specialists identified growth requirements of many alpine species in parks, including requirements for light, moisture, temperature, and nitrogen. The information was then used to simulate plant species responses to climate change and nitrogen addition, using the ForSAFE-VEG model. The model was developed in northern Europe to estimate soil chemistry and plant biodiversity responses to climate change and nitrogen pollution. The model is rooted in biogeochemical processes but also includes expert judgment to classify plant species according to their general patterns of response to stress. Based on information from the 2008 workshop, ForSAFE-VEG has recently been applied to a generalized tree line location representing national parks in the central and northern Rocky Mountains. Results of this preliminary model application suggest that ForSAFE-VEG is a useful tool in understanding interactions between nitrogen air pollution and climate change at high-elevation national park locations. For example, reducing nitrogen deposition and its associated stresses may be an effective strategy for increasing the resiliency of alpine plant communities to climate change.

Key words: alpine plant, climate change, deposition, model, nitrogen

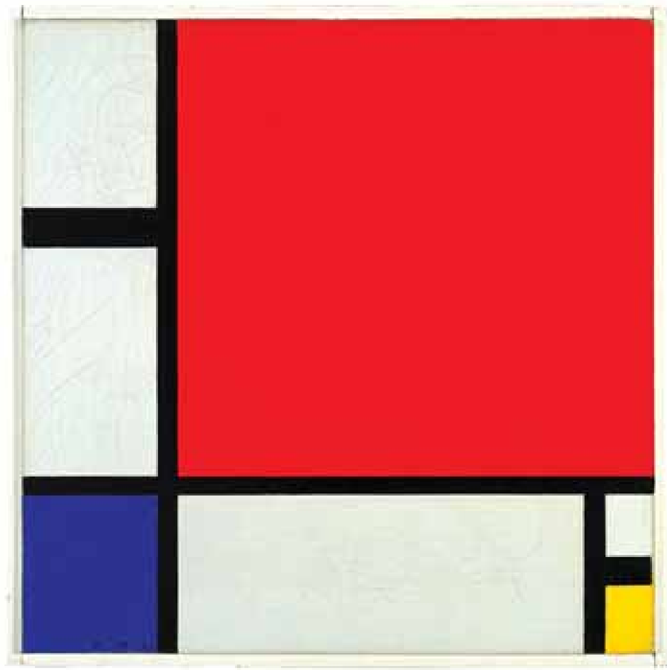

Figure 2. Piet Mondrian's *Composition with Red, Blue and Yellow*, from 1930. The canvas is divided into modular sectors, where colors are confined to a limited space and do not overlap. If one color should expand, it would necessarily replace another color partly or entirely. Similarly, if certain plant species expand their ranges, other species may be displaced.

Description of model

ForSAFE-VEG is an ecosystem model based on interactions among soil chemistry, hydrology, energy, carbon cycling, nitrogen cycling, tree growth and production, geochemistry, and ground vegetation (Sverdrup et al. 2008). Integral to the model is the ability to account for dynamic competition, that is, to forecast how species will interact under changing physical and chemical conditions. ForSAFE-VEG has developed and evolved over 20 years and has been tested extensively against field data in Europe (Sverdrup et al. 2007). A combination of controlled studies and the expert judgment of plant scientists has been used to train the model to simulate plant response to nitrogen and climate change. Each species has an optimal range that is influenced by competition with other plants and may vary over time. The model assumes that, in a given area with limited resources, conditions may be suitable for supporting a variety of species. If one species becomes more prevalent, another species will have to decline. The art of Piet Mondrian has been used to illustrate this principle (Sverdrup et al. 2011). On a Mondrian canvas, colors are confined to a sector and do not overlap (fig. 2). If one color expanded, it would be at the expense of another. Plant species behave similarly. If changing conditions allow a species to expand its coverage, it does so at the expense of other species, which usually have to retreat. ForSAFE-VEG simulates the results of plant and resource interactions. Would the model perform successfully when applied to high-elevation areas in the United States, where alpine plant species are different but have similar growth habits and requirements to their European relatives?

Science workshop

To begin to answer this question, we held a workshop at the offices of the NPS Air Resources Division in Lakewood, Colorado, in 2008, funded and cosponsored by the division and the Environmental Protection Agency. The workshop included European scientists with expertise in the ForSAFE-VEG model and U.S. scientists from the National Park Service, the U.S. Geological Survey, the USDA Forest Service, universities, and the private sector. The U.S. scientists had extensive experience with alpine and subalpine plants in the Rocky Mountains, the Pacific Northwest, and Alaska and included NPS plant specialists from North Cascades National Park, the Inventory and Monitoring Program office, and the Southwest Alaska Network. We asked them to summarize and evaluate information on plant response to air pollutants and climate in alpine and subalpine ecosystems in the United States. They also developed a preliminary classification for selected U.S. alpine plant species for the parameters required for input to the model. These included average lifespan of the species; requirements for nutrients, water, and light; response to excess nitrogen enrichment; ungulate grazing preference; rooting depth; and effective shading height. The scientists also summarized information about response to climate change and advised us regarding which aspects of climate change (e.g., temperature, precipitation, growing season, and snowpack depth and duration) should be used in the model.

Proof of concept

We next created a generalized plant community to represent the alpine and subalpine zones of the Rocky Mountains. This community was used to test the feasibility of using ForSAFE-VEG in the United States to simulate effects from climate change and air pollution. We ran the model over the period AD 1750–2400 to represent the range from preindustrial conditions to several hundred years in the future. Plant response data, generated from the workshop and from European studies, were available for 118 species, including grasses, forbs, lichens, mosses, trees, and shrubs. Data used to describe the geology, soils, air pollutant inputs, and climate of the generalized site were based in part on data from five national parks in the Rocky Mountains (Glacier, Yellowstone, Grand Teton, Rocky Mountain, and Great Sand Dunes). Geological data were extracted from spatial data sets on the NPS Data Store (http://science.nature.nps.gov/nrdata). Soil physical properties, including pH, percentage of clay, and depth to restricting layer, were derived from the STATSGO database (NRCS 2009). Historical climate data (temperature and precipitation) were obtained from PRISM (PRISM Climate Group at Oregon State University 2006) and were summarized as annual average values

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from 1971 to 2000. Air pollutant deposition was estimated from monitoring and modeling sources. We modeled future scenarios assuming climate change based on the Intergovernmental Panel on Climate Change (IPCC) A2 scenario (Pachauri and Reisinger 2007) and four levels of atmospheric sulfur and nitrogen deposition, ranging from assumed preindustrial background conditions to an absence of sulfur and nitrogen emissions controls with consequent higher levels of sulfur and nitrogen deposition (fig. 3). The A2 climate scenario assumes a relatively higher level of major greenhouse gases than some other IPCC scenarios, but as a result gives more information on impacts than a lower-emissions scenario. The A2 scenario is also being used by the North American Regional Climate Change Assessment Program (NARCCAP).

Although both nitrogen and sulfur deposition were considered in the model, sulfur effects were estimated to be minimal. Rates of sulfur deposition have historically been low in the Rocky Mountains (fig. 3) and are expected to remain relatively low in our modeled scenarios compared to nitrogen deposition because there are few coal-fired power plants, the major sources of sulfur emissions, in the region. Soil acidification, which can be caused by either sulfur or nitrogen deposition, but particularly sulfur deposition because of its strong acidification potential, is not expected unless sulfur deposition significantly increases. The ForSAFE-VEG model results suggest that soil acidification is unlikely to affect alpine plant communities under our expected scenarios. On the other hand, nitrogen emissions sources, including vehicles, industry, power plants, oil and gas production, and agriculture, are numerous in certain areas of the Rocky Mountains and nitrogen deposition is significantly elevated over preindustrial conditions. The model forecasted strong plant community responses to nitrogen deposition and we focus our discussion on those responses.

Figure 4 (page 62) shows estimated changes in plant species composition from AD 1800 to 2200 under the four nitrogen pollution scenarios, assuming the IPCC A2 climate scenario. For the figure, modeled species were sorted into dominant functional plant

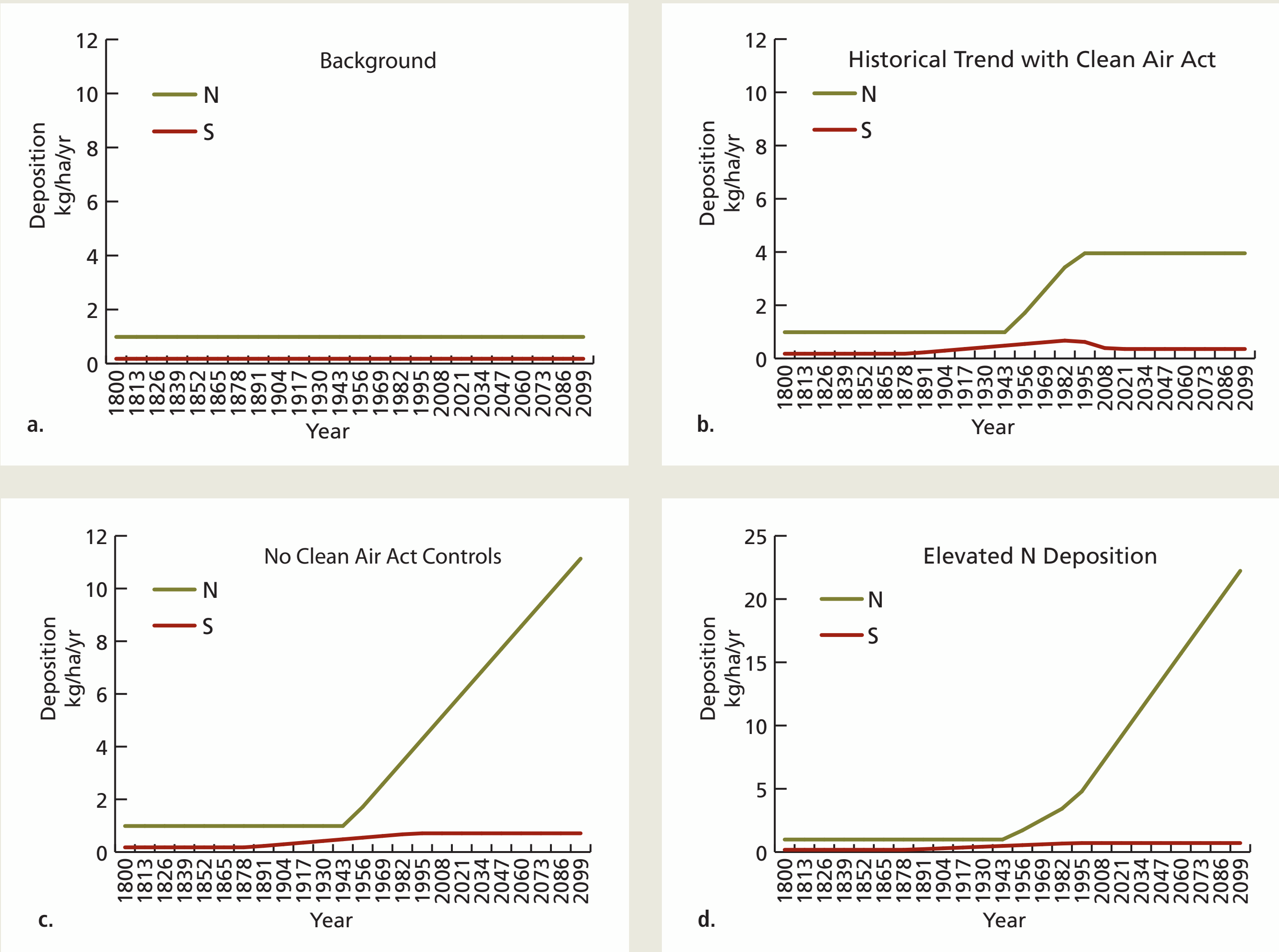
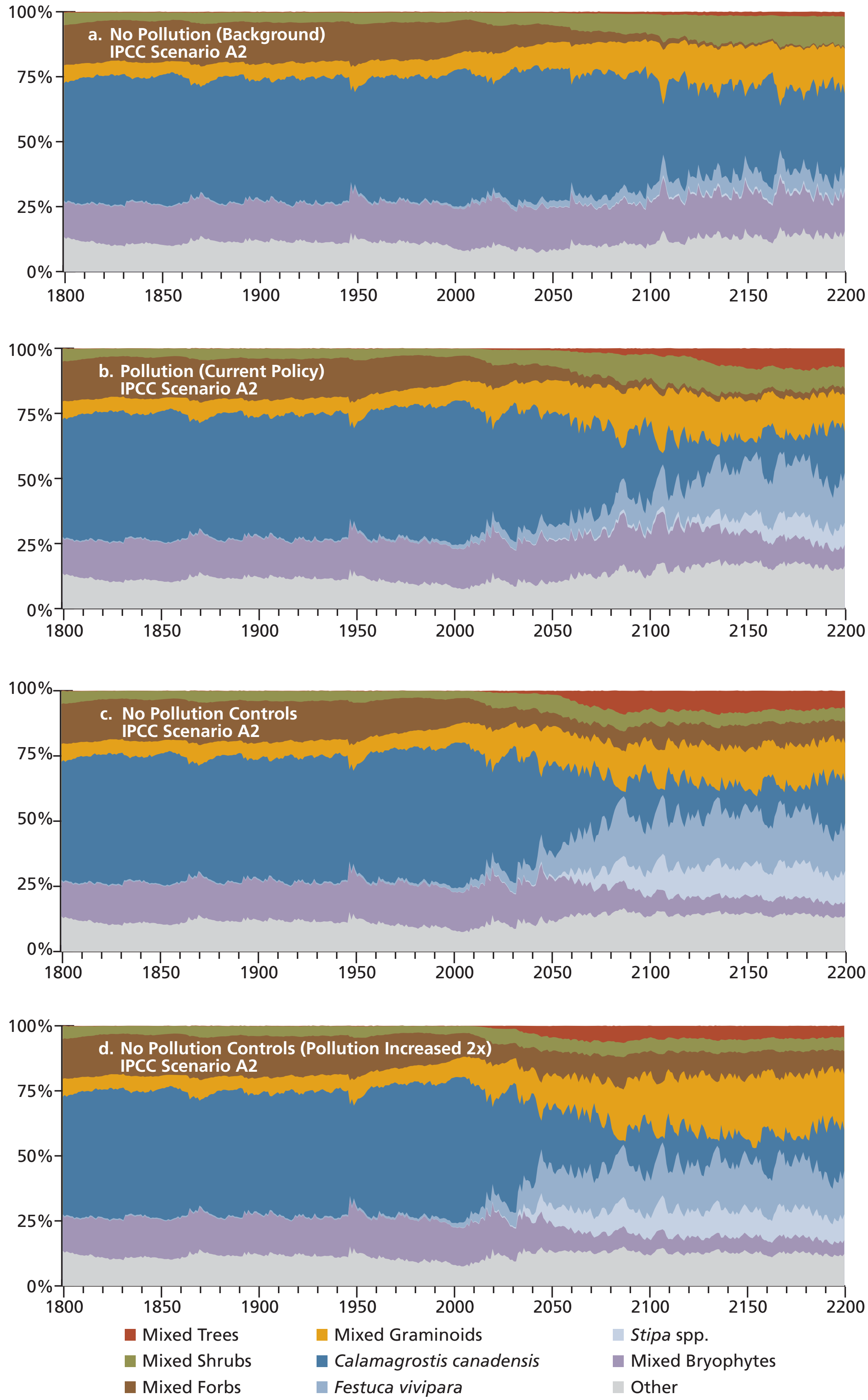


Figure 3. Deposition scenarios assumed for this model application: (a) the background scenario, assuming no industrialization of North America; (b) the historical trend with the Clean Air Act, cutting about 50% of sulfur (S) deposition, with minimal change in nitrogen (N) deposition; this scenario approximates recent policy; (c) no Clean Air Act controls on N and S emissions; and (d) future N deposition doubles as compared with scenario C (elevated N deposition). Deposition is assumed to remain constant after 2100.

groups, including mosses, grasses, forbs, shrubs, and trees. In addition, several individual species that were estimated to change significantly in abundance over time are depicted. The thickness of a given color band indicates the relative amount of functional plant group or individual species coverage. These thicknesses increase and decrease over time as species and groups become more or less abundant. The site responds with vegetation composition changes as a result of both climate change and nitrogen deposition input. If nitrogen deposition inputs do not change from natural background, but climate does (fig. 4a), ground vegetation is estimated to change significantly. Forbs like *Lupinus nootkatensis* (Nootka lupine) and the grass *Calamagrostis canadensis* (bluepoint grass) decrease in percentage of cover; *Festuca vivipara* (northern fescue) increases. Despite the assumed climate change, the model suggests that without extra nitrogen, the trees (e.g., *Picea* spp.—spruce) will be unable to advance appreciably to the higher alpine areas used in this exercise.

Under atmospheric nitrogen and sulfur deposition levels that reflect recent emissions controls in the United States (fig. 4b), plant species shifts are more pronounced as compared with natural background deposition and climate change. Invasion of trees above the present tree line is simulated to take place in response to nitrogen deposition of about 2.8 kilograms per hectare per year

Figure 4. Model simulations for plant species coverage based on the IPCC climate change scenario A2 for this region and (a) background S and N deposition, (b) approximate recent Clean Air Act emissions controls, (c) no Clean Air Act controls, and (d) elevated future atmospheric N deposition.



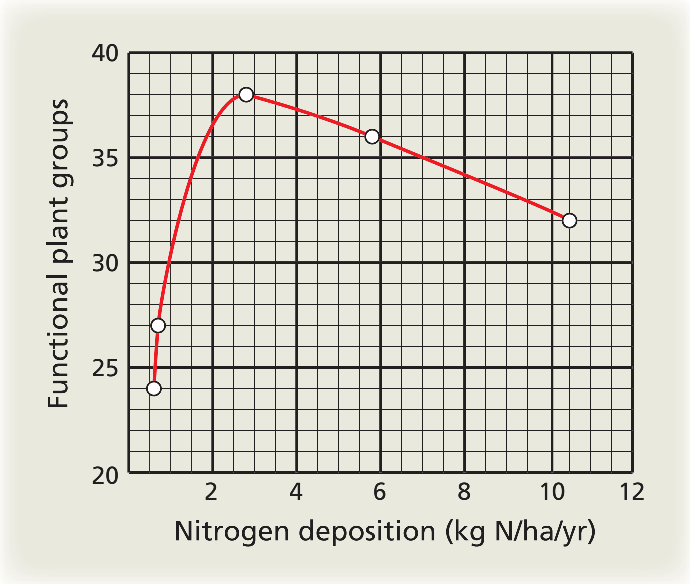


Figure 5. Model results indicate that in low-nitrogen systems like alpine ecosystems, as nitrogen increases, biodiversity increases initially. However, as nitrogen further increases, biodiversity starts to decline.

(kg/ha/yr)[1], and new species invade the area. For comparison, in 2010 the nitrogen deposition rate in Rocky Mountain National Park was about 4 kg/ha/yr. The model estimated that with climate change and increased nitrogen, mosses like *Pleuzobium schreberi* (Schreber's moss) will decrease and be partly replaced by grasses or sedges that increase in coverage (*Carex vaginata*—sheathed sedge) or invade (*Poa arctica*—arctic bluegrass).

With further increases in nitrogen deposition, more substantial change in biodiversity is simulated to take place (fig. 4c). This corresponds to a peak deposition of about 5.5 kg N/ha/yr. Model results suggest that the site will be invaded by tree species such as *Picea glauca* and converted from partially open to closed canopy with brushy understory vegetation. Shrubs like *Vaccinium uliginosum* (bog blueberry) decrease, being outcompeted by grasses and herbs. The grasses *Stipa* and *Festuca* are simulated to invade the uplands from lower elevations. *Calamagrostis* is reduced to a marginal grass from having been the most dominant.

If nitrogen inputs increase to higher levels (fig. 4d), the model suggests that larger biodiversity changes will occur. This elevated nitrogen deposition scenario corresponds to a peak deposition of about 10.5 kg N/ha/yr. Under this scenario, the modeled site will become forested, have more *Salix phylicifolia* (willow) undergrowth, and *Lupinus nootkatensis* will be reduced to a marginal species. *Vaccinium uliginosum* is now almost eliminated by grasses and herbs, and ferns are firmly established. Many species prevalent under background deposition will have been replaced totally; many new plant species will have invaded. Simulated biodiversity will have changed considerably.

[1]One kilogram per hectare is approximately equal to 0.9 pound per acre.

A combination of controlled studies and the expert judgment of plant scientists has been used to train the model to simulate plant response to nitrogen and climate change.

The model allows us to estimate the "critical load," defined as the amount of deposition below which some specified harmful change is not expected to occur to an ecosystem or to some attribute of an ecosystem (Porter et al. 2005). Based on the model results, a nitrogen critical load in the range of 1 to 2 kg/ha/yr would protect against a change of 5% in plant species coverage, as compared with natural background deposition.

The model also allows us to look at changes in biodiversity, defined as the number of functional plant groups present. Figure 5 shows that under very low nitrogen conditions, biodiversity is low at our hypothetical site. As nitrogen increases somewhat, biodiversity increases because nitrogen is a nutrient. But as nitrogen increases further, biodiversity starts decreasing as certain species are favored while others are eliminated, a pattern seen in certain other ecosystems (Clark et al. 2007).

Thus, model results suggest that this hypothetical ecosystem is vulnerable and prone to significant losses in plant biodiversity with warming climate and increasing atmospheric nitrogen deposition. The outputs show a response time that is very long, in the range of a century or more. Comparable results were found in Europe by Sverdrup et al. (2007) and Belyazid et al. (2011). This suggests that air quality management decisions made today will have ramifications far into the future. Reducing nitrogen deposition should be an important consideration when planning for climate change.

Conclusion

The results of preliminary ForSAFE-VEG modeling for a synthetic tree line site in the Rocky Mountains region are encouraging. The model appears to be a feasible tool for evaluating the interactions of climate change with air pollution, specifically deposition of atmospheric nitrogen. The model estimated the critical loading of nitrogen deposition above which plant biodiversity decreases. This critical load may now be exceeded at some places in the region. The results suggest that both climate change and nitrogen pollution can significantly affect alpine plant community composition and diversity. Reducing nitrogen pollution and deposition will reduce overall impacts of climate change on these ecosystems.

Next steps

A synthetic site was used for this test of the ForSAFE-VEG model. The NPS Air Resources Division plans to apply the model to data specific to a park ecosystem, possibly Rocky Mountain National Park. The model may prove to be an important tool in forecasting and ultimately mitigating the impacts of climate change.

References

Belyazid, S., D. Kurz, S. Braun, H. Sverdrup, B. Rihm, and J. P. Hettelingh. 2011. A dynamic modeling approach for estimating critical loads of nitrogen based on plant community changes under a changing climate. Environmental Pollution 159:789–801.

Bobbink, R., K. Hicks, J. Galloway, T. Spranger, R. Alkemade, M. Ashmore, M. Bustamante, S. Cinderby, E. Davidson, F. Dentener, B. Emmett, J.-W. Erisman, M. Fenn, F. Gilliam, A. Nordin, L. Pardo, and W. S. DeVries. 2010. Global assessment of nitrogen deposition effects on terrestrial plant diversity: A synthesis. Ecological Applications 20:30–59.

Bowman, W. D. 2000. Biotic controls over ecosystem response to environmental change in alpine tundra of the Rocky Mountains. Ambio 29:396–400.

Bowman, W. D., J. Larson, K. Holland, M. Wiedermann, and J. Nieves. 2006. Nitrogen critical loads for alpine vegetation and terrestrial ecosystem response—Are we there yet? Ecological Applications 16:1183–1193.

Clark, C., E. Cleland, S. Collins, J. Fargione, L. Gough, K. Gross, S. Pennings, K. Suding, and J. Grace. 2007. Environmental and plant community determinants of species loss following nitrogen enrichment. Ecology Letters 10:596–607.

E & S Environmental Chemistry, Inc. 2009. Alpine vegetation workshop: Response of alpine and subalpine plant species to changes in atmospheric N deposition. Proceedings of a workshop, 6–7 November 2008, Denver, Colorado. Accessed 4 March 2011 at http://www.nature.nps.gov/air/Pubs/pdf/2008_Alpine_Vegetation_Workshop_Final_Report.pdf.

NRCS (Natural Resources Conservation Service). 2009. U.S. general soil map (STATSGO2). U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, D.C., USA. Downloaded 5 February 2009 from http://soildatamart.nrcs.usda.gov.

Pachauri, R. K., and A. Reisinger, editors. 2007. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Porter, E., T. Blett, D. U. Potter, and C. Huber. 2005. Protecting resources on federal lands: Implications of critical loads for atmospheric deposition of nitrogen and sulfur. Bioscience 55:603–611.

PRISM Climate Group at Oregon State University. 2006. United States average annual precipitation and temperature, 1971–2000. PRISM Climate Group, Oregon State University, Corvallis, USA. Downloaded 29 January 2009 from http://www.prism.oregonstate.edu.

Sverdrup, H., S. Belyazid, D. Kurz, and S. Braun. 2008. Proposed method for estimating critical loads for nitrogen based on biodiversity using a fully integrated dynamic model, with testing in Switzerland and Sweden. Pages 3–37 *in* H. Sverdrup, editor. Towards critical loads for nitrogen based on biodiversity: Exploring a fully integrated dynamic model at test sites in Switzerland and Sweden. Background document for the 18th CCE Workshop on the Assessment of Nitrogen Effects Under the ICP for Modelling and Mapping. LRTAP Convention (UNECE), Bern, Switzerland, 21–25 April.

Sverdrup H., S. Belyazid, B. Nihlgård, and L. Ericson. 2007. Modeling change in ground vegetation response to acid and nitrogen pollution, climate change and forest management in Sweden, 1500–2100 A.D. Water, Air, and Soil Pollution: Focus 7:163–179.

Sverdrup, H., T. C. McDonnell, T. J. Sullivan, B. Nihlgård, S. Belyazid, B. Rihm, E. Porter, W. D. Bowman, and L. Geiser. 2011. Testing the feasibility of using the ForSAFE-VEG model to map the critical load of nitrogen to protect plant biodiversity in the Rocky Mountains region, USA. Water, Air, and Soil Pollution. doi:10.1007/s11270-011-0865-y.

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