Can we protect high-elevation wilderness vegetation from air pollution impacts?

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Our wilderness and alpine ecosystem areas are a unique resource. While these areas are in remote locations they are not isolated from long-range atmospheric transport. The increase in regional air pollution sources may expose them to anthropogenic pollutants. The Clean Air Act of 1990, as amended, charges the Federal Land Manager (FLM) with the *affirmative responsibility to protect air* quality related values (AQRVs) in Class I wilderness areas from adverse human-caused air pollution impacts. Class I areas are wildernesses larger than 5000 acres (including later expansions) that existed as of August 1977. This protection is available through implementation of the Act's Prevention of Significant Deterioration (PSD) provisions.

But there are constraints the PSD process imposes on the gathering of relevant data for the permit evaluation. Conventional approaches are inadequate to address impacts to vegetation within these constraints.

Constraints imposed by the PSD Permit process

The major constraint of the PSD process is the short review period the State and the FLM have to evaluate a permit application. The review period may be only several months, and it may not fall within the growing season. The PSD program is a preconstruction review and permitting process for major new or expanding sources of pollution, therefore it would be prudent to begin monitoring before a permit evaluation situation arises. The decision to grant, deny, or require modifications to a new permit is the responsibility of the State, the State requests input from the FLMs during the review process, then the FLM advises the State as to whether a proposed source's emissions will have an adverse impact on Class I area AQRVs. Any major facility seeking a new source permit for location or expansion in a clean air area must meet several requirements, as specified in the Clean Air Act. The PSD process is a rare opportunity for the FLM to influence future air quality and actually protect the resource

Numerous National Forests have developed monitoring plans (Air Resource Management Plans) to gather baseline data for their lands, and to attempt to detect any current impacts to AQRVs. While surface water chemistry and visibility are currently being monitored in some National Forest Class I areas of the Intermountain and Rocky Mountain regions, little monitoring for sensitivity to or impacts on vegetation by pollutants is currently underway. Are plants not sensitive to air pollution? Actually, many plants are very sensitive to some pollutants, but the tools to effectively predict the sensitivity of high-elevation plants are not available. Complex models exist for predicting visibility and water quality in a given deposition environment, yet models for predicting direct impacts to vegetation have not been developed. Therefore, permits are currently reviewed on the basis of potential impacts to visibility and surface water chemistry, while plant sensitivity is rarely considered. This effort may adequately protect wilderness ecosystems from effects of nitrogen and sulfur deposition, but may not adequately protect them from impact by chemicals such as ozone, which primarily affect plants.

Nor does the PSD process establish prioritization for the importance of different components of the ecosystem. Each wilderness is a unique compilation of biotic and physical factors that interact to form the ecosystem. Any procedure to estimate the sensitive component of any wilderness ecosystem must be adaptable to different permit application scenarios. It must be able to take into account the specific wilderness area that may be impacted, with its individual diversity of species, genotypes, pollutant chemicals, and physical conditions. Therefore, the optimal approach would incorporate data collected from the wilderness area in question with model estimates of pollutant transport and exposure.

The data to be collected must be simple and compatible with the constraints imposed by the Wilderness Act of 1964 (no motorized transportation or excessive destructive sampling). These constraints are complicated by the non-uniformity and complexity of the alpine landscape. Alpine areas are severe physical environments: high radiation, winds, and snow fall. The interaction of these factors with the topography creates a mosaic of micro-environments across the alpine landscape. The most obvious feature of this mosaic is the alternating pattern of windblown, snow-free sites with areas of deep snow accumulation. Distinct vegetative communities have evolved in response to these different snow regimes.

The same mosaic of snow regimes that cause differences in plant community structure also creates a mosaic of potential deposition rates of anthropogenic pollutants. It has been shown that distinct areas of the alpine tend to accumulate the deposition of fallout from nuclear testing while others do not. In light of the potential for such heterogenous pollutant loading rates, looking for the most sensitive component of the ecosystem is inadequate if it is only defined as the component with the lowest threshold of tolerance to a pollutant. More appropriately, the approach must be to identify the first component of the ecosystem that will exhibit a measurable change in response to exposure to a pollutant level and dynamic. The combination of two characteristics will provide a means of identifying which component of the system is most likely to show effects first in a given atmospheric

Table 1. **The components of plant sensitivity to atmospheric pollution.**

1. EXPOSURE— concentration of the pollutant in the air, precipitation, or soil.
2. PLANT UPTAKE ABILITY— how much pollutant gets into the plant.
   Uptake ability is a function of:
   - leaf conductance— uptake of gases (O_3, SO_2, NO_2);
   - leaf surface and crown structure—foliar absorption of wet deposition;
   - nutritional status— uptake from the soil.
3. INTERNAL BIOCHEMICAL REACTIONS—pollutant interaction within the cell. Progress is being made, but currently there are no consistent correlationsbetween biochemical characteristics of cells and their sensitivity to damage among species.

chemistry: 1) the relative pollutant loading rates to the mosaic of alpine micro-environments, and 2) the sensitivity of each community and its individuals to the pollutants delivered to its location.

Comparison of the problem to other air pollution effects programs

It is clear that the responsibility of determining the alpine plant species most likely to be affected once exposed to a polluted air mass is no small task -- we are dealing with incredible diversity in a harsh environment. This alone makes the situation different from past national air pollution-effects programs such as the National Acid Precipitation Assessment Program (NAPAP) and National Crop Loss Assessment Network (NCLAN). The NCLAN program was established to provide information on the economic impacts of ozone and sulfur dioxide on selected crop species while NAPAP aimed to help unravel the components of the apparent 'forest decline' in the U.S. The species studied under each of these plans were specified due to the nature of the programs. The PSD program provides no direction with regard to prioritizing the wilderness plant communities or species. The congressional mandate specifically implies that all the organisms in wilderness are of equal importance. The PSD program is also different from the other programs since it is designed to prevent damage from occurring, not to assess damage that has already occurred. Currently, there are no confirmed field observations of pollutant impacts to alpine wilderness plants in the Rocky Mountains to help construct a preliminary list of sensitive species.

Due to the differences between the PSD program and past programs, it is not surprising that the standard approach (dose-response studies) is not applicable here. The most obvious problem with the conventional approach is that the sensitivity of an extraordinary number of species must be assessed. It is not feasible to construct an exposure-impact relationship for each and every species found in all Class I wilderness areas.

Additionally, there is a unique problem with conducting dose-response studies in controlled environments with alpine plants. The growth form of many alpine plants is a consequence of the harsh environment in which they live. It is not possible to transport and grow alpine plants out of their alpine environment without altering their morphology and quite likely their physiology and pollutant sensitivity, and the expense and time required to attempt to simulate the alpine environment adequately are prohibitive. The severe environmental conditions in high-elevation areas may interact with the sensitivity of the species to pollutant impacts, further complicating the interpretation and extrapolation of data from experiments conducted under less severe conditions.

Conducting dose-response experiments with open-top exposure chambers in the alpine environment, outside of a wilderness area due to the obvious conflict between this activity and the provisions of the Wilderness Act, is problematic for two reasons (1) the chamber itself alters the growth environment of the enclosed plants, and (2) due to the remoteness of alpine areas, the cost of installing line power and preventing damage to the fumigation system by the elements is prohibitively expensive. Even with good air flow, enclosing plants in an open-top chamber results in a rise in the relative humidity and air temperature in the chamber. These environmental changes often affect the growth of the enclosed plants. In fact, an international study, International Tundra Experiment (ITEX), is being conducted which specifically uses open-top chambers to impose a climate change to small plots in the arctic and alpine to study the ecosystems' response to increased air temperature.

Open-air fumigation systems have been developed to allow control of air quality without the use of chambers. In these systems, a computer can be programmed to release pollutant from numerous tubes around a plot according to the wind patterns such that a specific air quality can be maintained. Considering the high winds in the alpine, it would be difficult and costly to conduct extensive open-air fumigation experiments in the field. This approach should be explored, yet due to the technological advances that it requires for application in the alpine, it is unlikely to provide information to the FLM in the near future.

What are our alternatives?

Because of the magnitude of the problem, it is unlikely that the actual sensitivity of all wilderness plant species will ever be known. Until we can experimentally determine plant sensitivity to air pollution in the alpine, we have to develop a way to estimate sensitivity from easily measured parameters, and prioritize our attention on those species that may be the first to be impacted. This requires information on the mechanisms of atmospheric

Anna Schoettle measuring gas exchange of alpine plants with a portable photosynthesis system pollutant effects that could be incorporated into a model. We know there are three components of sensitivity to direct impacts of atmospheric chemicals on plants: pollutant exposure, pollutant uptake by the plant, and biochemical sensitivity of the plant tissue to the assimilated pollutant (Table 1).

Pollutant exposure, the concentration of pollutant that the plant is in contact with and the dynamics and duration of that exposure, can be modeled and estimated from air pollution transport models. It is particularly difficult to make accurate predictions of potential atmospheric chemistries in mountainous terrain. Knowing the current air chemistry in Class 1 areas is necessary to assess current impacts and could be useful to estimate future exposure. Using these data alone to predict pollutant impacts to vegetation is unreliable. The relationship between exposure and impact is quite variable from species to species.

Pollutant uptake (the amount of pollutant that is actually assimilated into the plant) in combination with estimates of pollutant exposure, adds another level of resolution to the prediction of potential impacts. Examination of the mechanisms by which air pollutants affect plants has revealed that impact is more closely related to pollutant uptake than exposure.

Plant uptake can be divided into two categories, uptake of gaseous pollutants and uptake of water-deposited pollutants. Aerodynamic and stomatal conductance of plant leaves influence gaseous pollutant uptake and leaf wettability and crown architecture influence interception and assimilation of pollutants delivered in precipitation. With measurements of stomatal and leaf characteristics of alpine plants and estimates of ambient pollutant concentrations and durations from the air transport models it could be possible to estimate pollutant uptake by alpine plants. Relationships to estimate impact from estimates of gaseous pollutant uptake have been established for agronomic and tree species, and are generally consistant among species.

Measurements of leaf conductance can easily and quickly be made with a steady-state porometer. This instrument has been used in plant physiological research for decades, is fully field-portable, and can be carried and operated by a single person. Measurements on a leaf can typically be accomplished in less than a minute. Measurements can also be made with a portable photosynthesis system yet this instrument is more complex and expensive. In a survey of 24 alpine species in two alpine sites along the east side of the Rocky Mountains (Niwot Ridge, Nederland, Colorado and Glacier Lakes Ecosystem Experiments Site (GLEES), Snowy Range, Wyoming), a wide range in stomatal conductance was detected between species and within species among habitats, suggesting a range of potential sensitivity to the uptake of gaseous air pollutants. In a survey of 27 alpine species at GLEES, crown retention of precipitation could be accurately predicted on the basis of simple measurements such as crown height and diameter and the width of the leaves at the base of the petiole. Thus, by measuring these traits for alpine species, one could estimate the variability in sensitivity within and among species, and make some predictions about which species could be most susceptible, relative to one another, to the uptake of gaseous and water-deposited pollutants. The initial species rankings could help focus our efforts on those species and habitats that have the highest potential for pollutant uptake when conducting field surveys for current pollutant impacts. Making the measurements in each threatened wilderness area would further improve our predictive ability by avoiding extrapolations across genotypes and site characteristics.

Incorporation of the third component of sensitivity, the biochemical sensitivity of the plant tissues to assimilated pollutants (Table 1), into our estimates of plant sensitivity to pollutants could greatly increase the accuracy of the prediction. However, there is relatively little information available on factors that control this aspect of sensitivity in plants. At this time, the relationships between biochemical characteristics and sensitivity are not well enough understood among species to incorporate this level of detail into any wilderness vegetation monitoring program, yet could be added at a later time if research results become available.

While the potential sensitivity ranking of alpine species alone could be used to prioritize assessment efforts and field sampling, the methods used to devise the ranking (based on the plants' pollutant uptake ability) must be verified with a subset of alpine species before it could be used in the PSD review process. The relationship between pollutant exposure, uptake, and impact that has been demonstrated for agronomic and tree species would need to be confirmed for wild alpine species. Comparisons of exposure, pollutant uptake ability (leaf conductance), and impacts would need to be made under controlled fumigation conditions, preferably with an open-air fumigation system, in the alpine for a subset of plant species.

Summary

The Federal Land Manager has an affirmative responsibility to advise the State so as to protect air quality related values in Class I areas from adverse impacts from air pollution. Monitoring air and water quality and visibility may not provide the information needed to protect wilderness ecosystems from all air pollutant impacts. Ozone, for example, does not directly affect soil or water quality, yet is extremely phytotoxic to plants. If FLMs rely on the exposure-impact relationships established with other plant species to protect wilderness vegetation, potential impacts to alpine species could be predicted at a very coarse level. However, the correlation between exposure and impacts among plant species is poor. The addition of information on the ability of the plant species to take up pollutants could substantially improve the prediction due to the better relationship between uptake and impact observed in crops and tree species. The relative ranking of species for their ability to take up pollutants could also be used to prioritize attention in field surveys to assess current air pollution impacts. Prior to use in the PSD process, the relationship between pollutant uptake and impact observed in other species would need to be confirmed for wild alpine plants. Pollutant uptake ability could be modeled using simple measurements gathered in one field season. As information on the biochemical susceptibility of plants to pollutants becomes better known, this too could be incorporated into the model. Until impacts occur in the field, the actual sensitivity of alpine plants to pollutants in Class 1 wilderness areas will not be known. However, with the development of predictive tools and careful monitoring to estimate pollutant sensitivity, we may be able to help managers protect our wilderness ecosystems from ever experiencing impacts from atmospheric deposition.

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