

The Effects of Nitrogen Deposition, Ambient Ozone, and Climate Change on Forests in the Western U.S.

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Abstract—Nitrogen (N) deposition in the western United States is most severe near major urban areas or downwind of agricultural regions, particularly in areas where confined animal feeding operations such as dairies or feedlots are located. Nitrogen saturated ecosystems are predominantly found in hotspots located within 60 km of urban or agricultural emissions source areas, where N deposition inputs are 20 kg ha⁻¹ yr⁻¹ or greater. Nitrogen deposition gradients are steep with rapidly decreasing deposition with increasing distance from the source area. More subtle ecological effects of N deposition, such as fertilization effects and changes in sensitive biotic communities (for example, lichens and diatoms) occur over a much wider area than the severely affected hotspots. Effects on these sensitive ecosystem components are observed with N deposition levels as low as 3 to 8 kg ha⁻¹ yr⁻¹. Visual ozone injury in the West is most severe in pine trees in forests in southern California and in the southern Sierra Nevada in central California. Recent ozone exposure data from passive monitoring networks demonstrate that elevated ozone exposures can occur as far as 250 km from emissions source areas. The geographic scope of the areas affected by ozone has increased in the past 30 years as human populations and urban zones have increased in size, and this trend is expected to continue. The combined effects of ozone and N deposition result in profound changes in plant physiological function, nutrient cycling, C storage, fuel accumulation, and susceptibility to insect attack. Predicting future ecosystem condition under scenarios of increasing CO₂ and temperature and altered precipitation patterns presents a complex research problem, particularly for areas also exposed to ozone and N deposition. Research approaches including controlled studies, manipulative field experiments, simulation modeling, and a consideration of disturbances such as pests, introduced species, fire, and drought are needed. Combined biogeography-biogeochemistry simulation models (also known as dynamic general vegetation models) incorporating all of these interacting factors will be needed to advance our understanding of these complex interactions.

Introduction

Systematic studies of air pollution impacts on agriculture and natural ecosystems began about 50 years ago. Research on the effects of future climate conditions on crops and ecosystems is a more recent development. Trends in air pollution, concentrations of greenhouse gases, and future climatic changes are often referred to collectively as global change. Both greenhouse gases and air pollutants are primarily emitted from the combustion of fossil fuels, and air pollutants affect the capacity of ecosystems to sequester or emit greenhouse gases such as carbon dioxide, methane, or nitrogen oxides. One of the major objectives of the ecological research

community is to increase our understanding of the ecological and environmental impacts of the combined effects of air pollution and climate change. Air pollution effects in the future will occur within an environment of continuing increases in CO₂ and temperature and changing precipitation patterns. The major objective of this paper is to summarize what is known of likely nitrogen (N) and ozone effects on forests of the western United States under a changing climate. I will suggest likely future general ecosystem responses in the West based on empirical and manipulative studies in conjunction with simulation modeling results, although the latter are largely from other geographic areas and only include a subset of the important global change factors.

Table 1. Air pollution and climate change factors in the western United States and possible effects on forest ecosystems. The potential ecosystem effects mentioned are of necessity simplified generalizations based on past observations, experimental results, and current understanding. Actual ecosystem responses will depend on specific site factors and conditions, future air pollution and climate scenarios, and interactions between all these factors.

Factor	Observed and potential ecosystem effects
Ozone	Phytotoxic; reduced productivity; altered phenology of sensitive species; high concentrations can cause loss of stomatal control; premature foliar senescence and abscission; ozone predisposes plants to pests and diseases; reduced root:shoot ratio; geographic extent of damaging ozone levels expected to increase as urbanization and population growth continues in the West; ozone effects can cancel out CO ₂ -induced growth stimulation
Nitrogen deposition	Increase in plant productivity; may partially offset growth decrease caused by ozone; reduced root:shoot ratio; may contribute to stand densification; N saturation conditions; elevated nitrate leaching and nitrogenous trace gas emissions from soil; soil acidification in highest deposition sites
Ozone + N deposition	Reduced root growth, but increased stem growth and litter accumulation; increased fuel buildup
Increasing CO ₂	Increased plant growth; lower foliar nutrient concentrations; altered susceptibility to pathogens and pests; possibly altered litter decomposition rates; may reduce evapotranspiration losses
Increasing temperature	Increased plant growth initially, but may exacerbate drought stress as temperature continues to increase; may enhance ozone formation
Changing precipitation patterns	In early decades of this century is expected to increase forest growth, but in some areas of the West will likely lead to increased drought stress with more frequent extremely wet and dry years or because of drier summers
Drought	Increased drought will often be the primary controller of ecosystem condition
Pests and pathogens	Pest outbreaks are likely to increase with drought stress and the impacts of ozone, N deposition and increased CO ₂
Forest fires	Severe forest fires may increase due to increasing drought stress and associated tree mortality from multiple stress syndromes and stand densification from long-standing fire suppression efforts

Global Change Stress Factors

The primary climate change and air pollution stress factors to be considered in this paper are: nitrogen deposition, ozone, changing temperature and precipitation patterns, increasing CO₂, drought, forest pest outbreaks, and fire (table 1). Nitrogen and ozone air pollution have been impacting forest ecosystems in southern California for the past 50 years and we know something of their effects (Fenn and others 2003b). Carbon dioxide concentrations have been gradually increasing over this same time period and severe drought periods have also occurred. From 1999 to 2004, drought has been particularly severe in southern California and the southwestern U.S. (Piechota and others 2004), and insect outbreaks and fire severity in forests of southern California increased dramatically in 2003 (Westerling and others 2004). These and other changes in southern California forests may portend future impacts on western forests under future air pollution and global change scenarios. However, much of our understanding of air pollution and climate change impacts on ecosystems

are based on studies of single or possibly two factors. Multiple air pollution interactions are relatively poorly understood, and predictions of the combined effects of air pollutants within the context of increasing CO₂, and climate change are even more uncertain.

The extent of forested areas in the West that will be exposed to phytotoxic levels of ozone is on the increase. Projected increased temperatures will likely contribute to higher rates of ozone formation (Beedlow and others 2004). On a worldwide basis, the percentage of temperate and subpolar forests exposed to damaging levels of ozone (> 60 ppb) is predicted to increase from 29 to 60 percent by the end of this century (Fowler and others 1999). Nitrogen deposition is also expected to affect increasing acreages of forest in the West as urbanization and population growth continue in this fast growing region. The recent development of reliable passive monitors for measuring concentrations of gaseous pollutants (Bytnerowicz and others 2002) such as ozone, nitric acid vapor, nitrogen oxides, ammonia, and sulfur dioxide now makes it feasible to determine air pollution exposure patterns over large forested areas. For example,

from a network of passive ozone monitors throughout a large extent of the Sierra Nevada range in California, it was surprising to discover high summertime ozone concentrations in the Mammoth Lakes and Owens Valley regions of the eastern Sierra Nevada, approximately 165 to 250 km from any major pollutant sources (Frȳczek and others 2003). These findings demonstrate that elevated ozone concentrations can occur in unexpected areas and that passive monitoring networks are effective in characterizing pollution exposures over broad forested areas. Throughfall deposition of nitrogen and sulfur, a surrogate measure of total dry and wet deposition, can also be measured more routinely in a large number of remote sites because of the recent development of ion exchange resin collectors that require infrequent sample collection (for example, every six months; Fenn and Poth 2004). These monitoring tools, along with the ongoing development of portable active monitors of ozone and other pollutants, will continue to improve our capacity to relate air pollution exposures in the field to ecosystem effects.

We consider that in areas where drought severity increases significantly, this factor will override the impacts of other factors. Drought stress leads to tree mortality, either directly or due to predisposition of trees to pests and diseases. The end result is greater fire risk. Wildfire is the most important natural ecological disturbance in western North America (McKenzie and others 2004). In areas where soil moisture is only moderately reduced, increased atmospheric CO₂ may compensate by reducing evapotranspiration fluxes. However, if ozone levels are high, stomatal control can be disrupted (Grulke 1999), thus counteracting any CO₂-induced decrease in evapotranspiration. Ozone has also been shown to counteract the growth-stimulating effects of CO₂ (Isebrands and others 2003). The combined effects of ozone and N (or either pollutant alone) results in lowered root production (Fenn and others 2003b), which is likely to increase drought stress as well. These examples illustrate the complexity involved in attempting to predict ecosystem responses to changes in multiple air pollution and climate change factors, particularly because the many interacting factors are expected to elicit dynamic patterns of ecosystem responses based on evolving atmospheric, environmental, and biological conditions.

Climate Change Scenarios for the Western United States

We base our discussion of future climate change scenarios on simulations from the two primary global climate models used by the National Assessment Synthesis

Team (NAST 2000) of the US Global Change Research Program: the Canadian Climate Centre (CGCM1) and the Hadley Centre, United Kingdom (HadCM2) global climate models. Hereafter, they will be referred to as the Canadian and the Hadley models. Projected warming in the United States in the 21st century is 2.9°C for the Hadley model and 5.0°C for the Canadian model. Recently, results of models and expert opinion seem to be reaching a consensus on estimates for increased global temperature at the end of the century when CO₂ concentrations are expected to double. Although, uncertainty remains high, projections are converging on a projected global warming of 3°C (Kerr 2004). Murphy and others (2004) reported a five to 95 percent probability range for a 2.4 to 5.4°C temperature increase with CO₂ doubling and a most probable warming of 3.2°C.

Average warming over the Pacific Northwest is projected to reach 1.7°C by the 2030s and 2.8°C by the 2050s (table 2). Winter temperatures may rise 4.5 to 6.0°C by the 2090s (NAST 2000). Precipitation is expected to increase in most areas of the Pacific Northwest, mainly in the winter, with little change or a decrease in summer. The projected result of wetter winters and drier summers is decreasing water availability, especially in the Hadley model. By the 2090s, precipitation is projected to increase from a few percent to 20 percent in the Hadley model and from 20 to 50 percent in the Canadian model (NAST 2001).

In the Southwest (California, Nevada, Arizona, New Mexico, Utah, and western Colorado), average temperature is projected to increase 2°C by the 2030s and 4.5 to 6°C by the 2090s (table 2). The models project increased precipitation in winter, especially over California where runoff is expected to double by the 2090s. In much of the Pacific Northwest and in California, the Mediterranean climate characterized by warm dry summers, already creates conditions of seasonal drought stress, making these ecosystems prone to periodic pest outbreaks and fire. These conditions may worsen with climate change. Some areas of the Rocky Mountains are projected to get drier, possibly resulting in loss of alpine meadows (NAST 2000), but both models project more extreme wet and dry years. Because of greater precipitation in winter, possibly more as rain, and because of greater runoff (less water storage) and more extreme dry years, increased drought stress must also be considered as a likely scenario, notwithstanding predictions of an overall increase in precipitation. Likely scenarios for the West indicate increases in forest cover in the West and that desert areas will decrease with a wetter climate, resulting in increased coverage by woody species (NAST 2000). Due to uncertainties about regional precipitation, projections also include the possibility of generally warmer and drier

Table 2. Projected climate change scenarios for the western United States^a.

Region	Temperature increase	Precipitation pattern	Ecosystem impacts
Pacific Northwest ^b	1.7°C by the 2030s; 2.8°C by the 2050s	Projections for the region range from a 7% decrease to a 13% increase; increases are mainly in winter while decreases or small increases are in summer	Decreasing water availability and presumably greater drought stress, particularly over the longer term as temperatures increase
Southwest ²	2.0°C by the 2030s; 4.5 to 6.0°C by the 2090s	Projected to be wetter and warmer; increased precipitation projected in winter, especially in California; runoff may double in California by the 2090s; some areas of the Rocky Mountains may get drier; more extreme wet and dry years; there is also a chance that climate may get drier over much of the West during the 21 st century	Likely increase in biomass; reduction in desert areas and increase in woodlands and forests; if climate becomes drier opposite responses are likely; fire frequency expected to increase in either scenario

^a Climate change scenarios are mainly based on the two primary global climate models used by the National Assessment Synthesis Team (NAST 2000, 2001) of the US Global Change Research Program; the Canadian Climate Centre (CGCM1) and the Hadley Centre, United Kingdom (HadCM2) global climate models.

^b Pacific Northwest as here defined, includes Washington, Oregon and Idaho. The Southwest includes the states of California, Arizona, Nevada, Utah, New Mexico, and western Colorado.

conditions in the West (NAST 2000, 2001). Simulated projections provide a consensus that fire severity and incidence in the West will increase whether precipitation increases or decreases in the region (McKenzie and others 2004; NAST 2001).

Predictions of Ecosystem Responses to Global Change

A consensus finding of the NAST report suggests that over the short term increased temperature, moisture, and CO₂ is expected to result in C gains in most forest ecosystems in the coterminous United States (Aber and others 2001; NAST 2000, 2001). However, this partially depends on whether the fertilization effect of CO₂ is sustained or whether downregulation or acclimation occurs after a period of increased CO₂. Many initial studies of plants cultivated in pots in exposure chambers indicated that CO₂ growth stimulation would be transitory. Long and others (2004) reviewed results from FACE experiments which suggest that the stimulatory growth response to CO₂ may not be transitory. Mickler and others (2003) also reviewed several field studies that suggest that the CO₂ response may be long lasting. However, this yet remains an open question. In a recent review, Beedlow and others (2004) concluded that increases in C sequestration by forests as a result of CO₂ fertilization are unlikely because of other limiting factors such as soil N, air pollution, and water availability. Projections of forest growth increases in the next few decades of climate change must

be tempered by the possibility or likelihood that increased drought stress may occur in some regions; a response that will counteract predictions of forest growth increase. Greater year to year variability in precipitation patterns are predicted, which suggests that severe drought years will also be more common. Furthermore, in a warmer climate, if more winter precipitation in montane regions of the West occurs as rain as opposed to snow, runoff will be more rapid, likely reducing soil water retention and further contributing to drought stress.

A complete analysis of forest ecosystem response to global change will, in many cases, require that ozone and N deposition also be included along with the other factors commonly considered in global change scenarios. Responses to N deposition and ozone can be on the same order as responses to climate change (Aber and others 2001), which further illustrates the importance of considering these global change factors when evaluating ecosystem responses to changing atmospheric conditions. To date, no rigorous evaluations have been done of the combined effects of the primary climate change and air pollution factors such as increased temperature and CO₂, N deposition and elevated ozone exposure, and changing precipitation patterns that may lead to greater drought stress. The effects of these interacting factors on disturbance factors such as changes in pest or pathogen outbreaks and fire frequency and severity also must be considered. Clearly these are complicated scenarios, and simulation modeling will be needed to address these myriad interactions and complexities. Combined biogeography-biogeochemistry models have been developed

(referred to as dynamic general vegetation models) to evaluate ecosystem response to the interacting effects of temperature, precipitation, and CO₂ (Aber and others 2001). However, ozone and N deposition effects are not included in these models. Ozone exposure can disrupt stomatal control (Grulke 1999), and has been shown to cancel out the growth-promoting effects of CO₂ (Isebrands and others 2003). Similarly, tree responses to global change factors may depend on whether N is deficient, or in sufficient or excess supply. These examples of ozone and N availability illustrate how the addition of an additional stress factor can completely change the net ecosystem effect of global climate change and demonstrate why all relevant factors must be considered as we seek to improve our capacity to predict future ecosystem effects of global change.

As reviewed by Aber and others (2001), interacting effects of various combinations of two or three of these factors (CO₂, O₃, precipitation, or temperature) have been simulated for representative eastern regions and interactive effects of increased CO₂ and ozone have been studied in FACE experiments (Percy and others 2002), but direct investigations of higher level interactions including the primary global climate change factors in combination with N deposition and ozone have not been reported. Because of the absence of model evaluations of ecosystem responses to these multiple stress factors associated with global climate change, in the following section of this paper we will make a preliminary attempt at predicting some of the possible Western forest responses to global change/air pollution by reviewing a case study in the San Bernardino Mountains in Southern California where many of these stress factors have impacted these forests to various degrees.

San Bernardino Mountains Case Study of Multiple Stress Impacts

The San Bernardino Mountains (SBM) case study in Southern California is the best empirical field study in the Western United States indicating forest ecosystem responses to major global change stress factors. Nitrogen deposition and ozone exposure have presumably been affecting the forest ecosystem in the SBM for at least the last 50 years. Ozone injury on ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), a major component of the mixed conifer forest in the SBM, was first reported in the early 1950s (Miller and others 1963, Parmeter and others 1962). Summer drought stress is a natural condition in this Mediterranean climate. Drought becomes

particularly severe when successive unusually dry years occur, such as is the case since 1999. Over the past 50 years CO₂ concentrations have also been increasing and global warming is also underway, but these gradual increases have not yet exerted the effects that are expected to occur in future decades. Nitrogen deposition has caused major changes in biogeochemical cycling, and in conjunction with ozone, has caused significant physiological perturbations in ponderosa pine and California black oak (*Quercus kelloggii* Newb.). Because ozone exposure and N deposition are both high in the more exposed areas of the SBM, it is sometimes difficult to separate the effects of these two pollutants.

In the Western SBM, the physiological functioning of ponderosa pine trees has been dramatically altered in ways that are believed to increase its sensitivity to the main ecosystem stressors common to this region – drought and insect outbreaks (Fenn and others 2003b). Fine root production in ponderosa pine is dramatically reduced as is the number of annual foliage whorls that are retained. At Camp Paivika, the westernmost site in the SBM, little more than one annual whorl of foliage is retained on average. In essence, the pine trees function as “deciduous conifers” (Grulke and Balduman 1999). As a result of ozone-induced premature needle fall and N-induced greater foliar growth, litter accumulates to a much greater degree in the highly polluted sites. Nitrogen enrichment of the litter also inhibits long term litter decomposition. Nitrogen and ozone also result in a greater shoot:root ratio, resulting in greater C storage in bole and branches (Fenn and Poth 2001). The net result is that as long as fires are suppressed, air pollution exposure enhances fuel accumulation as litter on the ground and more dense forest growth aboveground. The increased fuel accumulation is expected to increase the already high fire risk. Reduced root growth and denser aboveground growth is also expected to increase drought stress and susceptibility to pests, which eventually leads to tree mortality and increased fire risk.

Widespread tree mortality and wildfire became a vivid reality in the SBM in the fall of 2003, during which time hundreds of thousands of trees were affected by the most severe drought conditions in the SBM in recorded history. Hundreds of thousands of trees died from drought, bark beetle infestations, and rampant forest fires. However, unusually high tree mortality, bark beetle outbreaks, and fire losses occurred throughout the SBM regardless of the level of ozone exposure or N deposition. This illustrates the key point that when drought stress becomes overly severe and prolonged, this stressor overrides other factors, including air pollution impacts. However, ozone and N deposition have been shown to further predispose trees to bark beetle attack in the SBM (Pronos and others

1999, Jones and others 2004), and as hypothesized above, decades of physiological air pollution impacts appear to worsen drought stress effects. Over the years, tree mortality in the SBM has been attributed to a multiple stress syndrome in which some or all of the following factors contribute to mortality: drought, ozone injury, N deposition and bark beetles (Fenn and others 2003b; Jones and others 2004). As tree mortality spreads over an area, this in turn increases the risk of severe fire losses. Fire risk is already high in many western forests as a result of nearly a century of successful fire suppression efforts, reminding us that projections of global change impacts must be made within the context of land use history.

Conclusions

Projections of climate change effects on forests over the first several decades of this century generally indicate increased forest growth in the United States. Precipitation is expected to increase over most of the West, although years of extremely high or low precipitation are also projected to increase. However, if assumptions of the fertilization effect of increased CO₂ are incorrect or overestimated, projections of increased forest growth may be at least partially nullified. Furthermore, these projections do not include the effects of ozone and N deposition. Forest responses to climate change can be significantly modified in areas where these pollutants are elevated.

A high degree of uncertainty in projections of future forest responses to global change (here defined to include climate change and air pollution effects) is inevitable based on our current knowledge base and technological tools for evaluating these complex scenarios. Complexity is high because the effects of many interacting factors must be considered over large spatial and temporal scales. These interactions cannot be tested experimentally because all the requisite factors cannot be adequately manipulated or controlled, and because of the long time frame needed to observe patterns of forest ecosystem responses. Thus, simulation modeling approaches, bolstered by experimental data on the effects of single factors or various stressor combinations, are needed to evaluate future impacts.

Evaluation of effects will be simplified for areas not significantly affected by air pollution. For example, in the western U.S., air pollution impacts mainly occur in "hotspots" near or downwind of urban or agricultural emissions source areas, with relatively large areas of little apparent pollution effects. However, sensitive indicator organisms such as diatoms and lichens are affected over larger areas than previously expected, including areas

with N deposition loadings as low as 3 to 8 kg ha⁻¹ yr⁻¹ (Fenn and others 2003a). The extent of forested areas in the West affected by ozone and N deposition is expanding because of rapid urbanization and increasing emissions from urban and agricultural emissions sources. Many of these emissions sources are also encroaching further onto lands adjacent to forested areas. Some areas, such as the Central Valley of California, are becoming more of a regional air pollution problem that affects the adjacent montane ecosystems (in this case the Sierra Nevada range). Realistic simulation model scenarios of future ecosystem responses to global climate change will be needed that include scenarios of high and low levels of ozone and atmospheric N deposition.

Common knowledge and empirical field results suggest that under conditions of prolonged or severe drought, this stress factor will override other global change factors. Thus, future drought conditions will be a major driver of ecosystem condition. Drought is projected to increase in some parts of the West, such as the Pacific Northwest. In the Northwest and in California where summer drought is typical, drought can become more common or severe even with a long term trend of greater precipitation. This is particularly true if extreme wet and dry years increase in frequency and if more precipitation in montane regions occurs as rain, resulting in rapid runoff and lower water retention. Increases in drought conditions will also lead to greater pest outbreaks, severe stand mortality and increased fire severity.

References

- Aber, J.; Neilson, R.P.; McNulty, S.; Lenihan, J.M.; Bachelet, D.; Drapek, R.J. 2001. Forest processes and global environmental change: Predicting the effects of individual and multiple stressors. *BioSci.* 51: 735-751.
- Beedlow, P. A.; Tingey, D. T.; Phillips, D. L.; Hogsett, W. E.; Olszyk, D. M. 2004. Rising atmospheric CO₂ and carbon sequestration in forests. *Frontiers in Ecology and the Environment* 2: 315-322.
- Bytnerowicz, A.; Tausz, M.; Alonso, R.; Jones, D.; Johnson, R.; Grulke, N. 2002. Summer-time distribution of air pollutants in Sequoia National Park, California. *Environ. Pollut.* 118: 187-203.
- Fenn, M. E.; Baron, J. S.; Allen, E. B.; Rueth, H. M.; Nydick, K. R.; Geiser, L.; Bowman, W. D.; Sickman, J. O.; Meixner, T.; Johnson, D. W.; Neitlich, P. 2003a. Ecological effects of nitrogen deposition in the western United States. *BioScience* 53: 404-420.
- Fenn, M. E.; Poth, M. A.; Bytnerowicz, A.; Sickman, J. O.; Takemoto, B. K. 2003b. Effects of ozone, nitrogen deposition, and other stressors on montane ecosystems in the Sierra Nevada. In: Bytnerowicz, A.; Arbaugh, M. J.; Alonso, R., eds. *Developments in Environmental Science, volume 2: Ozone Air Pollution in the Sierra Nevada: Distribution and Effects on Forests*. Amsterdam: Elsevier: 111-155.

- Fenn, M. E.; Poth, M. A. 2001. A case study of nitrogen saturation in western U.S. forests. In: Galloway, J.; Cowling, E.; Erismann, J.W.; Wisniewski, J.; Jordan, C., eds. *Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection: Proceedings of the 2nd International Nitrogen Conference on Science and Policy*. A.A. Balkema Publishers, Lisse, The Netherlands, and TheScientific World, www.thescientificworld.com. DOI 10.1100/tsw.2001.280: 433-439.
- Fenn, M. E.; Poth, M. A. 2004. Monitoring nitrogen deposition in throughfall using ion exchange resin columns: A field test in the San Bernardino Mountains. *J. Environ. Qual.* 33: (In Press).
- Fowler, D.; Cape, J. N.; Coyle, M.; Flechard, C.; Kuylensstierna, J.; Hicks, K.; Derwent, D.; Johnson, C.; Stevenson, D. 1999. The global exposure of forests to air pollutants. *Water, Air and Soil Pollut.* 116: 5-32.
- Frączek, W.; Bytnerowicz, A.; Arbaugh, M. J. 2003. Use of geostatistics to estimate surface ozone patterns. In: Bytnerowicz, A.; Arbaugh, M. J.; Alonso, R., eds. *Developments in Environmental Science, volume 2: Ozone Air Pollution in the Sierra Nevada: Distribution and Effects on Forests*. Amsterdam: Elsevier: 215-247.
- Grulke, N. E. 1999. Physiological responses of ponderosa pine to gradients of environmental stressors. In: Miller, P. R.; McBride, J. R., eds. *Oxidant Air Pollution Impacts in the Montane Forests of Southern California: A Case Study of the San Bernardino Mountains*, *Ecol. Stud.* 134. New York: Springer-Verlag: 126-163.
- Grulke, N. E.; Balduman, L. 1999. Deciduous conifers: High N deposition and O₃ exposure effects on growth and biomass allocation in ponderosa pine. *Water, Air and Soil Pollut.* 116: 235-248.
- Isebrands, J. G.; McDonald, E. P.; Kruger, E.; Hendrey, G. R.; Percy, K. E.; Pregitzer, K. S.; Sober, J.; Karnosky, D. F. 2003. Growth responses of aspen clones to elevated carbon dioxide and ozone. In: Karnosky, D. F.; Percy, K. E.; Chappelka, A. H.; Simpson, C.; Pikkariainen, J., eds. *Developments in Environmental Science, volume 3: Air Pollution, Global Change and Forests in the New Millenium*. Amsterdam: Elsevier: 411-435.
- Jones, M. E.; Paine, T. D.; Fenn, M. E.; Poth, M. A. 2004. Influence of ozone and nitrogen deposition on bark beetle activity under drought conditions. *For. Ecol. Manage.* (In Press).
- Kerr, R. A. 2004. Three degrees of consensus. *Science* 305: 932-934.
- Long, S. P.; Ainsworth, E. A.; Rogers, A.; Ort, D. R. 2004. Rising atmospheric carbon dioxide: Plants FACE the future. *Annu. Rev. Plant Biol.* 55: 591-628.
- McKenzie, D.; Gedalof, Z.; Peterson, D. L.; Mote, P. 2004. Climatic change, wildfire, and conservation. *Conserv. Biol.* 18: 890-902.
- Mickler, R. A.; McNulty, S. G.; Birdsey, R. A.; Hom, J. 2003. Responses of forests in the eastern US to air pollution and climate change. In: Karnosky, D. F.; Percy, K. E.; Chappelka, A. H.; Simpson, C.; Pikkariainen, J., eds. *Developments in Environmental Science, volume 3: Air Pollution, Global Change and Forests in the New Millenium*. Amsterdam: Elsevier: 345-358.
- Miller, P. R.; Parmeter, J. R., Jr.; Taylor, O. C.; Cardiff, E. A. 1963. Ozone injury to the foliage of *Pinus ponderosa*. *Phytopath.* 53: 1072-1076.
- Murphy, J. M.; Sexton, D. M. H.; Barnett, D. N.; Jones, G. S.; Webb, M. J.; Collins, M. 2004. Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature* 430: 768-772.
- NAST (National Assessment Synthesis Team). 2001. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, Report for the US Global Change Research Program; Washington DC. Cambridge, UK: Cambridge University Press. 620 p.
- NAST (National Assessment Synthesis Team). 2000. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, Overview Report. US Global Change Research Program; Washington DC. Cambridge, UK: Cambridge University Press. 154 p.
- Parmeter, J. R., Jr.; Bega, R. V.; Neff, T. 1962. A chlorotic decline of ponderosa pine in southern California. *Plant Dis. Rptr.* 46: 269-273.
- Percy, K. E.; Awmack, C. S.; Lindroth, R.L.; and others. 2002. Altered performance of forest pests under atmospheres enriched by CO₂ and O₃. *Nature* 420: 403-407.
- Piechota, T.; Timilsena, J.; Tootle, G.; Hidalgo, H. 2004. The western U.S. drought: How bad is it? *EOS, Transactions* 85: 301, 304.
- Pronos, J.; Merrill, L.; Dahlsten, D. 1999. Insects and pathogens in a pollution-stressed forest. In: Miller, P. R.; McBride, J. R., eds. *Oxidant Air Pollution Impacts in the Montane Forests of Southern California: A Case Study of the San Bernardino Mountains*, *Ecol. Stud.* 134. New York: Springer-Verlag: 317-337.
- Westerling, A. L.; Cayan, D. R.; Brown, T. J.; Hall, B. L.; Riddle, L. G. 2004. Climate, Santa Ana winds and autumn wildfires in southern California. *EOS, Transactions* 85: 289, 296.