

REMEASURED FIA PLOTS REVEAL TREE-LEVEL DIAMETER GROWTH AND TREE MORTALITY IMPACTS OF NITROGEN DEPOSITION ON CALIFORNIA'S FORESTS

Mark E. Fenn, Jeremy S. Fried, Haiganoush K. Preisler, Andrzej Bytnerowicz, Susan Schilling, Sarah Jovan, and Olaf Kuegler¹

Abstract—The air in California's forests spans a broad range of purity, from virtually no locally generated pollutants to highly elevated levels of pollutants in forests downwind of urban and agricultural source areas. Ten-year remeasurement data from Forest Inventory and Analysis (FIA) plots in California were used in combination with modelled atmospheric nitrogen (N) deposition to evaluate tree diameter growth and mortality responses across the state. After controlling for tree size, site productivity, climate attributes, stand density, and competition experienced by each tallied tree, we found significant N deposition effects on tree bole growth when N deposition exceeded a threshold of approximately 15 kg/ha/yr. Increased tree mortality for all 14 species combined appears to increase when N deposition exceeds 10 kg/ha/yr, although the confidence intervals on the response curve are large. Preliminary analyses suggest ozone modifies the growth response, particularly at lower N deposition levels.

Long term N deposition and ambient ozone are the two major pollutants impacting forests in California, USA. Little is known of the dose-response relationships for tree growth and mortality to the combined exposure to these two pollutants in the Mediterranean climate of California. In contrast to the spatially extensive field survey on which this study is based, controlled experiments with N generally involve N fertilization additions which cannot replicate the chronic atmospheric inputs of N to forest canopies as deposition in dry (gaseous and particulate), cloud-water, and wet forms. Likewise, many ozone studies are based on fumigation chamber experiments with seedlings or saplings or Free-Air Controlled Exposure studies using a limited number of tree species. We present a preliminary analysis of tree basal area

growth and mortality in response to these pollutants for 14 major tree species, most of them widely distributed across California, using data from the US Forest Service, Forest Inventory and Analysis (FIA) program.

METHODS

A statewide growth, removals, and mortality dataset containing ten-year remeasurement data from 1706 FIA plots (33,091 trees) in California forests provided the basis for evaluating the growth and mortality implications of atmospheric nitrogen deposition and ozone exposure for 14 tree species commonly encountered in California's forests. Nitrogen deposition ranges were limited for individual tree species so we analyzed N deposition effects for two broad species groups---conifers and hardwoods. We relied on measurements in the FIA dataset of trees, greater than 12.7 cm diameter breast height (d.b.h.) at the initial visit, conducted between 1/16/2001 and 10/26/2004 (Time 1) and that were remeasured approximately 10 years later, between 4/6/2011 – 11/12/2013 (Time 2). Relative basal area increment (BAI_{rel}) was calculated as the mean annual change in tree basal area between time 1 and time 2, scaled by the basal area at time 1:

¹ Research Plant Pathologist (MEF), PSW Research Station, USDA Forest Service, 4955 Canyon Crest Dr, Riverside, CA 92507; Research Forester (JSF), PNW Research Station, USDA Forest Service; Statistical Scientist (HKP), PSW Research Station, USDA Forest Service; Senior Scientist (AB), PSW Research Station, USDA Forest Service; IT Specialist (SS), PSW Research Station, USDA Forest Service; Research Ecologist (SJ), PNW Research Station, USDA Forest Service; Mathematical Statistician (OK), PNW Research Station, USDA Forest Service. MEF is corresponding author: to contact, call (951) 680-1565 or e-mail at mfenn@fs.fed.us.

$$Y = \text{BAI}_{\text{rel}} = 100 * (\text{BA2} - \text{BA1}) / (\text{BA1} \times \text{Dt})$$

Where BA1 and BA2 are, respectively, tree basal area at time 1 and 2, and Dt is the remeasurement interval in years.

In order to estimate effects of various factors on BAI_{rel} we used the following Generalized Additive Model (GAM) with a multiplicative log-normal error term:
 $Y = \text{Site effect} \times \text{Tree effect} \times \text{Climate} \times \text{Nitrogen} \times \text{error}$

Variables [and variable type] included in these model terms are as follows:

Site Effect:

- Crown ratio (cr1 and cr2), [continuous]
- mean annual increment (derived from site index), [continuous]
- basal area of trees larger than the subject tree, [continuous]
- BurnCode, (5 levels of effect of fire during the remeasurement interval on stand basal area) [categorical]
- Harvest, (5 levels of effect of harvest during the remeasurement interval on stand basal area) [categorical]
- Other disturbance, insect, disease [categorical]

Tree Effect:

- Diameter at time 1 [continuous]; tree species [categorical]

Climate Effect:

- Mean annual temperature & precipitation [continuous]
- moisture deficit [continuous]
- frost-free days [continuous]

Nitrogen:

- Total N based on the EPA CMAQ model with output adjusted based on throughfall N deposition data (Fig. 1; Fenn et al. 2010) [continuous].

Tree mortality response was evaluated with a logistic model. We have plans to more fully utilize two-week average ozone concentration data from passive sampler networks after developing a more biologically relevant ozone exposure index from the data. As

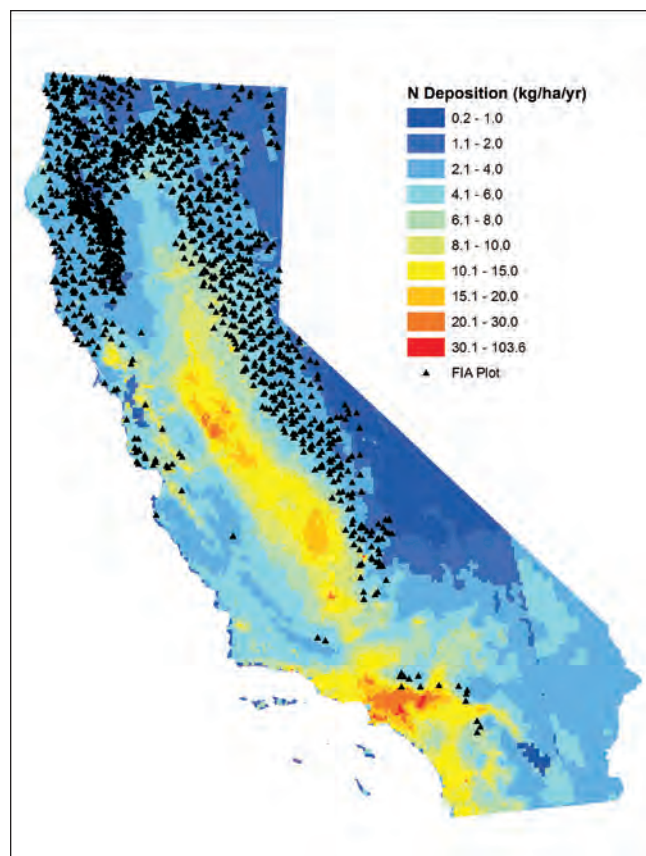


Figure 1—Modeled, annual N Deposition in California and locations of FIA plots used to estimate N deposition effects on tree growth.

supportive information, soil C and N data from the FIA P3 plots were also used to evaluate relationships between N deposition and N fertility of the soils in the P3 plots.

RESULTS

Above an N deposition threshold of ca. 15 kg/hr/yr, tree diameter growth appears to increase in response to increasing atmospheric N deposition. This is true for conifers and hardwoods, although we were not able to test the growth or mortality responses of individual species. In a model with no species effect other than diameter, growth also increased with increasing N deposition (Fig. 2). When a model with two species categories (conifer and hardwood) was employed, growth for the conifer species increased above N deposition of ca. 15 kg/ha/yr (Fig. 3a). However, at N deposition rates below this threshold, a bimodal response was evident, with potentially reduced growth

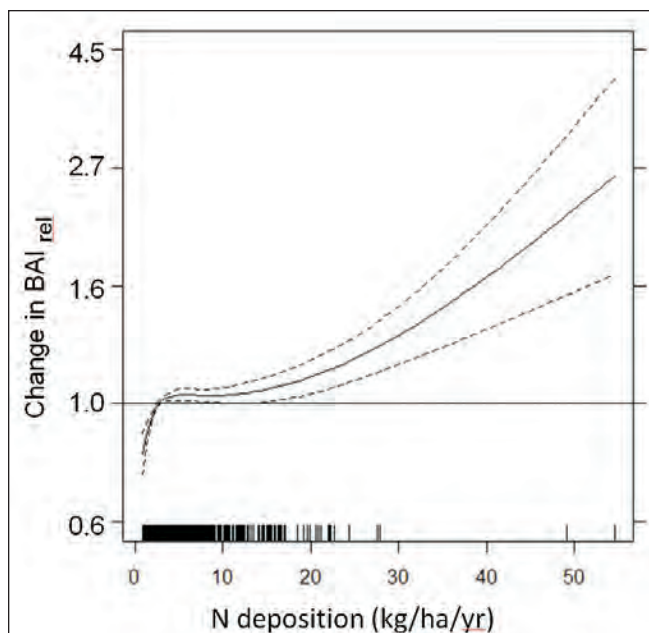


Figure 2—Estimated effect of total N deposition on relative basal area increment (BAI_{rel}) relative to BAI_{rel} at average N deposition, over full range of N deposition, for all 14 species combined. Values on the y-axis represent multiplicative change in BAI_{rel} relative to BAI_{rel} at average Ndep, which is ca. 4 kg/ha/yr. Dashed lines are 95 percent confidence bounds.

at low N deposition, followed by an increase over the range of 3-9 kg/ha/yr, and then another reduction, over the range 9-15, before steadily increasing at N deposition values greater than 15 kg/ha/yr. Similarly, with the lumped hardwood species, growth appears to decrease as N deposition goes from 1-10 kg/ha/yr, before increasing (Fig. 3b).

Tree mortality did not increase in response to N deposition until a threshold of ca. 10 kg/ha/yr at which point it steadily increased (Fig. 4). The probability of a tree dying over the ten-year period increased from 11 percent at the average level of N deposition (4.3 kg N/ha/yr) to 14 percent at 20 kg/ha/yr and 17 percent at 28 kg N/ha/yr.

Evidence of soil enrichment with N was seen in data on C:N ratios of the forest floor and mineral soil horizons (0-10 and 10-20 cm depths). Correlation coefficients were low (0.06 – 0.09) because of scatter in the data at the many sites where N deposition was

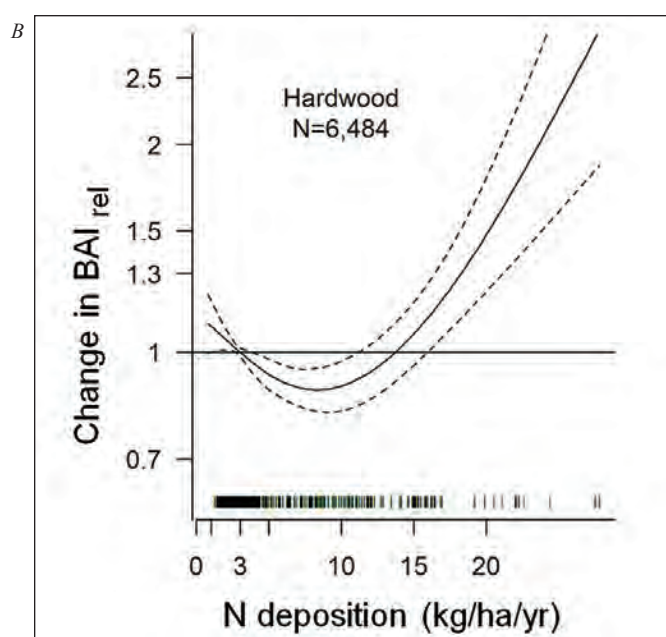
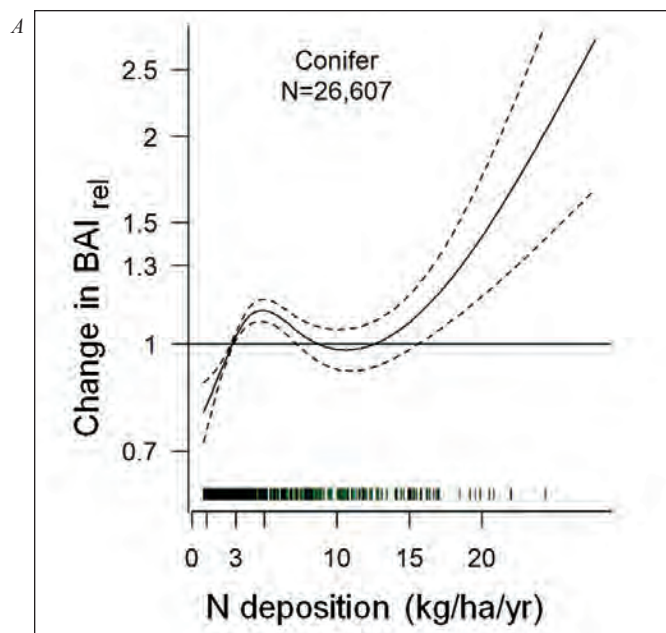


Figure 3—Estimated effect of total N deposition on relative basal area increment (BAI_{rel}) relative to BAI_{rel} at average N deposition, for a) conifers, and b) hardwoods, excluding the few plots where modeled N deposition exceeds 40.

low. C:N in the forest floor decreased from 45 to 25 as N deposition increased from 1 to 35 kg/ha/yr (data not shown). Over the same range of N deposition, C:N in mineral soil decreased from 24 to 10 and from 22 to 10 in the top two layers of the mineral soil.

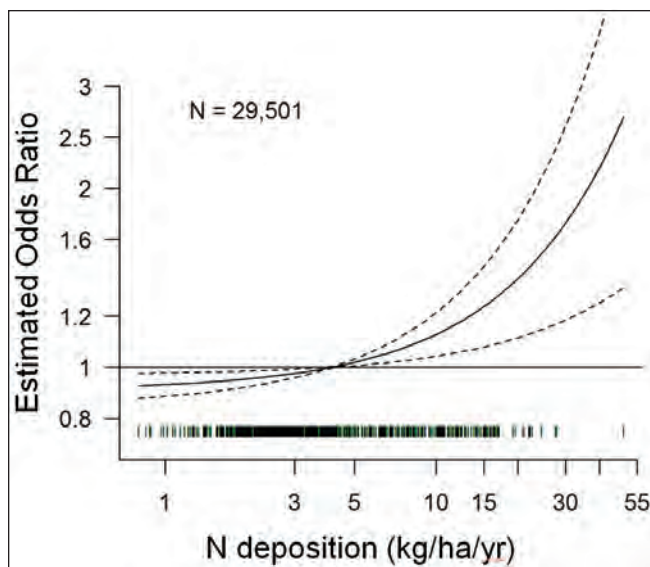


Figure 4—Estimated effect of total N deposition on tree mortality (odds relative to the odds at the average value of N deposition), for all 14 species combined.

DISCUSSION

Many studies have shown increased forest growth with increasing N deposition. In Italy, diameter growth increased steadily as N deposition levels increased beyond the lowest level of ca. 7 kg N/ha/yr (Ferretti et al. 2014). While it isn't entirely clear why we did not see an increase in growth until N deposition exceeded 15 kg/ha/yr, preliminary analyses suggest exposure to ozone may be muting the N deposition response at low N deposition in California. Above 15 kg N/ha/yr, we found consistent growth increases whether hardwoods and conifers were considered separately, or together. This does not mean that the growth response of every species will be positive, given that species responses to N deposition can differ greatly (Thomas et al. 2010).

Although tree growth appears to increase with N deposition, tree mortality also showed an increase with a threshold of ca. 10 kg/ha/yr. Future analysis plans include estimating effects of N deposition on stand level C increment and consideration of more biologically relevant ozone exposure indices (e.g., W126) and possible responses to N dep. of pests and diseases.

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