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Assessing relationships between red spruce radial growth and pollution critical load exceedance values

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ABSTRACT

Acidic sulfur (S) and nitrogen (N) deposition depletes cations such as calcium (Ca) from forest soils and has been linked to increases in foliar winter injury that led to the decline of red spruce (*Picea rubens* Sarg.) in the northeastern United States. We used results from a 30 m resolution steady-state S and N critical load exceedance model for New England to better understand the spatial connections between Ca depletion and red spruce productivity. Atmospheric deposition and other inputs were estimated for a 5-year period (1984–1988) in order to smooth year-to-year variations in climate and patterns of atmospheric transport. Deposition levels prior to the reductions that followed the 1990 Amendments to the Clean Air Act were used because tree health and productivity declines were expected to be most responsive to high acid loading. We examined how radial growth (basal area increment) of 441 dominant and co-dominant red spruce trees from 37 sites across Vermont and New Hampshire was related to modeled estimates of S and N critical load exceedance. We assessed growth using statistical models with exceedance as a source of variation, but which also included "year" and "elevation class" (to help account for climatic variability) and interactions among factors. As expected, yearly climate-related sources of variation accounted for most of the differences in growth. However, exceedance was significantly and negatively associated with mean growth for the study period (1951–2010) overall, and particularly for the 1980s and 2000s – periods of numerous and/or severe foliar winter injury events. Because high winter injury reflects the convergence of predisposing (cation depletion) and inciting (weather) factors, exceedance alone appears insufficient to define associated patterns of growth reduction. Significant interactions indicated that exceedance had little influence on growth at low elevations (where intrinsic conditions for growth were generally good) or high elevations (where growth was uniformly poor), whereas exceedance was significantly associated with reduced growth at mid elevations over long periods of time. Exceedance was also linked to reduced growth rebounds following a region-wide foliar winter injury event in 2003. Overall, our analyses suggest that modeled S and N critical load exceedance can help account for red spruce growth and rebound from injury in the field. Interestingly, recent growth for red spruce is above average for the 20th to 21st century dendrochronological record – indicating that the factors shaping growth may be changing. The influence of reduced pollution inputs on this recent growth surge is under investigation.

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1. Introduction

Anthropogenic processes, primarily pollutant additions of sulfur (S) and nitrogen (N) compounds that form acid deposition, disrupt nutrient cycles and lead to the leaching loss and depletion of base cations from eastern United States (US) forests (Driscoll et al., 2001). Although cation depletion can have numerous important effects on ecosystem function, calcium (Ca) loss, in particular, poses a unique threat to forest ecosystem health (Schaberg et al., 2001). Ca is highly vulnerable to leaching loss (DeHayes et al., 1999), and is a component of biochemical pathways that regulate carbon (C) metabolism and allow plants to sense and respond to environmental stress (Marschner, 2002). Particularly when the

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latter role of Ca is compromised, it can leave trees more vulnerable to inadequate stress response following exposure to a range of abiotic and biotic stressors (Schaberg et al., 2010). Although acidic deposition inputs have decreased significantly since their regional peaks in the 1960s and 1970s (Driscoll et al., 2001; Lawrence et al., 2012), the net leaching of base cations remains an ongoing problem (Talhelm et al., 2012; Greaver et al., 2012).

The mechanism whereby acid deposition-induced Ca depletion alters the stress physiology of red spruce (*Picea rubens* Sarg.) and predisposes trees to decline is particularly well-established (e.g., DeHayes et al., 1999; Hawley et al., 2006; Halman et al., 2008; Schaberg et al., 2011a). Red spruce foliage is barely cold tolerant enough to escape freezing injury under ambient winter temperatures, and this limited cold tolerance is further reduced by acid-induced Ca depletion (DeHayes et al., 1999). As a consequence, exposure to acid deposition increases the likelihood of winter injury and foliar losses that instigate growth declines and tree mortality (Schaberg and DeHayes, 2000).

Numerous studies have provided evidence that Ca depletion has been detrimental to the health and productivity of multiple tree species (e.g., Hawley et al., 2006; Huggett et al., 2007; Halman et al., 2011; Battles et al., 2014). However, the current patchwork of localized studies has been insufficient to define the broader threat posed by Ca depletion across the landscape. One solution to providing a more broadly applicable and spatially explicit estimate of the vulnerability of sites to acid deposition-induced Ca depletion is through the use of critical load exceedance models and associated maps. The critical load with respect to S- and N-induced Ca leaching, is a quantitative estimate of the amount of pollution deposition below which there is no harmful effect (e.g., net Ca leaching loss; Schaberg et al., 2010). When a site's threshold for pollution loading (critical load) is subtracted from the estimated amount of incoming dry and wet acidic deposition at that site, the exceedance of the critical load is determined. Sites with positive exceedance values are predicted to become vulnerable to pollution-induced reductions in health and productivity as Ca reserves are depleted over time. Past work has shown that tree growth is sensitive to soil pH and Ca levels and postulated that Ca losses due to acid deposition in exceedance of critical loads would increase the incidence of tree decline (e.g., Ouimet et al., 2001; Watmough, 2002).

One pollution critical load exceedance model grew out of the Conference of New England Governors and Eastern Canadian Premiers Forest Mapping Group (NEG/ECP, 2001). The NEG/ECP S and N steady-state critical load model estimates the various inputs and outputs that influence cation cycling at a particular site to determine nutrient levels and cycling that are the basis for critical load estimates (NEG/ECP, 2001). For each point on the landscape, this model integrates various site factors that influence cation cycling (e.g., forest type, climate, hydrology, soil mineral weathering, etc.) to produce a critical load estimate that is subtracted from modeled pollution inputs to generate the projected exceedance (an estimate of whether or not pollutant inputs lead to net cation depletion). Preliminary field tests of the NEG/ECP model have shown promise (Schaberg et al., 2010). While some previous studies have tested other regional critical load exceedance models with plot-based growth data, interest in doing so has grown in recent years. Ouimet et al. (2001), using a similar critical load exceedance model developed for Quebec, Canada, found significantly lower growth at both hardwood and conifer sites that were in exceedance compared to non-exceedance sites. Duarte et al. (2013) developed critical load exceedance estimates for over 4000 plots in the northeastern US. They found significant negative correlations between exceedance and growth for many tree species, but data were limited to the mid-1990s so that long-term trends, including periods after known stress events, were not evaluated.

Although prior field-testing of the NEG/ECP model has involved multiple tree species at a more limited geographic scale, red spruce serves as an ideal test species for broader regional analysis because of its known sensitivity to Ca depletion. Furthermore, in comparison to various measurements that reflect health and productivity conditions for a limited date/duration, the examination of xylem increment cores provide a high resolution record of woody growth over the life of the tree, supplying a unique and powerful tool for evaluating the impacts of Ca depletion over long time periods, including before, during and after peaks of acidic loading and other stress events.

In this study, we examined if spatially explicit, steady-state critical load exceedance estimates were associated with long-term reductions in red spruce growth and an altered rebound in growth following a severe winter injury event. We hypothesized that critical load exceedance would be associated with reduced growth overall and a more muted growth rebound following winter injury. We further hypothesized that the influence of critical load exceedance could vary over time and space as deposition patterns change. This evaluation is unique in its fine geographic scale (critical load exceedance modeled at a 30 m $\times$ 30 m resolution), which was assessed across a geologically and topographically complex landscape (37 plots throughout Vermont [VT] and New Hampshire [NH]), and analyzed over a long temporal scale (growth over 60 years). The results of this research provide insight into long-term trends in red spruce growth, including rebounds following a major stress event, and illuminate the potential for exceedance mapping to help account for tree health and productivity at a fine geographic scale in complex terrain. Although this work focused on red spruce in the northeastern US, the approach should, at a minimum, also be appropriate for evaluating other sensitive tree species (e.g., sugar maple – *Acer saccharum* Marsh.; Schaberg et al., 2001) in regions that have experienced high pollutant loading.

2. Materials and methods

2.1. Critical load and exceedance estimates

The NEG/ECP steady-state model (NEG/ECP, 2001; Schaberg et al., 2010) provides 30 m $\times$ 30 m estimates of critical load (Fig. 1a) and exceedance (Fig. 1b), the latter of which we evaluated relative to red spruce xylem radial growth. Exceedance estimates ranged from -4 to +4 keq ha^{-1} y^{-1} for the broader region. Within the NEG/ECP model, a steady-state ecosystem process model was coupled to extensive spatial databases to create maps with quantitative representations of the degree of potential Ca depletion (NEG/ECP, 2001). The model incorporates many factors that influence critical load including forest type, timber extraction intensity, prior land-use, atmospheric deposition rates, and site factors including climate, hydrology, and soil mineral weathering rates (NEG/ECP, 2001). Extensive field and modeling work was required to develop the spatial data layers needed to apply this model to New England. Weathering, one of the most important determinants of critical load, was estimated through bedrock composition, glacial redistribution of material and additional specific landscape information (e.g., precipitation, mean annual temperature). Direct cation loss through timber harvest was estimated based on harvesting records averaged by county and by ownership type (public vs. private) from combinations of state and federal sources. Atmospheric deposition of S, N (nitrate and ammonium), chloride (Cl), Ca, magnesium (Mg), sodium (Na), and potassium (K) were estimated for a 5-year period (1984–1988) in order to provide smoothing of year-to-year variations in climate and patterns of atmospheric transport. While the NEG/ECP model provides exceedance products based on two different time periods (1984–1988 and 1999–2003),