Forest Ecology and Management 327 (2014) 178–188

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Three-year growth response of young Douglas-fir to nitrogen, calcium, phosphorus, and blended fertilizers in Oregon and Washington

Douglas B. Mainwaring [a,*], Douglas A. Maguire [a], Steven S. Perakis [b]

[a] Department of Forest Engineering, Resources & Management, Oregon State University, Corvallis, OR 97331, United States
[b] US Geological Survey, Forest and Rangeland Ecosystem Science Center, Corvallis, OR 97331, United States

ARTICLE INFO

Article history:
Received 13 February 2014
Received in revised form 2 May 2014
Accepted 3 May 2014

Keywords:
Douglas-fir
Fertilization
Liming
Swiss needle cast

ABSTRACT

Studies of nutrient limitation in Douglas-fir forests of the Pacific Northwest focus predominantly on nitrogen, yet many stands demonstrate negligible or even negative growth response to nitrogen fertilization. To understand what nutrients other than nitrogen may limit forest productivity in this region, we tested six fertilizer treatments for their ability to increase stem volume growth response of dominant and co-dominant trees in young Douglas-fir plantations across a range of foliar and soil chemistry in western Oregon and Washington. We evaluated responses to single applications of urea, lime, calcium chloride, or monosodium phosphate at 16 sites, and to two site-specific nutrients blends at 12 of these sites. Across sites, the average stem volume growth increased marginally with urea, lime, and phosphorus fertilization. Fertilization responses generally aligned with plant and soil indicators of nutrient limitation. Response to nitrogen addition was greatest on soils with low total nitrogen and high exchangeable calcium concentrations. Responses to lime and calcium chloride additions were greatest at sites with low foliar calcium and low soil pH. Response to phosphorus addition was greatest on sites with low foliar phosphorus and high soil pH. Blended fertilizers yielded only marginal growth increases at one site, with no consistent effect across sites. Overall, our results highlight that calcium and phosphorus can be important growth limiting nutrients on specific sites in nitrogen-rich Douglas-fir forests of the Pacific Northwest.

1. Introduction

Nitrogen (N) is widely considered to be the most common growth limiting nutrient in terrestrial ecosystems worldwide, particularly in temperate forests (LeBauer and Treseder, 2008). In the Pacific Northwest, USA, field experiments in both natural and planted second growth forests demonstrate widespread N limitation of growth in Douglas-fir, the most abundant and commercially important conifer in the region (Miller and Pienaar, 1973; Peterson et al., 1984; Stegemoeller and Chappell, 1990). Consequently, N fertilization is widespread in commercial forests of the region, with nearly 40,000 ha of timberland fertilized annually in Oregon through the 1990s (http://www.oregon.gov/ODF/STATE_FORESTS/FRP/annual_reports.shtml). The magnitude of Douglas-fir growth response to N fertilization can depend on a number of factors, such as intrinsic site productivity (Edmonds and Hsiang, 1987; Miller et al., 1989), site N availability (Hopmans and Chappell, 1994; Peterson et al., 1984), degree of crown closure (Barclay and Brix, 1985), and the combination of crown size and foliar density (Brix and Ebell, 1969; Brix, 1983).

Douglas-fir response to N fertilization varies regionally across the Pacific Northwest, and in some cases, such as the coastal forest province, up to one-third of stands can show negligible and even negative growth responses to N fertilization (Peterson and Hazard, 1990). Some of these forest stands nevertheless continue to receive N fertilization due to a lack of methodology for identifying specific stands that are responsive to N and other nutrient(s) that may limit forest growth. In addition, historically the economic returns of fertilizing N-limited forests generally outweighed costs of occasionally fertilizing non-responsive stands. Improved nutrient management thus has the potential to increase the cost efficiency of fertilization for timber production, particularly as fertilization costs have risen. Improved N management can also reduce undesirable foliar nutrient imbalances (Mohren et al., 1986), pest and pathogen outbreaks (Turner and Lambert, 1986), soil fluxes of nitrous oxide and methane greenhouse gases (Castro et al., 1994) and nitrate leaching to waterways (Bisson et al., 1992), while improving soil carbon stabilization and storage (Swanston et al., 2004). Interactions between excess N and reduced

* Corresponding author. Tel.: +1 541 737 8107.
E-mail address: doug.mainwaring@oregonstate.edu (D.B. Mainwaring).

http://dx.doi.org/10.1016/j.foreco.2014.05.005
0378-1127/

growth due to pathogen susceptibility may be particularly important in coastal Douglas-fir forests. The endemic foliar fungal pathogen *Phaeocryptopus gaeumannii* (i.e., Swiss needle cast, or SNC) that is associated with excess foliar N in Douglas-fir (El-Hajj et al., 2004) has caused an estimated growth loss of 400,000 m^3 annually in 10–30 year old plantations in north coastal Oregon (Maguire et al., 2011).

Forest soils of the Pacific Northwest coastal region are among the most N-rich worldwide due to long-term disturbance cycles that promote early-successional biological N_2-fixation and soil N accretion by red alder (Perakis et al., 2011). Where such N-rich soils are planted to Douglas-fir, rates of soil available N supply can exceed plant N demands (Perakis and Sinkhorn, 2011), suggesting that other nutritional factors may limit Douglas-fir growth. Biogeochemical theory predicts that as N accumulates and geological parent materials weather, phosphorus (P) can be depleted from available forms and limit plant growth (Walker and Syers, 1976; Vitousek, 2004). Indeed, P is thought to be co-limiting with N in many ecosystems worldwide (Elser et al., 2007); in the Pacific Northwest, additions of P can improve growth of Douglas-fir seedlings when P is added alone (Heilman and Ekuan, 1980; Porada, 1987) and of young trees when added in combination with N (Gessel et al., 1979). High soil N that promotes nitrification and nitrate leaching in Douglas-fir forests also decreases soil pH (Perakis and Sinkhorn, 2011), which may reduce soil P availability by enhancing sorption onto iron-oxides (Haynes, 1982). Finally, high soil aluminum (Al) associated with andic soil properties in the region (Meurisse, 1976) may further decrease soil P availability (Johnson et al., 1986).

High N availability in soils may also lead more directly to the depletion of available base cations such as calcium (Ca) and magnesium (Mg) due to elevated nitrification, soil acidification, and coupled nitrate and base cation leaching loss (Aber et al., 1989; Perakis et al., 2013). In naturally N-rich Douglas-fir forests of the Oregon Coast Range, Ca is more likely than Mg to be deficient, as indicated by nutrient availability patterns in plants and soils, and contrasting patterns of Ca and Mg supply in atmospheric deposition relative to plant nutrient demands (Perakis et al., 2006). High nitrification and base cation depletion that lower soil pH also increase the solubility of potentially toxic elements such as Al and manganese (Mn) in these soils (Perakis et al., 2013). These processes may make it difficult to discern between base cation deficiency versus metal toxicity as factors limiting tree growth (Rengel, 1992; Cronan et al., 1989; Shortle and Smith, 1988). Studies on young Douglas-fir seedlings have shown that, under conditions of high Al concentration in the growing media, addition of Ca resulted in both increases in root development and root Ca concentration (Ryan et al., 1986; Porada, 1987). High Al also affects Douglas-fir root morphology (Curt et al., 2001) and inhibits Ca, P, Mg, Fe, and Zn uptake. Field experiments that manipulate Ca availability independent of pH are needed to discern effects of low Ca from elevated Al in high N soils.

We here report initial results of the "Beyond N" (BN) field experiments intended to advance our understanding of nutrients that may limit Douglas-fir growth on high-N forest soils of the Pacific Northwest. We focused our growth response measurements on tree stem volume growth which is of interest to commercial forestry in the region, and compared this to foliar and soil chemical factors to elucidate the nutritional deficiencies underlying the observed stem growth responses. We used novel fertilization compounds for this work, because forest fertilization experiments typically add nutrients in widely-available commercial formulations that can add other potentially growth limiting nutrients and/or alter soil pH in ways that confound hypothesized nutrient limitation patterns (e.g., Barron et al., 2009). We added P as monosodium phosphate, to minimize potentially confounding results stemming from application of P with N (i.e., as mono- and di-ammonium phosphate) or with Ca (i.e., triple super phosphate), a challenge commonly encountered when interpreting results of most operational fertilizer trials. Furthermore, sodium is the most abundant cation in precipitation in this coastal region, so the amount added in monosodium phosphate should be inconsequential. We added Ca separately as the neutral salt $CaCl_2$ and also as $CaCO_3$ (i.e., lime) to discern between potential effects of Ca as a nutrient versus an inducer of a pH shift, and because chloride is the most abundant anion in precipitation in this region. Finally, we also added nutrients in the form of two nutrient-blends formulated to address site-specific nutrient conditions, as assessed by soil chemistry in the first approach and by foliar chemistry in the second, and to provide information on full growth potential when nutrient limitation was relaxed. The specific objectives of this analysis were to determine if: (1) stem volume growth responds to any of six nutrient amendments designed to ameliorate possible nutrient limitations in Douglas-fir and (2) stem volume growth response can be predicted from initial soil and/or foliar chemistry.

2. Methods

2.1. Study sites

Sixteen study sites were distributed across a range in elevation, aspect, and needle retention classes in the Oregon and Washington Coast Ranges and west slope of the Cascade Mountains (43.28–46.60°N and 122.05–124.25°W; Fig. 1). Target stands were mid-rotation (av. = 19.1 years of age) Douglas-fir plantations of operational density (av. = 800 trees ha^{-1}) that had received no previous thinning or fertilization within the previous 10 years (Table 1).

Because identifying Douglas-fir stands that will respond to N fertilization has traditionally been very difficult (e.g.,Peterson and Hazard, 1990), the scope of inference was best described as the population of young Douglas-fir plantations that had not been previously fertilized. However, the wide range in initial foliar chemistry (Table 1), soil chemistry (Tables 2 and 3), soil taxonomic

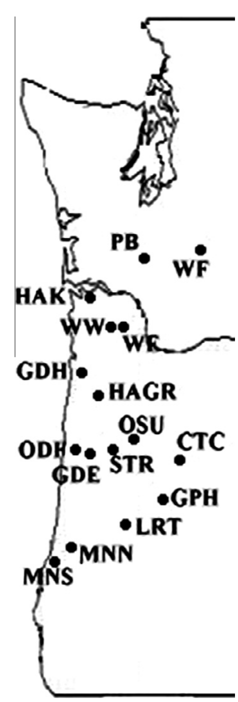

Fig. 1. Locations of the 16 "Beyond N" fertilizer trials in Oregon and Washington.