Forest Ecology and Management 345 (2015) 39–49

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Effects of fertilization and liming on tree growth, vitality and nutrient status in boreal balsam fir stands

Rock Ouimet *, Jean-David Moore

Ministère des Forêts, de la Faune et des Parcs du Québec, Direction de la recherche forestière, 2700 rue Einstein, Québec, QC G1P 3W8, Canada

ARTICLE INFO

Article history:
Received 2 December 2014
Received in revised form 16 February 2015
Accepted 19 February 2015
Available online 6 March 2015

Keywords:
Balsam fir
Fertilization
Liming
Boreal forest
Potassium

ABSTRACT

Two fertilization trials were carried out in young balsam fir (*Abies balsamea* (L.) Mill.) stands showing symptoms of tree decline or foliar chlorosis in boreal forests of eastern Laurentian Highlands in Quebec, Canada. In the first trial, trees showed strong decline symptoms; fertilization treatments consisted of combinations of two nutrients among N, K, and Mg, each at two rates. In the second trial, trees showed some needle chlorosis; various doses of N, K, K–Mg, and K-lime fertilizers were applied. In both trials, N fertilization (200 kg N ha^{-1}) resulted only in a short-term (2–3 years) increase in foliar N concentrations and radial growth. Potassium fertilization (100–400 kg K_2O ha^{-1}), however, led to an increase of at least 33% in both foliar K concentrations and radial growth, which lasted for the duration of the experiments (7–11 years). Liming (1–4 t dolomitic lime ha^{-1}) increased the pH, exchangeable calcium and exchangeable magnesium in the humus and top mineral soil horizons, but did not influence balsam fir foliar nutrient status or growth. Tree defoliation rate was mainly related to growth decrease and foliar K concentrations. The trials also show that K was the most limiting nutrient for balsam fir growth, and that the poor K nutrient status and vigor of balsam fir trees can be corrected by K fertilization. These results contrast with past fertilization studies that generally reported N as the most limiting nutrient in these boreal ecosystems. Climatic events may have also played a role in triggering the decline of balsam fir in one trial.

1. Introduction

The circumpolar boreal forest represents 32% of world forests and is the largest terrestrial ecozone on earth (approximately 14 million km^2). In Canada, the boreal forest accounts for 60% of the total economic value of the country's forestry sector, not considering its indirect effect on employment (Burton et al., 2003). Despite the boreal forest's critical ecological and economic importance, the biogeochemical processes that govern nutrient cycling (and tree growth) in this ecosystem, and its response to natural and anthropogenic disturbances such as logging, fire, insect defoliation, climate change, and atmospheric pollution are still not well known, particularly in North America. Yet, such information is essential for the long-term sustainability of commercial forestry in this forest biome.

In the late 1990s, foliage chlorosis was observed in balsam fir (*Abies balsamea* (L.) Mill.) – white spruce (*Picea glauca* (Moench) Voss) stands in the Laurentian Highlands on the Canadian boreal shield (Ouimet et al., 2013). Concerns were raised recently for this area regarding base cation depletion in soils (Duchesne and Houle, 2008; Robitaille and Boutin, 1990), nutritional deficiencies (Bernier, 1991; Gomez Segura, 2004), and growth reduction (Ouimet et al., 2001). A nutrient budget study in a forest catchment in this area recorded absolute annual K losses of −0.2 to −4.4 kg ha^{-1} yr^{-1}, which is substantial given the soil's small exchangeable K reservoir (~55 kg ha^{-1}; Duchesne and Houle, 2008). Significant Ca and Mg depletion was also recorded (5.1 and 1.3 kg ha^{-1}, respectively, over a 7-year period) (Robitaille and Boutin, 1990). In the last few decades, high levels of atmospheric acid deposition have exacerbated soil base cation leaching (Watmough et al., 2005). In addition, acidity levels exceeding critical loads have been reported for this area, which could have increased soil acidification and reduced forest growth (Ouimet et al., 2006).

To investigate the possible role of base cation deficiency in the poor growth and crown vitality of these forests, we carried out two fertilization trials in young balsam fir stands showing symptoms of tree decline or foliar chlorosis in the Laurentian Highlands. We hypothesized that balsam fir nutrition, crown vigor, and stem growth could be improved by fertilization or liming. Fertilization treatments with N (sometimes in combination with P and K) have had positive effects on conifers growing on mineral

* Corresponding author. Tel.: +1 (418) 643 7994x6533; fax: +1 (418) 643 2165.
E-mail address: rock.ouimet@mffp.gouv.qc.ca (R. Ouimet).

http://dx.doi.org/10.1016/j.foreco.2015.02.032
0378-1127/

soils in Norway (Nilsen, 2001), Sweden (Bergh et al., 2014; Nohrstedt, 2001), Finland (Saarsalmi and Malkonen, 2001), and Denmark (Vejre et al., 2001), particularly on poor sites planted with Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.). Various studies have shown that fertilization usually enhances tree growth in mature boreal fir stands in Eastern Canada and the northeastern USA (Briggs et al., 1984; Camiré et al., 1981; Krause, 1981). Increases ranging from 20% to 47% in radial growth, basal area, or merchantable volume were observed over 5 to 10 years following additions of N, N and P, or N, P and K. However, to our knowledge, liming of balsam fir trees in a boreal setting has rarely been tested.

We tested the following hypotheses in our two trials: (1) the addition of N, K, Ca and Mg from fertilizers and dolomitic lime will improve forest soil nutrient availability; following fertilization and liming, increased availability of nutrients and decreased soil acidity will improve (2) balsam fir nutrient status and (3) balsam fir growth and health.

2. Material and methods

2.1. Site description

The study was conducted at the Montmorency Experimental Forest of Laval University (MF), located on the eastern part of the Laurentian Highlands, ~80 km north of Quebec City, Quebec, Canada (47° 17′N, 71° 9′W). This mountainous plateau covers 7861 km^2 from 600 to 1166 m a.s.l., with over 2000 lakes and many summits higher than 1000 m. The slope ranges from 0% to 30%, with an average of approximately 10%. From 1971 to 2000, mean annual temperature averaged −0.6 °C and mean annual precipitation averaged 1300 mm, with 33% falling as snow. Vegetation is dominated by balsam fir (80%) in association with white birch (*Betula papyrifera* Marsh.), white spruce, and black spruce (*Picea mariana* [Mill.] BSP.). According to the *Canadian System of Soil Classification* (Soil Classification Working Group, 1998), soils are mainly Orthic Ferro-Humic Podzol (Orthic Podzols (FAO, 1998); Humic Haplorthods (Soil Survey Staff, 1999)). The humus is a mor, and the surface deposit is mostly an acid till derived from the local ancient Precambrian igneous and metamorphic bedrock (mangerite, granite, and granitic gneiss) with feldspar, plagioclase, and quartz as dominant minerals (Ouimet and Duchesne, 2005).

2.2. Experimental set-up

We set up two fertilization trials in balsam fir stands at MF in 1998 and in 2000. In both trials, spreading was done manually within a 2-m radius of each individual tree. The first fertilization trial (herein called "REVEW") was located at Basin 6 of the *Ruisseau-des-Eaux-Volées* Experimental Watershed (Plamondon and Ouellet, 1980). At the beginning of the experiment, the stand was composed of 24-year-old balsam firs and white spruces. The stand had been clearcut in the early 1900s and again in 1974–1976 (Table 1). This stand showed severe decline symptoms: needle loss from the inside toward the outside of the crown, needle chlorosis, dwarf internodes with short needles, reduced radial growth and, in some more serious cases, death of twigs and branches. This was the same site used for the fertilization trial of declining white spruce reported by Ouimet et al. (2013). Before fertilization, 54 dominant balsam firs (at least 6 m apart from one another) were selected randomly. Their mean (±SD) tree height and diameter at breast height (DBH) in 1998 were 5.5 ± 0.6 m and 8.8 ± 1.3 cm, respectively (Table 1). In addition to an unfertilized control, the REVEW trial included 6 combinations of N, K and Mg fertilizers at fixed doses, alone (N, K and Mg) or combined two by two (N–K, N–Mg and K–Mg, Table 2). In June 1998, the 7 treatments were randomly assigned to trees, with eight replications per treatment.

The second fertilization trial (herein called "Montmorency") was carried out in three young forest stands (Laflamme, Belvédère, and Crête). The stands had been clearcut in the early 1940s and again in 1979–1982. In 2000, stands were 19 to 22 years old (Table 1), and trees displayed only some needle yellowing. In each of the 3 stands, 68 dominant balsam firs (at least 7 m apart) were selected randomly, for a total of 204 trees. Their mean tree height and diameter ranged between 4.7–11.4 m and 3.5–7.0 cm, respectively. In addition to a control, the Montmorency trial included a single N fertilizer treatment and various combinations of K and Mg fertilizers, with or without lime ($CaMg(CO_3)_2$), for a total of 17 treatments (Table 2). In October 2000, the treatments were randomly allocated to 4 replicate trees in each stand, for a total of 12 replicates by treatment.

Table 1
Characteristics of the selected trees at the beginning of the fertilization trials.

Trial (year)	Stand age (yrs)	Tree height ± SE (m)	Tree DBH ± SE (cm)	Origin[a] (year)
REVEW (1998)	24	5.51 ± 0.08	8.80 ± 0.17	CT (1974–76); PT (1987–88)
Montmorency (2000)				
Belvédère	19	5.46 ± 0.26	3.85 ± 0.13	CT (1982); PT (1990)
Crête	22	4.69 ± 0.20	3.53 ± 0.09	CT (1979); PT (1992)
Laflamme	22	11.14 ± 0.24	6.96 ± 0.10	CT (1979); no PT

[a] CT: clearcut (stem-only harvesting); PT: precommercial thinning.

2.3. Field observations and sampling

Foliage from the upper third whorl of each tree was collected on two opposite branches in early October of 1998, 1999, 2002, and 2008 in the REVEW trial, and of 2001, 2002, 2004, 2006, 2007 in the Montmorency trial. This time of year is usually considered best for sampling conifer foliage in the region, given the stability of foliar concentrations (Brazeau and Bernier, 1973). Current-year and one-year-old foliage samples were treated separately. Tree DBH was measured at the same time using a diameter tape with a 1 mm precision.

At the time of the final foliar sampling at the REVEW site in October 2008, two trained foresters assessed the defoliation rate of each subject tree using the method described in the International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests Manual (ICP Forests, 2006), with the difference that a scale of 4 classes of percent defoliation was used ([0, 1], (1, 10], (10, 50], and (50, 100)).

At the final sampling (REVEW: October 2008; Montmorency: October 2007), two increment cores were also taken on each subject tree to measure basal area increment (BAI). Annual rings were measured using WinDendro software (version 6.1D, Regent Instruments Inc.) and validated using signature rings. Ring width values were converted to BAI using the *dpl* R package (Bunn, 2008), version 1.5.6.

In October 2007, 2 soil samples were also taken within 2 m of each subject tree in the Montmorency trial. The FH horizon of the forest floor and the first 15 cm of mineral B horizon were sampled separately. Replicate samples were pooled for each horizon and tree, air-dried, and passed through a 2-mm sieve prior to physico-chemical analyses.

2.4. Chemical analyses

The collected needles were initially dried at 65 °C, then ground to 250 μm. Their total N (Kjeldahl) concentrations were