Seasonal Leaching Losses of Nutrients Under Containerized 2+0 White Spruce Seedlings Grown Outdoors in Forest Nurseries

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Abstract

In forest nurseries of Québec, containerized 2+0 seedlings are produced outdoors where they can receive rainfall in addition to irrigation. These water inputs can lead to nutrient leaching losses. Two experiments with 2+0 white spruce (*Picea glauca* [Moench.] Voss) grown outdoors in containers were conducted to quantify seasonal leaching losses of nutrients (experiment 1 with no treatment [natural conditions] and experiment 2 with three irrigation and nitrogen [N] fertilization treatments). For both experiments, nitrogen was the most leached nutrient (roughly two-thirds nitrate and one-third ammonium) followed by phosphorus, potassium, calcium, and magnesium. In experiment 2, seedlings receiving the lowest irrigation, and N fertilization treatment had the greatest nitrogen use efficiency (89 percent) compared with the two other treatments (55 and 68 percent, respectively), while also having the lowest nutrient leaching losses without affecting morphology or nutrient concentrations. These results suggest that decreasing irrigation treatments can reduce water use and fertilizer leaching without compromising seedling quality.

Introduction

Pollution of groundwater and surface waters by nitrate (NO_3^-) has been reported throughout the world due to agricultural and horticultural practices (Broschat 1995, Colangelo and Brand 2001, Follett and Hatfield 2001, Goulding 2000, Pepper et al. 1996, Stevenson 1982). Although the areas and the amount of nitrogen (N) fertilizer applied in forest nurseries are small compared with those in agriculture and horticulture, NO_3^- leaching is a significant environmental issue in forest nurseries (Dumroese et al. 1992, 1995, 2005, Gagnon and Girard 2001, Juntunen 2003, Juntunen et al. 2002, 2003, Lamhamedi et al. 2002, Landis et al. 1991, Park et al. 2012). Indeed, leaching of NO_3^- can lead to groundwater contamination and to NO_3^- concentration in drinking water that could exceed the standard for NO_3^- of 45 parts per million (ppm) (10 ppm of NO_3^--N) for North America (Health Canada 2008, EPA 2009) and of 50 ppm (11.3 ppm of NO_3^--N) for Europe (European Community 1998).

In the 19 forest nurseries (13 privately owned and 6 government owned) of Québec (Canada), 96 percent of the 128 million seedlings produced in 2017 were grown in containers (Arseneault 2017). These seedlings receive weekly N, phosphorus (P), and potassium (K), fertilizations to meet morphological (e.g., height, diameter, height/diameter) and physiological (minimal foliar N concentrations of 1.6 percent for seedlings grown in cavities with volumes < 200 cm^3 [12 in^3] and 1.8 percent for cavities ≥ 200 cm^3) quality criteria before outplanting (Veilleux et al. 2014). In Québec nurseries, containerized seedlings are grown for 2 years; 1+0 seedlings are produced in white, unheated polyethylene tunnels during their first season, whereas during their second year, 2+0 seedlings are cultivated outdoors. Although all these seedlings are fertilized to satisfy their weekly NPK growth needs (Langlois and Gagnon 1993) determined by Plantec software (Girard et al. 2001), losses of nutrients by leaching can occur along their two growing seasons if water inputs (rainfall, irrigation) exceed the water-holding capacity of their low-density, peat moss-based substrates, which range between 0.08 and 0.12 g/cm^3 (0.0018 and 0.0026 oz/in^3).

Several irrigation experiments conducted in forest nurseries of Québec with containerized 1+0 black spruce (*Picea mariana* [Mill.] B.S.P.) (Bergeron et al. 2004, Lamhamedi et al. 2003) and white spruce (*Picea glauca* [Moench.] Voss) (Lamhamedi et al. 2001) seedlings grown in tunnels showed that volumetric water content (VWC; percent, volume per volume [v/v]) of 60 percent had the greatest leaching losses of nutrients compared with 15, 30, or 45 percent VWC. Because containerized 2+0 seedlings are grown outdoors in these nurseries, they receive rainfall, which makes them more prone to important seasonal nutrient leaching losses than 1+0 seedlings due to generally high VWC (> 50 percent, v/v). In a leaching study with containerized 2+0 white spruce seedlings growing outdoors (Gagnon and Girard 2001), continuous monitoring of substrate VWC showed that it varied between 50 and 70 percent throughout the growing season and that 30 percent of the applied N was lost by leaching as NO_3^- (Gagnon and Girard 2001). Similar N loss (32 percent) was observed with containerized ponderosa pine seedlings (Dumroese et al. 1995). Other leaching experiments carried out in Québec forest nurseries with containerized 2+0 white spruce seedlings grown outdoors (Gagnon and Girard 2003, 2011, Lamhamedi et al. 2006) and also in tunnels to control irrigation treatments (Stowe et al. 2010) showed that nutrient losses by leaching were important when these 2+0 seedlings were irrigated in excess.

This paper presents the results of two leaching experiments carried out with containerized large 2+0 white spruce grown outdoors in Québec forest nurseries. In the first experiment, no irrigation or fertilization treatments were applied to enable measurement of the magnitude of nutrient leaching losses under natural conditions. In the second experiment, three irrigation and fertilization treatments were applied to compare their effects on nutrient leaching losses and seedling growth. The purpose of these studies was (1) to develop accurate and efficient measurement tools to quantify seasonal leaching losses of mineral nutrients (N, P, K, calcium [Ca], and magnesium [Mg]) for containerized 2+0 seedlings grown outdoors and (2) to test and implement irrigation and fertilization practices and software to increase the N use efficiency of seedlings and thereby decrease leaching losses of N and other nutrients in forest nurseries.

Materials and Methods

In Quebec forest nurseries, containerized seedlings produced in cavity volumes greater than 300 cm^3 (18 in^3) are deemed large seedlings. More details about cultural conditions of these 1+0 and 2+0 seedlings are summarized in Gagnon and DeBlois (2014). Two leaching experiments were carried out with large 2+0 white spruce seedlings grown outdoors in two governmental forest nurseries of Québec (Direction générale de la production de semences et de plants forestiers of the Ministère des Forêts, de la Faune et des Parcs [MFFP]). All seedlings were produced in peat-vermiculite substrates (3:1, v/v) with a mean bulk density of 0.1 g/cm^3 and were fertilized biweekly with NPK according to the rates calculated by Plantec software (Girard et al. 2001). They also received small amounts of Ca and Mg, as well as micronutrients present in commercial soluble fertilizers. After each fertilization, a light irrigation was conducted to rinse their foliage.

Experiment 1—Evaluation of Leaching Under Natural Conditions

Large 2+0 white spruce seedlings were grown outdoors in 25-350A containers (25 cavities with a volume of 350 cm^3 [21 in^3] each, IPL, Inc., Saint-Damien, Québec, Canada) at Normandin nursery in the Saguenay-Lac St. Jean region of Québec (48°48’48” N, 72°45’00” W), Canada. A completely randomized design totaling 1,820 containers divided into 4 replicates was installed May, 10–12, 2000 (figure 1a).

Leachate collectors (LC) were installed under containers to quantify nutrient leaching losses during the growing season. LCs made in 1999 (Gagnon and Girard 2001) were used in this experiment (figure 1b). Each LC had the same area as the container (1314 cm^2 [210 ft^2]: 37.0 cm [14.8 in] by 35.5 cm [14.2 in]) and was made from a vinyl cloth stretched over a plastic frame connected to a 4-L (1.1-gal) bottle to collect the leachate. Between May 12 and October 18, 20 LC (5 LC/replicate x 4 replicates) were used to measure the substrate solution leached under 20 containers (500 seedlings).

Between May 12 and September 5, 2+0 seedlings received 30 fertilizations totaling 221 mg (0.0074 oz) N (33 percent urea, 29 percent ammonium [NH_{4+}], and 38 percent NO_{3}-), 45 mg (0.0015 oz) P, and 109 mg

(0.0036 oz) K per seedling. Fertilization was performed with a tractor-mounted boom sprayer (Model Multi 33, Timm Enterprises Inc., Oakville, Ontario, Canada) (figure 1c) equipped with a 720-L (191-gal) reservoir and two ramps of nine nozzles each (Model Teejet XR 11002, TeeJet Technologies, Spraying Systems Co., Wheaton, IL). The sprayer released the fertilizer at a pressure of 207 kPa (30 psi) and a dose of 936 L per ha (102 gal per ac).

Irrigation was performed with sprinklers (Rain-Jet, model 66U, Harnois, Québec, Canada) at a pressure of 207 kPa (30 psi) arranged in a square pattern (7.3 by 7.3 m, [24.0 by 24.0 ft]) and placed at a height of 110 cm (44 in) above the center aisle of the growing area (figure 1a). Irrigation was managed using IRREC irrigation software (Girard et al. 2011).

Between May 19 and October 2, 60 seedlings (15 seedlings x 4 replicates) and their root plugs were harvested every 2 weeks. At each sampling date, substrate fertility was determined on one composite sample of 15 root plugs for each of the 4 replicates (n = 4).

Figure 1. (a) Large 2+0 white spruce grown outdoors in 25-350A containers at the Normandin nursery with weather station position above the containers to monitor environmental variables. (b) Leachate collector used to measure the losses of substrate solution under seedlings. (c) Tractor-mounted boom sprayer used to fertilize 2+0 container seedlings at the Normandin nursery. (Photo (a) by Daniel Girard, 2000; Photo (b) by Daniel Girard, 1999; and photo (c) by Jean Gagnon, 2016)

Experiment 2—Evaluation of Leaching Based on Irrigation and Nitrogen Fertilization Treatments

Large 2+0 white spruce seedlings were grown outdoors in 25-310 containers (25 cavities with a volume of 310 cm^3 [19 in^3] each, IPL, Saint-Damien, Québec, Canada) at the Saint-Modeste nursery in the Bas St-Laurent region of Québec (47°50′10″ N, 69°23′10″ O). A completely randomized block design with three treatments and four blocks was installed on May 28, 2009 (figure 2a). The three treatments were:

T0 - medium irrigation (244 mm [9.6 in]) + high N fertilization (260 mg/seedling [0.0087 oz])

T1 - high irrigation (318 mm [12.5 in]) + high N fertilization (250 mg/seedling [0.0083 oz])

T2 - low irrigation (189 mm [7.4 in]) + low N fertilization (200 mg/seedling [0.0067 oz]).

The T0 treatment represents the operational control. Treatments were applied using the irrigation and fertilization softwares IRREC and FERTIRREC (Girard et al. 2011, Gagnon and Girard 2011, Gagnon et al. 2012).

An LC of 0.5 m^2 (5.4 ft^2) (1 m [3.3 ft] width by 0.5 m [1.6 ft] length) in stainless steel (1.6 mm [0.06 ft]

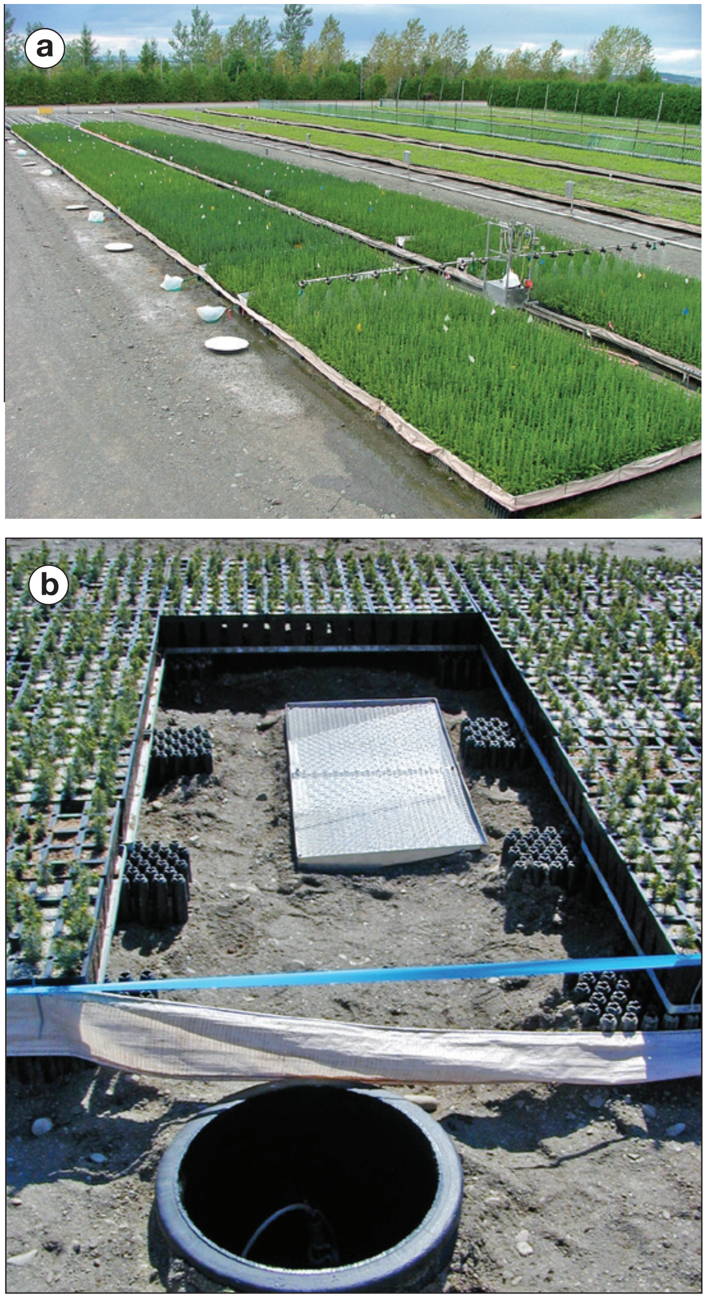

Figure 2. (a) Large 2+0 white spruce grown outdoors in 25-310 containers at the Saint-Modeste nursery were fertilized and irrigated with a mobile boom. (b) Stainless steel leachate collector and its recovery well for measuring leaching losses under containerized 2+0 white spruce seedlings at the Saint-Modeste nursery. (Photos by Daniel Girard, 2009 and 2003)

thick with a weight of 10 kg [22 lb]) was used for this experiment (figure 2b). This LC enabled collection of leachate under four containers at a time. A mesh was installed at the top of the LC to prevent clogging from debris. To harvest the leachate, each LC was connected with a plastic pipe (1.9 cm [0.8 in] diameter) to a 1-m (3.3-ft) deep recovery well containing a 20 L (5.3 gal) reservoir (figure 2b). A total of four LCs per treatment (one per block) was used to collect the substrate solution leached between June 8 and September 28.

From June 10 to September 24, 25 fertilizations were carried out using the mobile boom (figure 2a). The total NPK applied per seedling was T0: 260 mg N (0.0092 oz; 2 percent urea, 44 percent NH_4^+, and 54 percent NO_3^-), 39 mg P (0.0013 oz), 113 mg K (0.0038 oz); T1: 250 mg N (73 percent urea, 11 percent NH_4^+, and 16 percent NO_3^-), 57 mg P (0.0019 oz), 108 mg K (0.0036 oz); and T2: 200 mg N (63 percent urea, 20 percent NH_4^+, and 37 percent NO_3^-), 43 mg P (0.0014 oz), 86 mg K (0.0029 oz). The mobile boom was calibrated to operate at a pressure of 207 kPa (30 psi). The nozzles used (# 8006) produced a water flow of 0.88 mm (0.03 in), and this flow led to 8,770 L per ha (958 gal per ac) of fertilizing solution per pass.

The mobile boom irrigation system (Aquaboom; Harnois Industries, Saint-Thomas de Joliette, Québec, Canada) (figure 2a) was calibrated to operate at a pressure of 207 kPa (30 psi) and had two ramps of nine nozzles each (Teejet, TeeJet Technologies, Spraying Systems Co., Wheaton, IL). The nozzles (# 8010) produced a water flow of 1.9 mm (0.07 in) or 19,000 L per ha (2,077 gal per ac) per rail pass. During the study, the total irrigation water applied per seedling was T0: 244 mm, T1: 318 mm, and T2: 189 mm. These water amounts do not result in hydric stress or negative effects on the growth and physiological processes of containerized 2+0 white spruce seedlings (Lamhamedi et al. 2006, Stowe et al. 2010).

Seedlings and their root plugs were harvested on June 8, August 3, and September 28. At each date, 96 seedlings per treatment (24 seedlings x 4 blocks) were harvested. Between these 3 main harvests, 6 other harvests of seedlings and substrate (48 seedlings/treatment: 12 seedlings x 4 blocks) were carried out to adjust the NPK fertilizations of the 3 treatments as a function of the seasonal evolution of dry mass and seedling nutrient concentration. For each treatment, substrate fertility was determined on 1 composite sample of either 12 or 24 root plugs for each of the 4 blocks (n = 4).

Seedling, Leachate, and Substrate Measurement

After each harvest, seedling morphology for each experiment (height, root-collar diameter, shoot, root, and total dry mass) was measured and nutrient concentrations in seedlings and substrates were analyzed. Each seedling was separated into shoot (needle and stem) and root, and these two components were oven dried at 60 °C (140 °F) for 48 hours in order to get dry mass for each of these components (weighing by groups of five and six seedlings for experiments 1 and 2, respectively).

After water inputs (rainfall, irrigation, fertilization) in both experiments, leachate was collected, and its volume (ml) was measured. For experiment 1, leachate samples were composited into one sample for each of the four replicates. For experiment 2, there were four samples per treatment (1 per block). Leachate samples were kept frozen until laboratory analysis of their nutrient concentration (urea, NH_4, NO_3, P, K, Ca, Mg), pH, and electrical conductivity (EC). Prior to analysis, samples were passed through a filter of 0.45 µm. For each leachate sample analyzed, the quantity of each nutrient leached was obtained by multiplying the volume (ml) by its concentration (ppm or mg/l), and thereafter the loss per seedling (mg/seedling) of each nutrient was calculated.

For leachate, urea was determined by liquid chromatography (HPLC Agilent-1200 chromatograph with diode array detector) using a Sugar-Pak I column from Waters. Inorganic N was determined by colorimetry with a continuous flow spectrophotometer (model QuickChem 8000, Lachat Instruments, Milwaukee, WI, USA), whereas P, K, Ca, and Mg were determined by using inductively coupled argon plasma analysis (model ICAP 9000 or 61E, Thermo Instruments, Franklin, MA, USA). For seedling analysis, after grinding and acid digestion of seedling tissues, composite samples were analyzed for N (Kjeldahl method) and for P, K, Ca, and Mg (inductively coupled argon plasma analysis). Nutrient content of each seedling part (shoot, roots, and total) was calculated (concentration by dry mass) to accurately reflect nutrient uptake and accumulation. Substrate nutrients were extracted by vacuum filtration (Whatman filters # 4) after saturating in water for 90 minutes. Urea, mineral N, and other nutrients (P, K, Ca, and Mg) were determined by using the same analysis methods described previously for the leachate. The laboratoire de chimie organique et inorganique (ISO/CEI 17025) de la Direction de la recherche forestière, MFFP du Québec, performed all nutrient analyses (leachate, tissue, and substrate).

Environmental Variables and Substrate Water Content

For both experiments, a weather station was installed in May at 3.5 m (11.5 ft) above the ground to continuously monitor environmental variables (air temperature, relative humidity, wind speed, and rainfall) (figures 1a and 3a). Water inputs were monitored with rain gauges (model TE525M, Texas Instruments, Dallas, TX, USA) installed at the ground level among containers (one for experiment 1 [figure 1a] and one per treatment for experiment 2). These data were monitored every 15 min (May 12 to October 18) for experiment 1 and every 2 h (May 28 to October 6) for experiment 2 by using a CR10X data logger (Campbell Scientific, Logan, UT, USA) (figure 3b).

Substrate VWC was measured continuously by time domain reflectometry (Topp and Davis 1985) using a portable moisture monitoring system MP-917 (ESI Environmental Sensors Inc., Victoria, BC, Canada) equipped with double-diode humidity probes (figure 3b). To convert the time domain reflectometry signal to VWC (cm^3 H_2O/cm^3 substrate) in peat-vermiculite substrate (3:1, v/v), calibration of the MP-917 parameters was determined by Lambany et al. (1996, 1997) and then was successfully tested with this substrate (Gagnon and Girard 2001, 2003, Lamhamedi et al. 2001, 2003, 2006, Stowe et al. 2010). Each of the 8 probes of the MP-917, which consisted of 2 parallel stainless steel waveguides (407 mm long, 3.17 mm diameter, spaced 10 mm apart), was inserted through the middle of the root plugs in the 5 central cavities of a container to measure substrate of a total of 40 seedlings for experiment 1 and 40 seedlings per treatment for experiment 2. These probes were connected permanently to the MP-917 via a coaxial multiplexer (ESI Environmental Sensors Inc., Victoria, BC, Canada) to juxtapose the substrate VWC with the environmental variables (figure 3b).

Statistical Analyses

For experiment 1, simple averages and standard errors were calculated for the collected data. For experiment 2, statistical analyses to determine differences among treatments were performed using the MIXED procedure of SAS (version 9.4, SAS Institute, Cary, NC, United States). When required, a simulation-based approach taking account of multiplicity was used to assess differences. Normality of the residuals was

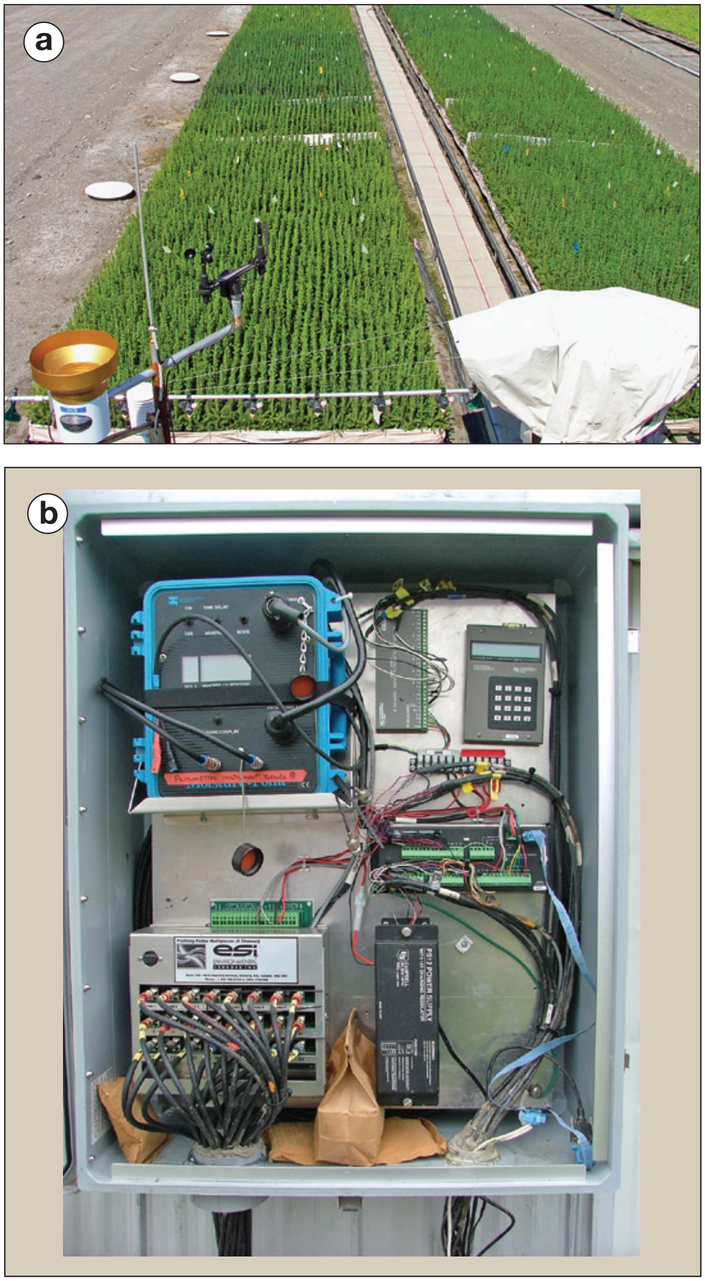

Figure 3. (a) Weather station above the 25-310 containers to monitor environmental variables of 2+0 white spruce seedlings grown at the Saint-Modeste nursery. (b) Waterproof case containing a MP-917 soil moisture system (blue device), a CR10X data logger, and an ESI coaxial multiplexer. (Photos by Daniel Girard, 2009)

confirmed using the Shapiro-Wilk's statistic, and homogeneity of variance was validated using standard graphical methods. Differences were deemed significant when $p < 0.05$. A cubic model was used to simulate total of water inputs (rainfall, irrigation, fertilization) for three inputs. For substrate N fertility, a logarithmic transformation of the data was done to validate the hypotheses of normality and homogeneity, and untransformed data are presented.

Results—Experiment 1

Water Input, Leachate, and Volumetric Water Content

Between May 18 and October 18, large 2+0 white spruce seedlings grown outdoors in 25-350A containers at Normandin nursery received 871 mm (34.8 in) of water inputs (43 percent in rainfall and 57 percent in irrigation) corresponding to a water input of 114.7 L (30.4 gal) per container. Leachate amounted to 47 L (12.5 gal) per container, which is a 41-percent loss of the water inputs. Leachate volume varied between 25 and 164 ml per seedling (1 and 7 oz/seedling) over 25 leachate collections for a total of 1.9 L/seedling (64 oz/seedling). During the same period, substrate VWC varied between 37 and 69 percent with an overall average of 53 percent.

Nutrient Leaching Losses

Nitrogen was the most leached nutrient, averaging 96 mg per seedling cavity (0.0032 oz) with two-thirds as NO_3^- and one-third as NH_4^+. Other nutrient losses in decreasing order were K (63 mg [0.0021 oz]), P (27 mg [0.0009 oz]), Mg (23 mg [0.008 oz]), and Ca (8 mg [0.0003 oz]) per seedling cavity. Compared with the amount of NPK applied between May 18 through October 18, the percentage of N, P, and K lost by leaching was 43, 60, and 58 percent, respectively.

Seedling Morphology and Nitrogen Status in Seedlings and Substrate

At the end of the growing season (October 2), seedling morphological variables (± standard error [SE]) were height of 17.0 ± 0.5 cm (6.8 in), diameter of 4.56 ± 0.15 mm (0.2 in), shoot dry mass of 2,501 ± 174 mg (0.08 oz), root dry mass of 1,163 ± 98 mg (0.04 oz), and total dry mass of 3,664 ± 261 mg (0.12 oz). Between May 19 and October 2, N concentration increased from 1.58 to 2.43 percent, and total N content increased from 8 to 89 mg, representing an N uptake of 81 mg per seedling. Seedling P concentration increased from 0.18 to 0.42 percent, and P uptake averaged 14.5 mg per seedling. Seedling K concentration increased from 0.38 to 0.57 percent, and K uptake averaged 19.1 mg per seedling. Also during this period, the average substrate N concentration (± SE) of NH_4-N, NO_3-N, and total N (NH_4 + NO_3) were 103 (± 10), 168 (± 21), and 271 (± 29) ppm, respectively.

Nitrogen Use Efficiency

Nitrogen use efficiency (NUE) was calculated as the ratio of N absorbed by seedlings to the N applied during their second growing season. Between May 19 and October 2, seedlings absorbed an average 81 of the 221 mg N applied, resulting in an NUE of 37 percent.

Results—Experiment 2

Water Input, Leachate, and Volumetric Water Content

Between May 28 and October 6, total water inputs varied significantly among treatments (figure 4a). During this period, rainfall totaled 291 mm (11.5 in). Water inputs from fertilizations amounted to 73 mm (2.9 in), 66 mm (2.6 in), and 60 mm (2.4 in) for the T0, T1, and T2 treatments, respectively. Seedlings in the T2 treatment received significantly less water than both T0 and T1 treatments with 189 mm (7.4 in) compared with 244 mm (9.6 in) and 318 mm (12.5 in), respectively.

The total amount of leachate per seedling did not differ significantly between T0 and T1 treatments, whereas the leachate from the T2 treatment was significantly less than the two other treatments (figure 4b). Similarly, the seasonal average of substrate VWC in the T2 treatment was significantly lower than the T0 treatment (figure 4c).

Nutrient Leaching Losses

Nitrogen was the most leached nutrient regardless of treatment and was proportioned roughly two-thirds in NO_3^- and 1/3 in NH_4^+, whereas losses of urea were either negligible or zero (figure 5). The T1 and T2 treatments had significantly less N, K, Ca, and Mg leaching losses compared with the T0 control treatment. Conversely, T1 and T2 treatments had significantly greater leaching losses of P compared with the T0 treatment (figure 5). Overall, the percentage of applied N lost by leaching was 49, 29, and 21 percent for T0, T1, and T2 treatments, respectively.

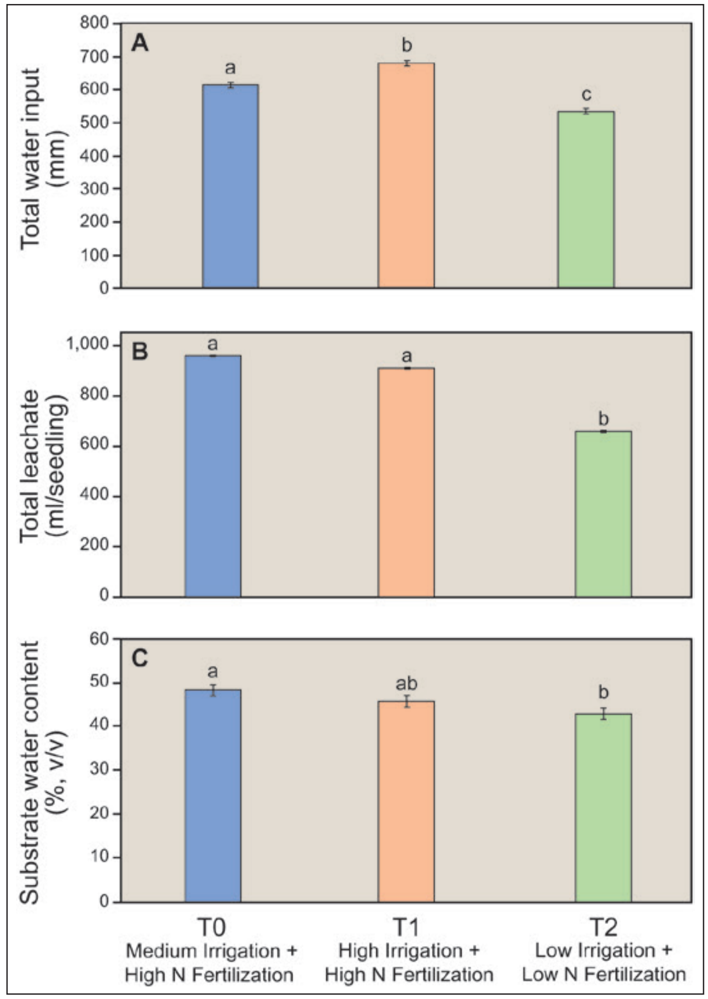

Figure 4. (a) Total amount of water input (rainfall, irrigation, and fertilization) for each treatment between May 28 and October 6 that large 2+0 white spruce seedlings grown outdoors in 25-310 containers at the Saint-Modeste nursery received. (b) Total amount of leachate per seedling during the period of active growth (June 8–September 28) of seedlings. (c) Seasonal average of volumetric water content (percent, v/v) of the substrate of 2+0 seedlings between June 12 and September 28. For each variable, bars with different letters differ significantly at $\alpha = 0.05$ (± standard error).

Seedling Morphology and Nitrogen Status in Seedlings and Substrate

At the end of the growing season (September 28), T2 seedlings were significantly larger than seedlings in the other two treatments (figure 6). Both N concentration and content did not differ significantly among the three treatments at the end of the growing season (figure 7a and 7b). The concentration of mineral N ($NH_{4+}NO_3$) in the substrate ranged among treatments as follows—T0: 365 to 1200 ppm, T1: 83 to 1450 ppm, and T2: 132 to 1083 ppm, but no significant differences were present (figure 7c).

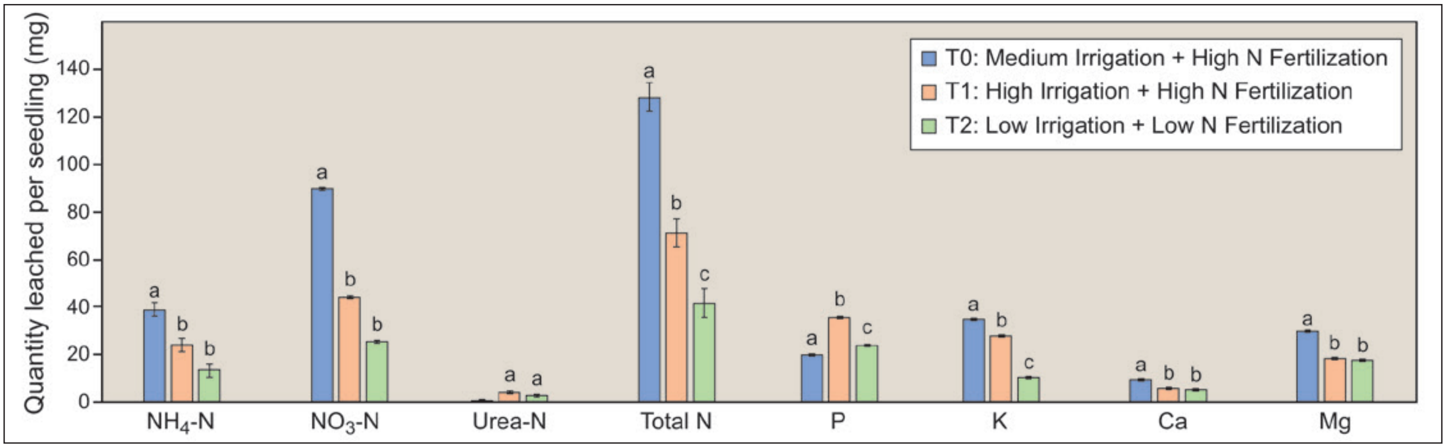

Figure 5. Nutrients lost by leaching during the period of active growth (June 8–September 28) of large 2+0 white spruce seedlings grown outdoors in 25-310 containers at the Saint-Modeste nursery. For each variable, bars with different letters differ significantly at $\alpha = 0.05$ (± standard error).

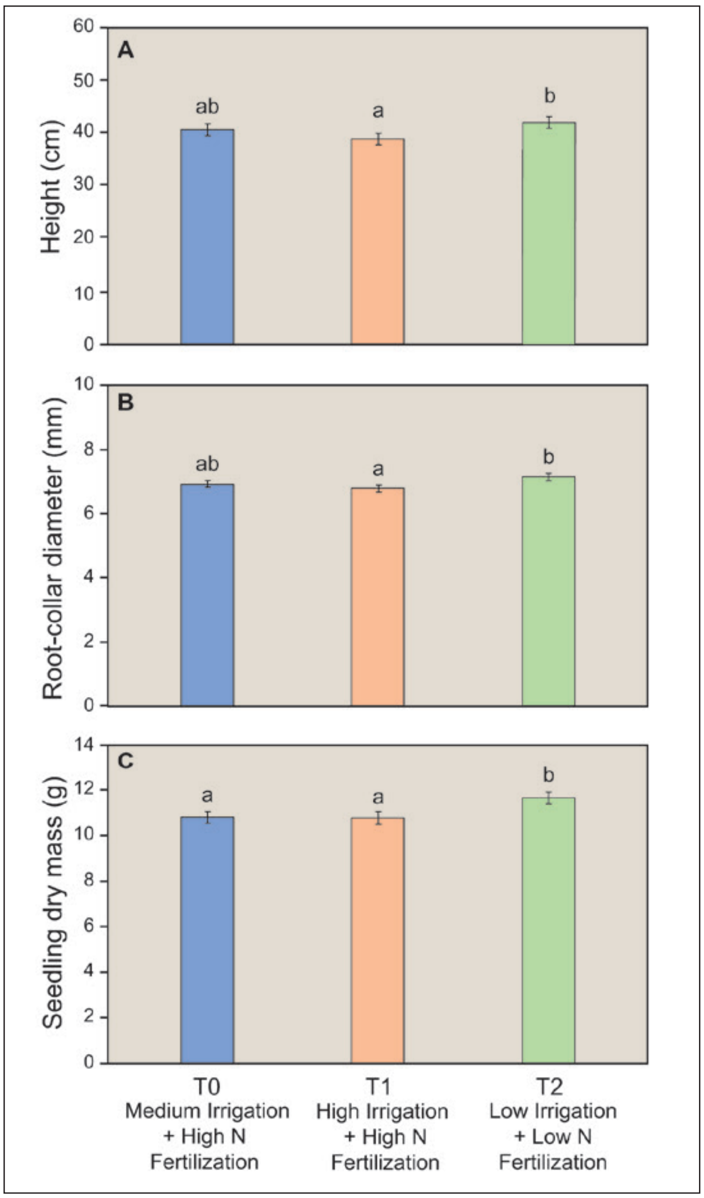

Figure 6. (a) Height, (b) root-collar diameter, and (c) total dry mass of large containerized 2+0 white spruce seedlings for each treatment at the end of the season (September 28) at the Saint-Modeste nursery. For each variable, bars with different letters differ significantly at $\alpha = 0.05$ ($n = 60$; ± standard error).

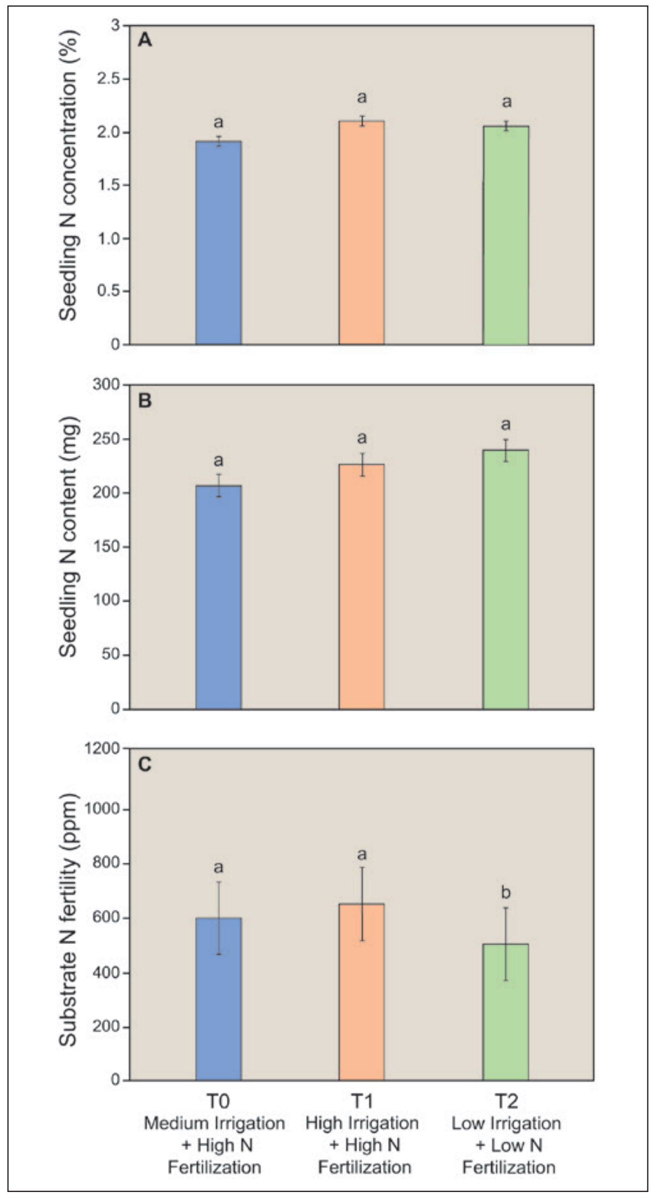

Figure 7. (a) Nitrogen concentration and (b) nitrogen content of large containerized 2+0 white spruce seedlings at the end of the season (September 28) at the Saint-Modeste nursery. (c) Seasonal average of substrate N fertility of 2+0 white spruce. For each variable, bars with same letters did not differ significantly at $\alpha = 0.05$ ($n = 4$ composites samples; ± standard error).

Nitrogen Use Efficiency

The NUE was 55 percent for T0 ([144 mg N absorbed /260 mg N applied] x 100), 68 percent for T1 ([169 mg N absorbed/250 mg N applied] x 100), and 89 percent for T2 ([179 mg N absorbed/200 mg N applied] x 100).

Discussion

The leachate loss observed in experiment 1 (47 L per container) was of the same order of magnitude as a previous study in similar natural conditions where 51 L per 25-350A container were lost with a substrate VWC varying between 50 and 70 percent during the season (Gagnon and Girard 2001). In experiment 2, however, irrigation treatments significantly influenced leachate volume. These results demonstrate that managing irrigation to maintain a lower substrate VWC lowers water use, leachate, and nutrient losses without compromising seedling morphology. In a similar study, Stowe et al. (2010) evaluated three irrigation regimes (30, 40, and 55 percent, v/v) on large containerized 2+0 white spruce seedlings grown in a tunnel and found that reduction of VWC from 55 to 30 percent reduced the total leachate volume 65 percent and the quantity of N leached 52 percent.

Among all nutrients, N was the most leached nutrient (roughly 2/3 NO_3^- and 1/3 NH_4^+) in both experiments. Gagnon and Girard (2001) also found 30 percent of applied N was lost by leaching. The greater loss of NO_3^- compared with NH_4^+ can be explained by the fact that, unlike the cation NH_4^+, the anion NO_3^- is not retained by the negative charges of the peaty substrate. By varying irrigation and fertilization in experiment 2, seasonal quantities of leached nutrients (N, P, K, Ca, and Mg) also varied. Although seedlings in all treatments were fertilized with three N sources (NH_4^+, NO_3^-, and urea), urea losses were either negligible or zero. These zero or very low losses of urea can be explained by the fact that ureaze enzyme, which is ubiquitous in soils (Stevenson 1982), rapidly hydrolyzes into NH_4^+ so that the applied urea that is not rapidly absorbed by seedlings will be quickly converted into NH_4^+. In a forest nursery soil (loamy sand), 64 percent of urea was converted into NH_4^+ after only 1 day of incubation in a growth chamber, and after 4 days, all the applied urea was hydrolyzed into NH_4^+ (Gagnon and Camiré 2001). In a peat-vermiculite substrate incubated in a growth chamber, 25 and 95 percent of urea were converted into NH_4^+ after 1 and 7 days, respectively (Gagnon 2009).

The T2 seedlings in experiment 2 received the lowest amount of irrigation and N fertilization but were not significantly smaller than the two other treatments, nor did they have lower N concentration or contents at the end of the season. As a result, T2 seedlings had the greatest NUE of all three treatments, with 89 percent compared with 55 and 68 percent for T0 (control) and T1, respectively. The lower irrigation volume led to significantly smaller leachate amounts and corresponding N losses by leaching compared with the two other treatments and, therefore, more N was available in the substrate to be absorbed by T2 seedlings. Park et al. (2012) showed that among three nutrient fertilization methods (constant, three-stage rate, and exponential fertilization) applied to containerized yellow poplar (*Liriodendron tulipifera* L.) and Japanese larch (*Larix leptolepsis* [Siebold et Zucc.] Endl.), exponential fertilization increased NUE of both yellow poplar (63, 61, and 85 percent, respectively) and Japanese larch (35, 30, and 53 percent, respectively) and also reduced nutrient leaching losses. Similarly, Dumroese et al. (2005) showed that NUE of containerized western white pine (*P. monticola* Dougl. ex D. Don) was 50 percent with constant fertilization, whereas it increased to 75 percent with exponential fertilization, which also resulted in decreased nutrient leaching losses.

Concerning the fertilization of containerized seedlings grown outdoors, it is important to avoid applications when it is windy, because it will lead to drift losses of nutrients. The equipment used to fertilize is also important. In previous studies of Gagnon and Girard (2001, 2003, and 2011), the use of leachate collectors placed between containers showed that fertilizer losses by drift averaged to 20 percent when fertilization was performed with a tractor-mounted boom sprayer and 5 percent when a mobile boom irrigation system was used under similar wind-speed conditions. These greater nutrient losses by drift obtained with a tractor are due to the smaller sized fertilizer droplets caused by higher pressure applications. To minimize drift losses of fertilizer, it is more appropriate to use a mobile boom irrigation system for fertilization and to fertilize when wind conditions are minimal.

Conclusions

These two experiments quantify leaching losses of N (NO_3-, NH_4+) and other nutrients (P, K, Ca, and Mg) from large containerized 2+0 seedlings grown outdoors when water inputs exceed the water-holding capacity of their peaty substrate. To minimize these nutrient losses, growers must take into account short-term rainfall forecasts before irrigation and fertilization of outdoor-grown container seedlings. Also, they must manage irrigation and fertilization schedules to optimize NUE and minimize N losses by leaching. Monitoring container weights is an important tool. To improve the substrate monitoring, wireless networks of electronic scales, which permit real-time measurements of substrate VWC of several containers at the same time, can be particularly useful (Girard and Gagnon 2016) for managing irrigation of containerized seedlings.

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