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# Growth and Photosynthetic Response of Pot-in-pot-grown Conifers to Substrate and Controlled-release Fertilizer

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***Abstract*. Container production of landscape conifers, including pot-in-pot (PIP) production, is increasing relative to field production in the northern United States. Because much of the research on PIP has been performed in the southern United States, this study focused on characterizing the growth and physiological response of PIP-grown conifers to fertilizer and substrate to improve production for growers in northern climates. In May 2006, we potted 90 seedlings each of *Abies fraseri*, *Picea glauca* var. *densata*, *P. pungens glauca*, and *Pinus strobus* into 11.2-L containers. Substrate consisted of pine bark (B) and peatmoss (PM) in ratios of 90:10, 80:20 or 70:30 (vB:vPM). Trees were top-dressed with controlled-release fertilizer (15N–4P–10K) at rates of 0.25, 0.5, and 1.0 g of nitrogen per liter of container (g·L$^{-1}$). After 2 years, growth response to substrate varied by species; however, all species grew as well or better in the 80:20 mix than in the other mixes. In response to fertilizer addition, adding 0.5 or 1 g N/L increased height growth compared with 0.25 g. Increasing the fertilizer rate from 0.5 g N/L to 1 g did not increase height growth. Foliar nitrogen increased with each fertilizer addition although height growth did not increase beyond 0.5 g·L$^{-1}$, indicating possible luxury consumption. Furthermore, net photosynthesis rates of spruce trees declined with fertilization in the second year of the study, possibly as a result of increased water stress due to greater total leaf area per tree. Chlorophyll fluorescence was not consistently correlated with foliar nutrition. From a practical standpoint, results of the study indicate that 0.5 g N/L will provide adequate nutrition for these crops. A substrate mix of 80% bark:20% peatmoss produced maximal or near-maximal growth for all four species tested.**

Traditionally, landscape conifers have been field-grown and sold balled and burlapped (B&B). Soil loss resulting from harvesting field-grown trees can be nearly 100 tons per acre for a 5-year rotation and harvest can only take place in the spring and fall (Pollock and Mathers, 2002). If diseases such as phytophthora, especially common in firs, become established in soils, they can result in extensive mortality and in some cases have caused nurseries to be abandoned (Kuhlman et al., 1989). Moreover, consumer preference of container material has been steadily increasing (Halcomb and Fare, 1995). Container production has been increasing relative to B&B and now accounts for nearly 30% of the coniferous evergreen sales in the upper Midwest (NASS, 2007).

Pot-in-pot (PIP) production is an increasingly popular component of the overall container production trend. Because PIP plants are grown in containers, they are lightweight, easy to harvest, and root systems are not disturbed by digging and transplanting (Ruter, 1997). However, unlike aboveground container (AGC) production, the PIP containers are placed into socket pots, which are sunk in the ground providing stability and protection of the root zone from extreme air temperatures. In ornamental nurseries in the southern United States, PIP production results in moderated root zone temperatures, especially during the hot summer months, and improves growth compared with field- or AGC-produced plants (Roberts, 1993; Ruter 1993, 1995, 1998, 1999). The system has also been adopted as a method of providing winter protection in northern climates (Neal, 2004).

Pot-in-pot production is also suitable for developing niche markets such as living Christmas trees. Living Christmas trees appeal to consumers who would otherwise choose artificial trees as a result of environmental concerns (Genovese, 2007). Other consumers desire a second or third Christmas tree for their home (Behe et al., 2005). Some growers have found that Christmas trees as large as 6 feet tall can be grown in 37.9-L pots using a lightweight substrate and still be manageable for a consumer to take into their home (Genovese, 2007). Small, dense trees such as Black Hills spruce [*Picea glauca* (Meonch) Voss var. *densta* Bailey] or Serbian spruce [*P. omorika* (Panèiæ) Purkyne] grown in a 1-gallon (3.7-L) container could be placed on a tabletop and decorated and are desirable options for a small apartment or as an additional tree (Behe et al., 2005). Living Christmas trees produced in a PIP system and displayed indoors for up to 20 d during the holiday season perform better in the landscape after transplanting compared with field-dug trees (Nzokou et al., 2007).

Landscape conifer growers converting from field production to PIP face several key challenges. Among these are selection of appropriate container substrate and nutrition management. Growing conditions in PIP systems are not the same as either field or AGC production. Lightweight organic substrate is used rather than field soil and root zone temperatures are more stable than in AGC plants (Young and Bachman, 1996). Selection of an appropriate container substrate is critical because container substrates can impact plant nutrient and water relations.

In many commercial growing operations, fertilization regimes are often based on visual ratings (Parent et al., 2005), which can miss symptoms of "hidden hunger" or "luxury consumption" (Landis and van Steenis, 2004). Suboptimal nutrition can result in impaired physiological function, particularly as reduced photosynthetic rates that can reduce growth (Gough et al., 2004; Samuelson, 2000). Applying fertilizer in excess of a tree's physiological needs, in contrast, can result in leaching of nitrate and other nutrients resulting in environmental degradation (Juntunen et al., 2002, 2003). Moreover, nursery producers are increasingly interested in optimizing nutrient additions as a result of recent volatility in the price of nitrogen-based fertilizers.

The overall goal of this project was to develop fertilizer and substrate recommendations to optimize growth of containerized conifers, reduce potential environmental impacts, and reduce costs for growers using the PIP production system. Specific objectives were to: 1) determine the growth and physiological response of conifers to increasing fertilizer levels; 2) determine the effect of substrate on growth and physiology of PIP-grown conifers; and 3) determine the relationships among plant nutrition, physiological responses, and growth.

## Materials and Methods

### Site description

This experiment was conducted at the Michigan State University (MSU) Horticulture Teaching and Research Center, Lansing, MI. The soil was a loamy sand (83.1% sand, 8.7% silt, 9.3% clay), which provided adequate drainage of the containers in the PIP system. To install socket pots for the PIP system, holes were made with a 40-cm diameter auger spaced ≈1 m on-center. We then placed landscape cloth over the entire plot, secured it with standard landscape staples, cut an "x" in the cloth above each hole, and placed the socket pots (GL1200; Nursery Supplies, Inc., Chambersburg, PA) so the rims were ≈2.5 cm above the surface of the ground. The mean daily temperature during the growing season (June through September) was 25 °C for 2006 and 26 °C for 2007; total precipitation during that time was 318 mm in 2006 and 295 mm in 2007 (MAWN, 2007). Average air temperature during the winter months (Dec. 2006 through Mar. 2007) was –1 °C with a minimum of –22 °C (MAWN, 2007).

### Plant material

In May 2006, 90 seedlings (2 + 2 or plug + 2) each of *Abies fraseri* (Pursh) Poir., *Picea glauca* var. *densata*, *P. pungens* Engelm. var. *glauca* Regel, and *Pinus strobus* L. (Table 1) were potted in 11.2-L (#3) containers (EG1200; Nursery Supplies, Inc.).

### Container substrates

Seedlings were potted in one of three substrate mixes selected to provide a range of physical properties. Substrate consisted of composted pine bark (B) and Canadian peatmoss (PM) in ratios (vB:vPM) of 70%:30%, 80%:20%, or 90%:10% (Renewed Earth, Kalamazoo, MI). Thirty trees of each species were potted in each substrate mix.

### Fertilizer treatment

Controlled-release fertilizer (Osmocote® Plus 15-9-12, 8–9-month Northern release rate; The Scotts Co., Marysville, OH) was top-dressed in the spring of 2006 and 2007. Each tree received one of three rates: low (0.25 g N/L), medium (0.5 g N/L), or high (1 g N/L). The medium and high rates were chosen based on the manufacturer's recommended rates and to bracket a common standard used in the commercial nursery industry of 0.75 g N/L. The low rate was selected to determine if an acceptable crop of these species could be grown with reduced fertilizer inputs.

Table 1. Means (± SE) of initial caliper and height, taken 18 May 2006, for four conifer species grown in a pot-in-pot production system under three fertilizer rates and three substrate combinations.

| Species | Caliper (mm) | Ht (cm) |
|---|---|---|
| *Abies fraseri* | 9.43 (± 0.18) | 30.90 (± 0.68) |
| *Picea glauca* var. *densata* | 8.83 (± 0.18) | 23.97 (± 0.52) |
| *Picea pungens glauca* | 9.57 (± 0.21) | 27.20 (± 0.64) |
| *Pinus strobus* | 9.74 (± 0.27) | 36.99 (± 1.11) |

### Experimental design

The experimental design was a split plot in a randomized complete bloc design with species as the main plot effect and factorial combinations of fertilizer × substrate as the subplot. Trees were arranged in the PIP system to allow for blocking in time of physiological measurements (described subsequently). There were 10 blocks, each consisting of four rows, one for each species; each row had nine trees, one for each of the fertilizer × substrate combinations.

### Irrigation

Irrigation was initially applied using overhead sprinklers to promote establishment after transplanting. In mid-June 2006, microsprinkler spray stakes (TS-90; Chapin Watermatics Inc., Water Town, NY) were installed, one per pot, and set to apply ≈0.35 $L \cdot min^{-1}$. Trees were then irrigated twice per day using an automated valve (8014 DuraLife; L.R. Nelson Corp., Peoria, IL) at 0700 HR and 1730 HR, for 5 min each cycle, totaling ≈3.5 L of water applied daily per tree. Trees were irrigated from early May to mid-November in both 2006 and 2007. Total alkalinity of the irrigation water was 6.4 $mEq \cdot L^{-1}$ $CaCO_3$.

### Nitrate-N, pH, and electrical conductivity in leachate

The pourthough extraction procedure (Altland, 2006; Bilderback, 2001; Wright, 1986) was used to collect leachate from a subsample of two species, *A. fraseri* and *P. strobus*, with fertilizer × substrate combinations of 0.25 g N/L × 70:30 (B:PM), 0.25 g × 90:10, 0.5 g × 80:20, 1.0 g × 70:30, and 1.0 g × 90:10. This sampling scheme permitted sampling in a reasonable time, allowed examination of a range of conditions and allowed for valid statistical testing of substrate × fertilizer interactions. Samples were collected about every 2 weeks from June to Aug. 2007. Equal volumes of water were applied to each tree and allowed to drain; leachate was collected into 20-mL vials and stored in a cooler at 2.5 °C. Electrical conductivity (EC; ExStik II EC500; Omni Controls Inc., Tampa, FL) and pH (Accumet® basic AB15 m; Thermo Fisher Scientific Inc., Waltham, MA) were measured in the laboratory within 1 week after collection. Nitrate-N analysis was then conducted by the MSU Soil and Plant Nutrient Laboratory using flow injection with cadmium reduction (Huffman and Barbarick, 1981).

### Growth

We measured height and caliper of all trees at the beginning and end of the 2006 and 2007 growing seasons. Height was measured from the rim of the pot to the tip of the leader (most vertical central shoot); caliper was measured in an east–west orientation level with the rim of the pot. Terminal growth of *P. strobus* was measured every 2 weeks until growth stopped, usually in mid-July. Terminal shoots of *P. strobus* were pruned to 25 to 30 cm (in proportion to the overall height of the tree) according to standard nursery practice. Height growth for *P. strobus* was determined as leader length before pruning. *Picea* spp. and *A. fraseri* were not pruned except to maintain a single terminal leader. Height growth of all other species and caliper growth were calculated by subtracting the initial measurements from the final measurements.

### Gas exchange

*Picea spp. and Abies fraseri.* We measured photosynthetic gas exchange on *A. fraseri*, *P. glauca* var. *densata*, and *P. pungens glauca* with a portable photosynthesis system (LI-6400; LI-COR, Inc., Lincoln, NE) in July and Aug. 2006 and May, June, July, and Sept. 2007. On each date, measurements were taken between 0900 HR and 1700 HR; however, data collection typically spanned multiple days. A 0.25-L conifer chamber attachment (LI-6400-05; LI-COR, Inc.) was used to enclose a single shoot of the current season's growth on each tree. Light saturated photosynthesis ($A_{max}$) and shoot conductance to water vapor ($g_{wv}$) were measured on shoots exposed to full sunlight on days with photosynthetic photon flux density greater than 1200 $\mu mol \cdot m^{-2} \cdot s^{-1}$. To reduce variation resulting from temperature, leaf chamber temperature was maintained at the predicted high temperature for each day of measurement. Air flow through the chamber was 500 $mL \cdot min^{-1}$ with the reference $CO_2$ maintained at 400 $\mu mol$ $CO_2$/mol. Vapor pressure deficit (VPD) was maintained at ≈3 kPa. Shoots were tagged so subsequent measurements were taken on the same shoot throughout each year. We collected the tagged shoots at the end of each growing season and scanned them with a leaf area meter (LI-3000; LI-COR, Inc.) to determine projected shoot area. Intrinsic water use efficiency was

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calculated by dividing $A_{max}$ by $g_{wv}$ for each measurement.

*Pinus strobus.* We measured gas exchange of *P. strobus* using the same system described previously; however, Because the shoots would not fit in the conifer chamber, a 3 × 2-cm leaf chamber with a red/blue light-emitting diode light source (LI-6400-02B; LI-COR, Inc.) with quantum flux maintained at 1500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ was used to enclose a portion of the needles. Light-saturated photosynthesis ($A_{max}$) and needle conductance to water vapor ($g_{wv}$) were measured on needles of *P. strobus* in July and Aug. 2006 and May, June, July, and Sept. 2007. We placed two fascicles of needles from the current season (a total of 10 needles) lengthwise in the chamber, making sure the needles did not overlap. Air flow, chamber temperature, and VPD were maintained as described previously. Needle surface area was determined for *P. strobus* needles using a dissecting microscope to measure the radius on a subsample of needles. Total surface area of each needle was calculated by assuming each needle represented one-fifth of a cylinder (Johnson, 1984).

### Chlorophyll fluorescence

A portable chlorophyll fluorescence meter (Plant Efficiency Analyzer; Hansatech Instruments Ltd., Norfolk, U.K.) was used to measure the ratio of variable fluorescence to maximum fluorescence ($F_v/F_m$) for individual needles from each tree. The needles were dark-acclimated for a minimum of 15 min before readings were taken. Dates of measurement of $F_v/F_m$ coincided with measurements of $A_{max}$.

### Foliar analysis

We collected approximately five shoots (for single-needle conifers) or 20 fascicles (for pines) from each tree on 15 Aug. 2006 and again on 12 Oct. 2007 for foliar nutrient analyses. To facilitate sampling and analyses, foliar samples were combined across substrate type. The shoots and fascicles were placed in paper bags and oven-dried at 60 °C for 1 week. After drying, needles were ground in a coffee grinder until they passed through a 40-mesh (0.42 mm) sieve. The prepared samples were analyzed for foliar nutrients at a commercial laboratory (Waters Agricultural Laboratories, Inc., Camilla, GA). In 2006, samples from three of the 10 blocks were analyzed for full foliar nutrient concentration and the remaining blocks were analyzed only for nitrogen concentration. All samples collected in 2007 were analyzed for full foliar nutrient concentration.

### Tree needle weight

Total shoot or needle weights were determined for a subsample of trees at the end of the 2007 growing season. One block of trees was selected, and each tree was destructively harvested. For the single-needle conifers, shoots were separated by year; 2007 growth was removed first by pruning all shoots beyond the 2006 terminal bud scar and placing them in a paper bag. Next, 2006 growth was removed (as determined by the 2005 terminal bud scar) and placed in a second paper bag. Finally, the remaining shoots were removed and placed in a third paper bag. For *P. strobus*, needles were removed from the shoots and also separated by year using the same method as for the single needle conifers. Shoots and needles were oven-dried at 60 °C for 1 week and then weighed. We then performed a regression analysis between the shoot or needle weights and stem volume index (caliper$^2$ × height) to estimate total shoot or needle weights for every tree. As a result of a significant species effect, separate regression equations were developed for each species.

### Statistical analysis

All variables were tested for normality using PROC UNIVARIATE and Levene's test. Height and caliper growth were normalized using a square root transformation. A log transformation was used to normalize stem volume growth; $NO_3$ and EC in leachate; *P. strobus* $A_{max}$ and transpiration data; and transpiration and conductance for the single-needle conifers. Chlorophyll fluorescence was normalized by squaring the data.

PROC MIXED (SAS Inc., Cary, NC) was used to determine Type 3 analyses of variance (ANOVAs) for species, treatment, date, and interaction effects. Effects for gas exchange, nitrate-N, pH, EC, and $F_v/F_m$ data were analyzed using repeated measures within PROC MIXED. Correlations between $F_v/F_m$ and foliar nutrient concentrations were determined using PROC CORR.

## Results

*Pourthrough samples.* Leachate $NO_3$ concentration, EC, and pH levels were affected ($P$ < 0.0001) by fertilizer addition (Fig. 1). Species and substrate effects and interaction effects associated with substrate and fertilizer were not significant or weak relative to fertilizer and date effects; therefore, leachate data were averaged across species and substrate to simplify data presentation. Leachate $NO_3$ concentrations and EC were consistently higher with the 1.0 g N/L container fertilizer treatment compared with the 0.25 or 0.5 $g \cdot L^{-1}$ treatments (Fig. 1). Seasonal trends in $NO_3$ and EC indicate a broad plateau, suggesting that nutrient release from the controlled-release fertilizer (CRF) was consistent across the growing season until late summer. Leachate pH decreased with increasing fertilizer addition (Fig. 1) indicating the acidifying effect of the CRF offset the high pH and alkalinity of the irrigation water, especially at the 1 g N/L fertilization rate.

*Growth responses.* The overall ANOVA of stem caliper and height growth indicated highly significant ($P$ < 0.0001) effects of year

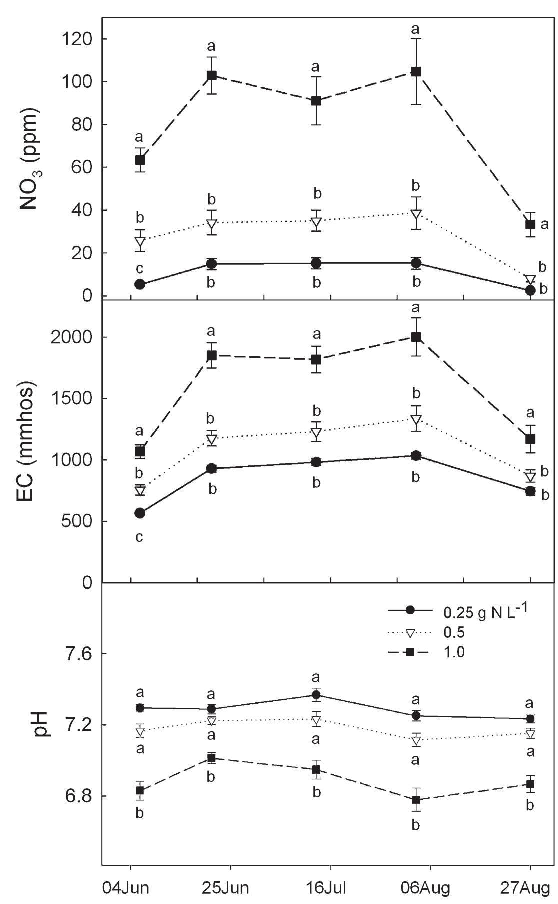


Fig. 1. Mean nitrate-N concentrations, electrical conductivity (EC), and pH (± SE) for pourthrough leachate samples for *Abies fraseri* and *Pinus strobus* (data combined) grown in a pot-in-pot production system under three fertilizer levels. Means averaged across three substrate combinations.

and interaction effects of species and fertilizer with year; therefore, 2006 and 2007 growth data were analyzed separately (Table 2). Fertilizer rate and species significantly affected ($P < 0.0001$) stem caliper growth in both years. The interaction of fertilizer × substrate effects for height and caliper growth were not significant; therefore, growth responses to fertilizer are presented across all substrate types (Fig. 2). Species differed in caliper growth response to fertilization as indicated by significant interactions of species and fertilizer (Table 2). In the first season after transplanting (2006), stem caliper increased with increasing fertilizer for all species (Fig. 2). Growth of *Picea glauca* trees increased at a greater rate at the highest fertilizer level than the other species in 2006. In the second season after transplanting, caliper growth response to fertilization for all species began to plateau after 0.5 g N/L. Caliper growth of *Abies fraseri* and *Picea pungens* increased slightly from 0.5 to 1.0 g N/L, but the difference was not significant ($P > 0.05$) for either species. Addition of 0.5 g N/L resulted in a much larger increase in growth of *Pinus strobus* trees than trees of the other species, resulting in the significant species × fertilizer interaction for caliper growth in 2007. In contrast to caliper growth, fertilization affected ($P < 0.0001$) height growth in 2007 only (Fig. 2). In 2007, height growth response to fertilization followed a similar trend as caliper growth with growth beginning to plateau near 0.5 g N/L. There was no difference ($P > 0.05$) in height growth between 0.5 and 1.0 g N/L for any of the species tested.

The effect of container substrate on height and caliper growth was smaller than the effect of fertilization (Table 2). Increasing the proportion of peatmoss in the container substrate increased caliper growth in 2006, whereas in 2007, caliper growth was greatest at the intermediate container mix (Table 3) Height growth did not respond to substrate in 2006. In 2007, height growth increased slightly with increased proportion of peatmoss in the mix and height growth of trees in the 70:30 (PB%:PM%) was greater ($P < 0.05$) than growth of trees in the 90:10 mix. Across species, there were no differences ($P > 0.05$) in either growth variable between trees grown in the 80:20 or 70:30 mix. *Pinus strobus* trees grown in the 80:20 grew less in height than trees in the other mixes, resulting in a significant species × substrate interaction for height growth in 2006.

Table 2. Summary analysis of variance for caliper height growth of *Abies fraseri, Picea glauca* var. *densata*, *Picea pungens glauca*, and *Pinus strobus* trees grown for 2 years in a pot-in-pot system under three fertilizer rates and three container substrate combinations.

| | | 2006 | | 2007 | |
|---|---|---|---|---|---|
| Source of variation | df | Caliper growth | Ht growth | Caliper growth | Ht growth |
| Block (B) | 9 | 2.68 | 2.74 | 1.57 | 1.91 |
| Species (Spp) | 3 | 10.09*** | 63.95*** | 8.95** | 18.08*** |
| Fertilizer (F) | 2 | 82.10*** | 2.69 | 51.70*** | 89.25*** |
| Spp × F | 6 | 3.01* | 1.21 | 3.31** | 0.78 |
| Substrate (Sub) | 2 | 5.88** | 0.48 | 4.31* | 4.53* |
| Spp × Sub | 6 | 1.89 | 4.76** | 1.63 | 2.07 |
| F × Sub | 4 | 2.69* | 1.11 | 0.85 | 0.32 |
| Spp × F × Sub | 12 | 1.20 | 2.47* | 0.91 | 0.97 |

* Column means significantly different at $P < 0.05$; **, column means significantly different at $P < 0.01$; ***, column means significantly different at $P < 0.0001$.

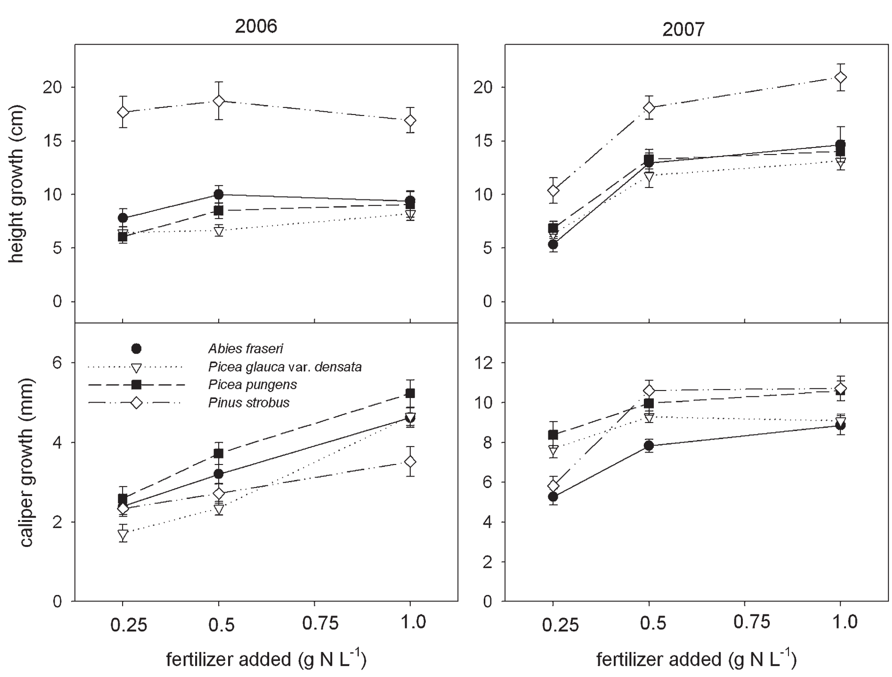


Fig. 2. Mean height and stem caliper growth of *Abies fraseri*, *Picea glauca* var. *densata*, *Picea pungens*, and *Pinus strobus* grown in a pot-in-pot production system under three fertilizer levels. Error bars ± SE of mean.

*Physiological responses.* As a result of differences in shoot morphology, gas exchange rates of the single-needle conifers (*Abies* and *Picea* species) were calculated on projected shoot area basis, whereas *P. strobus* measurements are based on total needle area. Therefore, results for the gas exchange parameters are presented separately for the two groups.

Net photosynthesis ($A_{max}$) and shoot conductance to water vapor ($g_{wv}$) response of the spruces and firs to fertilization differed between years. In 2006, photosynthetic rates were generally greater at higher fertilizer levels (Fig. 3). During the 2007 season, however, $A_{max}$ was unaffected for *Abies fraseri* and deceased at higher fertilizer rates for the *Picea* trees (Fig. 3). When the data were averaged across species and fertilizer treatment, $A_{max}$ was greater at higher peatmoss ratios during the first growing season. However, in 2007, there were no differences between rates for the varying substrate compositions (data not shown). Species affected ($P < 0.0001$) $A_{max}$; rates were nearly double for the *Picea* species compared with *A. fraseri*. For *Pinus strobus*, net photosynthesis and needle conductance to water vapor were unaffected ($P > 0.05$) by substrate or fertilizer in either year (Fig. 4).

*Foliar nutrition and variable chlorophyll fluorescence.* Foliar nitrogen concentrations of foliar samples varied ($P < 0.0001$) by species and year. *Picea* species had greater N concentrations compared with *A. fraseri* and *P. strobus* over both years, and in 2007, *Picea pungens* had higher foliar N levels than *P. glauca* var. *densata*. Fertilization increased N concentration of needles for all species; however, differences between the 0.25 and 0.5 g N/L additions were more pronounced in 2006 than in 2007 (Fig. 5). Fertilization effects on concentrations of other major elements were small relative to effect of foliar N. Of eight species × year combinations, fertilization increased foliar phosphorus twice (*Pinus strobus* in 2006 and *Abies fraseri* in 2007) and foliar potassium (K) once (*Abies fraseri* in 2006). In three instances, foliar nutrient concentrations decreased with fertilization (foliar K of *Picea glauca* in 2006 and Picea *pungens* 2007 and foliar magnesium of *Pinus strobus* in 2007).

Year and species affected ($P < 0.01$) chlorophyll fluorescence ($F_v/F_m$). Within species and years, fertilization did not affect chlorophyll fluorescence, except for reduced $F_v/F_m$ of *Picea pungens* trees at the lowest level of fertilization in 2006 (Fig. 5). Correlation analysis of $F_v/F_m$ with foliar nutrient concentrations indicated that $F_v/F_m$ was not consistently correlated with foliar nutrition (Table 4).

## Discussion

Overall, species and fertilization had larger effects on growth and physiology of conifers grown in the PIP system than the ratio of peatmoss to pine bark in the container substrate. Plants grew as well or better in the intermediate substrate mix (80:20 pine bark: peatmoss) than any of the other combinations for each species. Therefore, growers using pine bark and peatmoss substrates can potentially use a single mix for all species compared in this study rather than mixing special combinations for different species.

Table 3. Mean stem caliper growth and height growth of conifers grown in substrates comprised of three different ratios of pine bark (PB) and peatmoss (PM).

| Substrate (PB%:PM%) | 2006 Caliper growth (mm) | 2006 Ht growth (cm) | 2007 Caliper growth (mm) | 2007 Ht growth (cm) |
|---|---|---|---|---|
| 90:10 | 3.00 a[z] | 10.6 a | 8.13 a | 11.3 a |
| 80:20 | 3.30 ab | 10.0 a | 8.95 b | 12.54 ab |
| 70:30 | 3.60 b | 10.6 a | 8.75 ab | 13.0 b |

[z]Means within a column followed by the same letter are not different a $P < 0.05$. Mean separation based on Tukey's studentized range test.

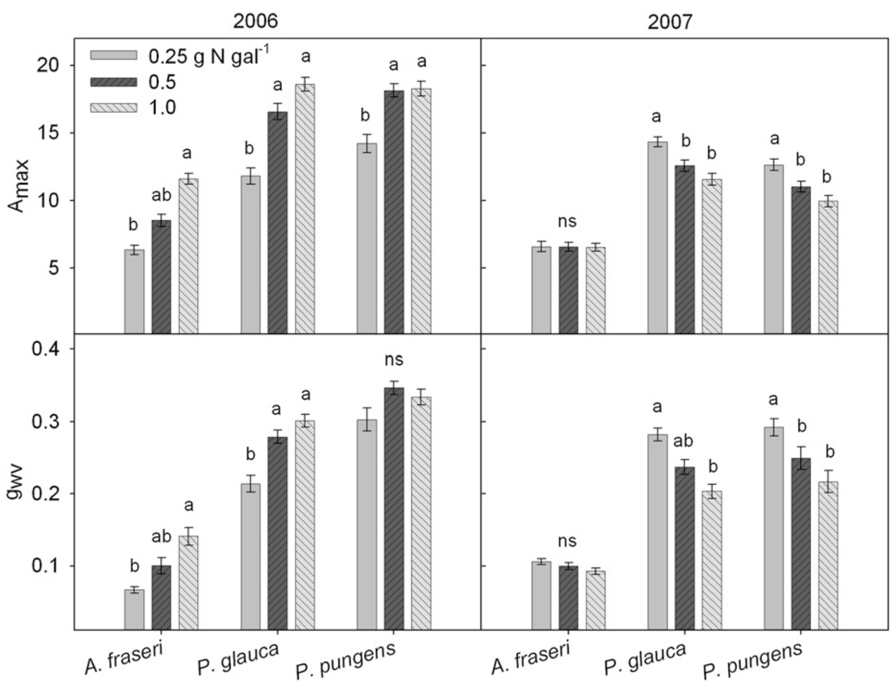


Fig. 3. Mean photosynthetic rate ($A_{max}$; μmol $CO_2$/m²/shoot area/s) and conductance ($g_{wv}$; mol $H_2O$/m²/shoot area/s) (± SE) for *Abies fraseri*, *Picea glauca* var. *densata*, and *Picea pungens* grown in a pot-in-pot production system under three fertilizer levels; data averaged across three substrate combinations. Means within a species headed by the same letter are not different at $P < 0.05$. Mean separation based on Tukey's studentized range test. Photosynthesis and conductance main effects are significant for species in both 2006 and 2007 ($P < 0.0001$).

Caliper growth was more responsive to fertilization in the first year than height growth. This is not surprising considering that height growth typically occurs early in spring and is largely influenced by bud formation during the previous season. Stem caliper growth, in contrast, continues throughout the season and is more affected by the current environmental conditions and cultural factors. During the second season, growth was more reflective of treatments applied in the study than in seedling production, and differences between treatments were more clearly expressed. In the present study, maximum growth in 2007 occurred with fertilizer additions of 0.5 g N/L container or greater.

Nitrogen is a component of chlorophyll and enzymes involved in the photosynthetic reactions; therefore, photosynthetic rates of conifers are typically dependent on needle N concentration (Strand, 1997) and increase with fertilization (Samuelson, 2000). In the present study, photosynthetic response to fertilization varied by year for spruce and fir trees. In the first year of the study, photosynthetic rates followed the anticipated pattern and increased with increased nutrient availability. In the second year of production, however, photosynthetic rates declined or remained constant although foliar N increased consistently with N availability. We speculate that the decline in photosynthetic gas exchange with fertilization is the result of increased moisture stress associated with increased leaf area production and plant water use. This hypothesis is supported by several lines of evidence. Total shoot weight (and therefore leaf area) increased with increasing fertilizer addition (data not shown). The greater shoot area results in increased transpirational water loss. This is consistent with the decrease in leaf conductance with increased fertilizer addition. Therefore, growth response to fertilization in the second year of the study may have been limited by water stress at the highest fertilizer levels.

Critical nutrient levels (minimum foliar N at which growth reaches 90% of maximum) have been identified for various conifer species, particularly those common in Christmas tree production. In a study in New York, Slesak and Briggs (2007) found that critical foliar N concentrations ranged between ≈1.4% and

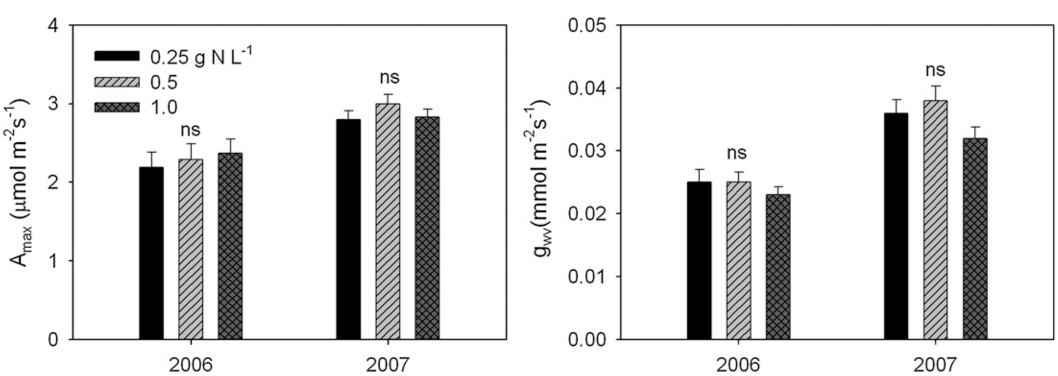


Fig. 4. Mean photosynthetic rate ($A_{max}$; μmol $CO_2$/m²/needle area/s) and conductance ($g_{wv}$; mol $H_2O$/m²/needle area/s) (± SE) of *Pinus strobus* trees grown in a pot-in-pot production system under three fertilizer levels; means within a year are not different at $P \leq 0.05$.

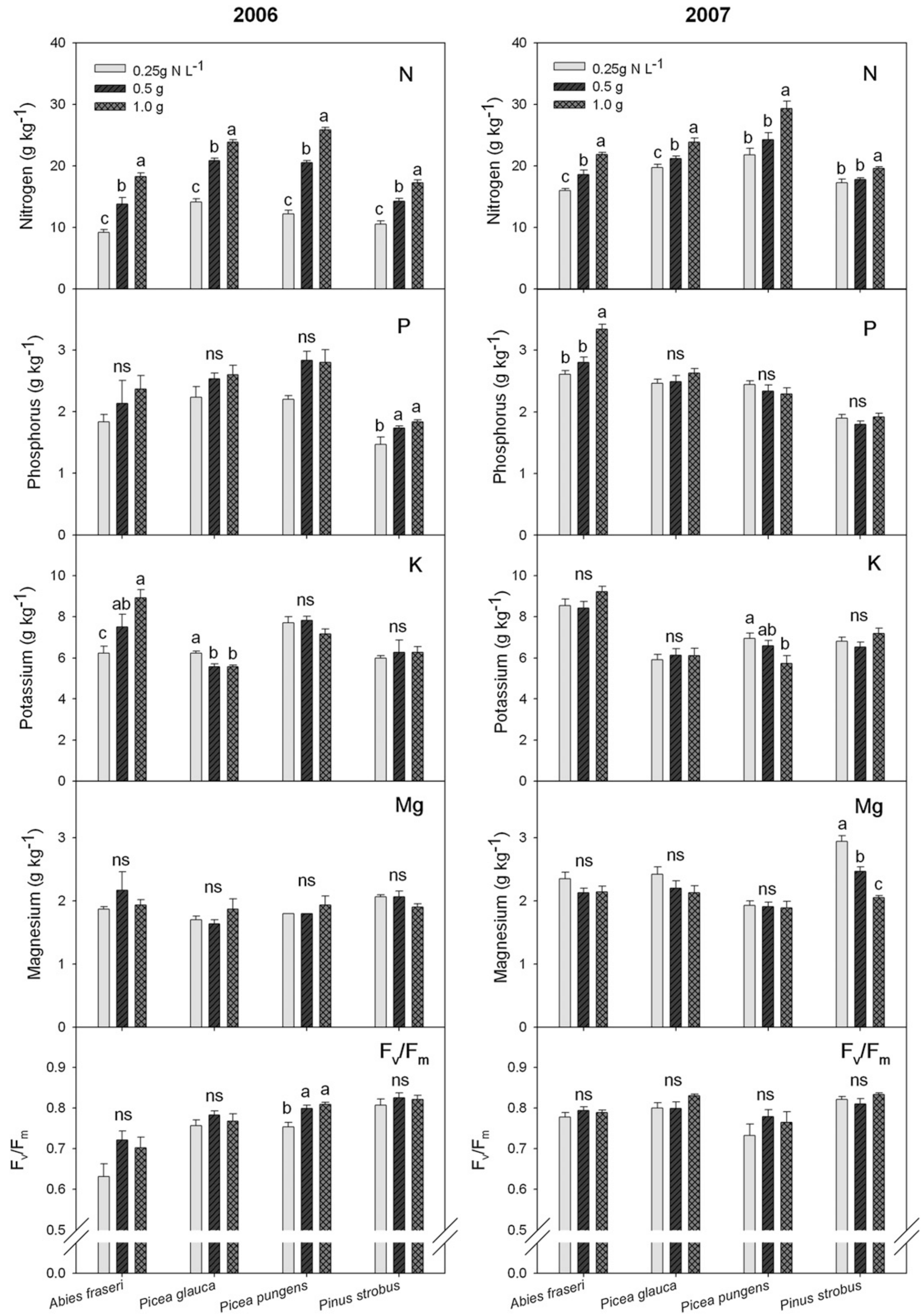

Fig. 5. Mean (± SE) foliar nutrient concentration and chlorophyll fluorescence of *Abies fraseri*, *Picea glauca* var. *densata*, *Picea pungens*, and *Pinus strobus* grown in a pot-in-pot production system under three fertilizer levels. Means within a species headed by the same letter are not different at $P < 0.05$. Mean separation based on Tukey's studentized range test.

1.8% for various species of *Abies*. Rothstein and Lisuzzo (2006) referred to a critical level of 1.5% for their study on *A. fraseri*. In the current study, we identified a critical foliar N concentration for *A. fraseri*, of ≈1.8%, which is close to the value reported by Slesak and Briggs (2007) and Rothstein and Lisuzzo (2006). Growth rate for *P. strobus* also leveled off ≈1.8%. The *Picea* species had slightly higher critical levels: ≈2.1% for *P. glauca* var. *densata* and 2.4% for *P. pungens glauca*.

Several studies have shown potential for relating chlorophyll fluorescence ($F_v/F_m$) with foliar nutrient concentrations (Cregg et al., 2004; Ritchie, 2006; Strand, 1997) and $F_v/F_m$ has been correlated with foliar concentrations of phosphorus (Loustou et al., 1999), iron (Morales et al., 2000), and magnesium (Laing et al., 2000). The lack of consistent correlations between $F_v/F_m$ and foliar nutrition in the current study may be related to several factors. The response of $F_v/F_m$ to foliar nutrition often shows a threshold response (Cregg et al., 2004). In this study, the low fertilizer level (0.25 g N/L) appeared to be sufficient to keep needle chlorophyll

Table 4. Pearson correlation coefficients for chlorophyll fluorescence ($F_v/F_m$) and foliar nutrient concentrations of *Abies fraseri*, *Picea glauca* var. *densata*, *Picea pungens*, and *Pinus strobus* grown in a pot-in-pot production system under three fertilizer levels.

| Year | Species | Nitrogen | Phosphorus | Potassium | Magnesium | Calcium | Copper | Manganese | Iron |
|---|---|---|---|---|---|---|---|---|---|
| 2006 | *Abies fraseri* | 0.14 | 0.05 | 0.28 | 0.08 | –0.03 | –0.01 | –0.12 | –0.43* |
| | *Picea glauca* var. *densata* | 0.12 | –0.07 | –0.10 | –0.05 | 0.07 | 0.04 | –0.12 | –0.21 |
| | *Picea pungens* | 0.51** | 0.52* | 0.23 | 0.37 | 0.48* | 0.54* | 0.54* | –0.30 |
| | *Pinus strobus* | 0.15 | 0.01 | –0.15 | –0.04 | –0.10 | 0.04 | 0.10 | 0.02 |
| 2007 | *Abies fraseri* | 0.27* | 0.14 | 0.00 | –0.21 | –0.09 | 0.25* | 0.12 | 0.15 |
| | *Picea glauca* var. *densata* | 0.17 | 0.29* | 0.12 | 0.15 | 0.11 | –0.20 | 0.24* | 0.18 |
| | *Picea pungens* | 0.01 | –0.10 | –0.15 | –0.08 | –0.25* | –0.06 | 0.09 | –0.10 |
| | *Pinus strobus* | 0.06 | 0.10 | 0.05 | –0.06 | 0.02 | –0.10 | 0.16 | –0.14 |

*, **Correlation with $F_v/F_m$ significant at 0.05 and 0.001, respectively.

levels above the point at which $F_v/F_m$ begins to decline. In some cases, growth dilution may have precluded increases in foliar nutrient concentrations. Lastly, antagonisms for uptake among certain elements (e.g., K, magnesium, and calcium) may result in decreases in foliar concentrations with fertilization (Mengel and Kirkby, 1982) resulting in poor or negative correlations with $F_v/F_m$.

## Conclusions

Based on growth and physiological responses, conifers grown in PIP systems in northern climates should receive no less than 0.5 g N/L, and applications of 1.0 g N/L may increase caliper growth during the first year. Growth response to fertilization may have been limited by water availability in the second year of the study. Our results indicate that growers may use one standard mix for the species in this study with a recommended a ratio of 80% pine bark to 20% peatmoss. When monitoring foliar N, levels should be at least 1.8% for *A. fraseri* and *P. strobus*, 2.1% for *P. glauca* var. *densata*, and 2.4% for *P. pungens glauca* for foliar samples collected in late summer. Within the range of fertilization examined in this study, chlorophyll fluorescence was not consistently correlated with foliar nutrient concentrations.

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