Slow Release Fertilization Reduces Nitrate Leaching in Bareroot Production of *Pinus strobus* Seedlings

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Abstract: The nitrate (NO_3^-) leaching potential from bareroot tree nurseries is great, yet no researchers have investigated the effect of slow release fertilization on NO_3^- leachate concentrations. The effects of slow release fertilizer on nitrate-nitrogen (NO_3–N) leachate concentrations, seedling morphology and nutrient content, soil nitrogen (N), and cation leachate concentrations were studied in the bareroot production of *Pinus strobus* (L.) (eastern white pine) seedlings in southwestern Wisconsin. Three fertilizer treatments were used: slow release 1 (SRF1, 19N:6P_2O_5:1K_2O); slow release 2 (SRF2, 12N:0P_2O_5:42K_2O); and a conventional fertilizer (Conv, 15.5N:0P_2O_5:0K_2O). A total of 180 and 52 kg N/ha (161 and 47 lb/ac) were applied in the Conv and SRF treatments, respectively. Over a 2-year period, soil leachate concentrations were collected weekly (May to December) from porous cup samplers installed at a depth of 1 m (3.3 ft) below the surface; soil was collected every 2 weeks, and plant tissue was collected once at the end of each growing season (late August). There were no differences in seedling morphology (height, diameter, dry mass) during the first or second growing season. Seedling nutrient concentrations were the same for all treatments at the end of first growing season, but Conv-treated seedlings contained greater concentrations of N (33 g/kg N for Conv compared to 30 g/kg for SRF) by the end of the second growing season. Nitrate-N leachate concentrations were greater for the Conv treatment compared to both SRF treatments during the first and second growing seasons. However, treatment did not affect cation leachate concentrations. Similarly, there was little difference in soil N among treatments. Overall, SRF reduced NO_3–N leachate concentrations in bareroot nursery tree production without sacrificing seedling quality.

Keywords: ground water contamination, nutrient uptake, environmental quality

Introduction

Concern over nonpoint ground-water contamination has directed much attention and research into reducing ground-water pollution by nitrogen-based fertilizers in agricultural systems. In bareroot nurseries, multiple applications of fertilizer nitrogen (N) have been applied throughout the growing season in an attempt to raise soil N (van den Driessche 1988). However, soil N is often in excess of plant N uptake, which results in the leaching of nitrate (NO_3^-) from the root zone (Weed and Kanwar 1996; Bundy and Malone 1998). Once leached from the root zone, NO_3^- can enter the ground water and, in large concentrations, is a public health concern (Goodrich and others 1991).

Few researchers have investigated NO_3^- leaching potential from bareroot tree nurseries relative to agricultural systems where N cycling is well documented (Tyler and Thomas 1977; Lowery and others 1998; Brye and others 2001). Nitrate-N leachate concentrations of 35 mg/L and 15 to 20 mg/L were measured at 15-cm and 1-m (6-in and 3.3-ft) depths, respectively, in an investigation of 6 bareroot nurseries in the midwestern US (Schultz and others 1993). Similarly, a study performed by the US Department of Agriculture (USDA) Forest Service found NO_3–N concentrations in 11 Forest Service nurseries as high as 55 mg/L, but NO_3–N concentrations consistently occurring between 1 to 11 mg/L (Landis and others 1992).

Most bareroot tree nurseries are located on loamy sands for increased ease of planting, pruning, harvesting, and management of soil fertility parameters. Because these soils are highly susceptible to leaching of NO_3^-, calcium (Ca^{2+}), potassium (K^+), and magnesium (Mg^{2+}) (Fisher and Binkley 2000), bareroot tree nurseries rely on conventional, soluble N-based fertilizers, applied several times throughout the growing season to maintain a steady supply of N. As a result, rates of conventional N-based fertilizer application in bareroot tree nurseries often exceed rates applied in other agricultural systems (Shultz and others 1993).

Application of slow release fertilizer (SRF), also commonly referred to as controlled release fertilizer (CRF), in bareroot tree nurseries has remained limited despite research suggesting comparable growth results from compounds such as isobutylidene diurea (Benzian and others 1969, 1971) and Osmocote® (van den Driessche 1988) on slow-growing conifer species. Moreover, the use of SRF has been shown to reduce NO_3–N leaching in containerized nursery systems (Rathier and Frink 1989; Yeager and others 1993). Low use rates may be blamed on lack of nursery formulations and availability of SRFs. However, new polymer-based technology has allowed for more SRF fertilizer formulations suitable for bareroot tree nursery production. In addition, SRFs are available in a variety of nutrient release periods (for example, 3-month, 6-month, 12-month) allowing nursery managers to tailor SRFs to target nutrient demand.

The objective of this study was to compare the effects of conventional and slow release fertilization of *Pinus strobus* (L.) (eastern white pine) seedlings within a bareroot tree nursery on: 1) NO_3–N leachate concentrations; 2) soil N levels; 3) seedling quality (that is, morphology and nutrient content); and 4) cation concentrations in soil and leachate. We hypothesized that the nutrient release rate characteristic of SRF would more closely parallel seedling N demand, thereby reducing N loss from the rooting zone without sacrificing seedling quality. To our knowledge, this report is the first to evaluate NO_3–N leaching under conventional fertilizer and SRF treatments in bareroot tree production.

Materials and Methods

Site Description

The study was conducted in southwestern Wisconsin in the Lower Wisconsin River Valley (LWRV) at the FG Wilson State Tree Nursery, Boscobel, WI (43° 14'N, 90° 70'W) operated by the Wisconsin Department of Natural Resources (WDNR). The soil is classified as Sparta loamy fine sand (*Entic Hapludolls*) with very dark gray loamy fine to medium sand at the surface that grades to yellowish-brown fine to medium sand at depths between 46 and 61 cm (18 and 24 in) (Soil Conservation Service 1951). Runoff was not considered as a potential source of N loss because of the level topography and high infiltration rate characteristic of the alluvial sand plain within the LWRV (Hart and others 1994). Following cultural practices at the nursery, organic matter additions, primarily peat, are supplied as needed to maintain the organic matter content close to 20 g/kg (0.3 oz/lb). Seedbeds are left fallow (sorghum-sudan grass and winter wheat are planted as cover crops to minimize wind erosion) for 2 y following seedling harvest and fumigated with methyl bromide prior to seeding.

Experimental Design

In the fall of 1998, *P. strobus* seeds were sown mechanically into seedbeds at a density of 377 seedlings/m^2 (35 seedlings/ft^2). Two Polyon® (Pursell Technologies, Inc., Sylacauga, AL 35150) polymer-coated slow release fertilizer (SRF) treatments, slow release fertilizer treatment 1, SRF1 ($19N:6P_2O_5:12K_2O$, comprised of 9.0% NO_3–N, 10.0% NH_4–N) and slow release fertilizer treatment 2, SRF2 ($12N:0P_2O_5:42K_2O$, comprised of 12.0% NO_3–N) both with a 5- to 6-month release at 27 °C [81 °F]), and a conventional water-soluble fertilizer, Conv ($15.5N:0P_2O_5:0K_2O$, comprised of 15.5% $CaNO_3$–N) were randomly applied to 6 of the 8 rows within a designated seedbed (rows adjacent to irrigation lines were not used), so that each treatment was applied to 2 rows (Figure 1).

All fertilizer treatments were topdressed using a tractor-propelled Gandy spreader. During the first (1999) and second (2000) growing seasons, both SRFs were applied at 24 kg N/ha (21.5 lb N/ac) per application, and Conv fertilizer was applied at 18 kg N/ha (16 lb N/ac) per application over intervals typical of the nursery conventional fertilization regime (Table 1). Following nursery protocol, 2 applications

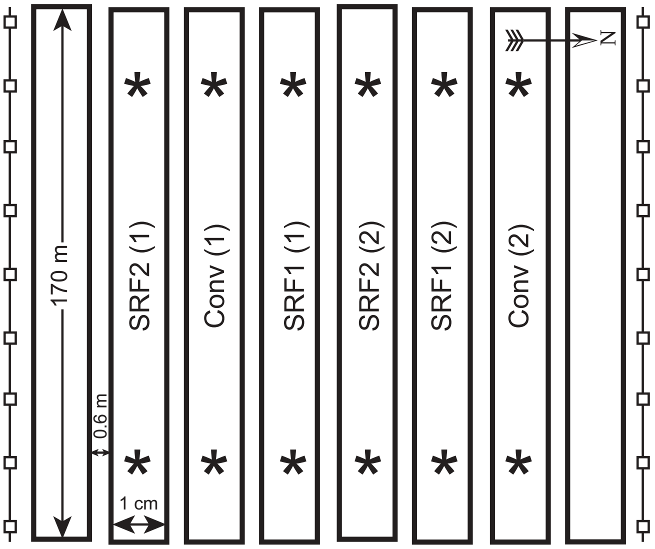

Figure 1—Schematic showing seedbed dimensions, fertilizer treatments (number in parentheses after treatment represents row number used in statistical analysis), and location of porous cup samplers (star).

Table 1—Summary of N application (kg N/ha), and application date over 2 years for conventional (Conv), slow release 1 (SRF1), and slow release 2 (SRF2) fertilizer treatments.

Treatment	Nitrogen application	Application date
	kg/ha	*Julian day*
1999		
Conv[a]	18	144, 154, 161, 169, 180, 187, 193, 204, 223, 232
SRF1[b]	24	146, 180[d]
SRF2[c]	24	146, 180[d]
2000		
Conv	18	130, 138, 145, 151, 158, 168, 174, 182, 203, 210
SRF1	24	132[d], 171
SRF2	24	132[d], 171

[a] Water soluble fertilizer 15.5N:$0P_2O_5$:$0K_2O$ and 18N:$46P_2O_5$:$0K_2O$ on Julian day 187, 232.
[b] Slow release fertilizer 19N:$6P_2O_5$:$12K_2O$.
[c] Slow release fertilizer 12N:$0P_2O_5$:$42K_2O$.
[d] Plus 15% water soluble 21N:$7P_2O_5$:$14K_2O$.

of Epsom salts ($MgSO_4$) at 134 kg/ha (119 lb/ac) and 3 applications of potassium sulfate (K_2SO_4) at 90 kg/ha (80 lb/ac) were applied to all treatments. Shortly after the first application of slow release fertilizer on May 26, 1999 (Julian day 146), heavy rainfall dislodged and transported a significant quantity of the slow release capsules into the shallow tractor furrows between rows. To compensate for the displaced fertilizer, both SRFs were reapplied, along with 15% water-soluble fertilizer to act as a N boost, and manually incorporated into the top 1 in (2.5 cm) of the soil. Because our study was conducted within the production area of the nursery, cultural practices such as pest control, weeding, and irrigation followed routine nursery operations in all treatments.

Leachate Sampling and Analysis

Leachate samples were collected using ceramic porous-cup samplers (PCS) (Timco Mfg Co, Prairie du Sac, WI 53578) fitted with high-density polyethethlyene tubing (0.43 cm [0.17 in] inside diameter) attached to both sample and vacuum lines of the sampler. Prior to installation, each porous-cup sampler was rinsed 3 times with deionized water and tested for leaks under a positive pressure of 100 kPa (1 bar) according to the manufacturers reported air-entry value (McGuire and others 1992). The samplers were installed on May 19, 1999 (Julian day 139), at 1 m (3 ft) below the surface following procedures described by Hart and Lowery (1997). Samplers were positioned as illustrated in Figure 1. A hand pump was used to apply a 65 kPa (0.65 bar) falling head, negative pressure to all PCS after each sampling. The first sample, collected on May 26 (Julian day 146), was discarded to minimize contamination. Beginning on June 2 (Julian day 151), samples were collected weekly through September and every other week through mid-December. Samples were transported back to the laboratory in an ice-filled cooler and stored at 4 °C (39 °F) until analysis.

To determine leachate ion concentrations, a 0.2 µm filter luer-locked to a 3 ml syringe was used to subsample the leachate samples into an amber vial with a penetrable Teflon-lined rubber cap. Nitrate-N concentrations were determined using a Dionex DX500 ion chromatogram (Dionex corporation, Sunnyvale, CA 94088). Total minerals were determined by inductively coupled plasma analysis (ICP) using a Quantometer 34000 (Thermo Jarrell Ash Corporation, Franklin, MA 02038). We followed the same sample preparation and analysis protocol for all water samples collected from irrigation inlets.

Rainfall and irrigation data were collected using a tipping bucket rain gauge attached to a cylindrical drum recorder. In addition, 3 manual, wedge-shaped rain gauges, spaced 1.5 m (5 ft) apart, were installed adjacent to the tipping bucket to record irregular spatial distribution within the irrigation system. Local temperature data were interpolated from nearby automated weather observation stations.

Soil Sampling and Analysis

Soil samples were collected every other week beginning May 19, 1999 (Julian day 139), using a 1.9-cm (0.75-in) diameter manual soil probe from 0 to 15 cm (0 to 6 in). Two composite soil samples comprised of 6 to 8 cores were collected within each treatment row, one at each end. Soil samples were immediately subsampled for determination of total N, NH_4–N, and NO_3–N. Kjeldahl total N, along with 2 *M* KCl extractable NH_4–N and NO_3–N were analyzed according to the Wisconsin Procedures for Soil Testing and Plant Analysis (1987) using flow injection analysis (FIA). The remaining portions of the soil sample were dried in a forced air dryer at 60 °C (140 °F) then passed through an 841-µm sieve. Forest soil analyses performed included pH (electrometric), percent silt and clay (Cenco-Wilde), organic matter content (potassium dichromate in H_2SO_4 by oxidation and titration), available P (0.002 *N* H_2SO_4 Murphy-Riley), and 1 *M* NH_4OAc-extractable potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) according to Wilde and others (1979).

Seedling Collection and Analysis

At the end of each growing season (late August), 40 to 80 seedlings were randomly sampled from each treatment row and measured for height (root collar to terminal bud) and diameter (immediately above the root collar). Seedlings were rinsed with deionized water and dried in a forced air dryer at 60 °C (140 °F) for 3 days. After dry weights were measured, plant tissues were ground and wet-ashed using a 6:1 ratio of HNO_3:$HClO_4$ acids and analyzed for P, K, Ca, and Mg by ICP analysis. Kjeldahl tissue nitrogen was analyzed according to the Wisconsin Procedures for Soil Testing and Plant Analysis (1987) by FIA.

Nitrogen Loading Analysis

Nitrogen loading to the ground water was calculated by:

$$\mathbf{J_w = D_w C}$$

where J_w (mass/volume^2/time) is the loading or solute flux, C (mass/volume^3) is NO_3–N concentration, and the drainage rate (D_w) (volume/time) was calculated using the following equation:

$$D_w = (P+I) - (ET+RO) \pm \Delta S$$

The P = precipitation (volume/time) and I = irrigation rate (volume/time), which was measured on site. ET = potential evapotranspiration rate (volume/time) interpolated from nearby automated weather observation stations, RO = runoff (volume/time, assumed to be zero for Sparta sand), and ΔS = change in water storage over time (volume/time, also assumed to be zero for the Sparta sand over a long period of time) (Hart and others 1994; Lowery and others 1998).

Statistical Analyses

The MIXED procedure in SAS (SAS 1998) was used to fit 3 different models comparing the main effect of fertilizer treatment (Conv, SRF1, SRF2) on each of 3 response variables:

- *Full* model: **Y = m + type + row(type) + e,** where **Y** = response variable; **m** = overall mean; **type =** effect of fertilizer treatment; **row(type)** = random effect of row number (1 or 2) nested within type; **e** = residual error term;
- *Reduced* model: **Y = m + type + e**;
- *Point* model: **Y = m + type + point + type*point + e,** where **point =** random effect of sample position (east or west); **type*point** = interaction between effect of fertilizer treatment and sample position.

A likelihood test was used to evaluate the significance of row number as a random effect between models 1 and 2, and model 3 was performed to check if sample position was random. Pearson linear correlations were computed using the CORR procedure in SAS.

Results

Leachate

Nitrate-N concentrations in irrigation water ranged from 5.62 to 9.32 mg/L, and pH fluctuated between 7.10 and 8.08 throughout the study. Concentrations of K^+, Ca^{2+}, and Mg^{2+} in irrigation water ranged from undetectable to 8.86 mg/L, 21.3 to 40.0 mg/L, and 10.0 to 19.31 mg/L, respectively.

During the first growing season (1999) mean NO_3–N leachate concentrations were greater ($P < 0.05$) in the Conv treatment compared to both SRF treatments (Figure 2). There were no significant differences between SRF treatments. In the Conv treatment, NO_3–N concentrations peaked in late July at 66 mg/L and remained above 50 mg/L until December (Figure 2). Two similar peaks in NO_3–N concentrations were evident in each SRF treatment, the first in early August (SRF1 at 35 mg/L; SRF2 at 44 mg/L) and the second in early October (SRF1 at 43 mg/L; SRF2 at 48 mg/L). Thereafter, NO_3–N concentrations steadily declined to approximately 18 and 26 mg/L in SRF1 and SRF2, respectively (Figure 2).

During the second growing season (2000), peak NO_3–N leachate concentrations for all treatments were considerably less than the peak concentrations recorded in 1999. As in the first growing season, NO_3–N concentrations for the Conv treatment were greater ($P < 0.05$) than each of the SRF treatments (Figure 3). Likewise, no significant differences were observed between SRF treatments. In the Conv treatment, there were 2 separate NO_3N peaks; the first peak occurred in early June (20 mg/L) and the second in late August (16 mg/L) (Figure 3). The maximum NO_3–N leachate concentrations observed for the SRF1 and SRF2 treatment were 3 and 8 mg/L, respectively. In the later portion (Julian days 310 to d 330) of the second growing season, NO_3–N leachate concentrations in the Conv treatment declined to levels observed in both SRF treatment groups (~ 4 to 5 mg/L) (Figure 3).

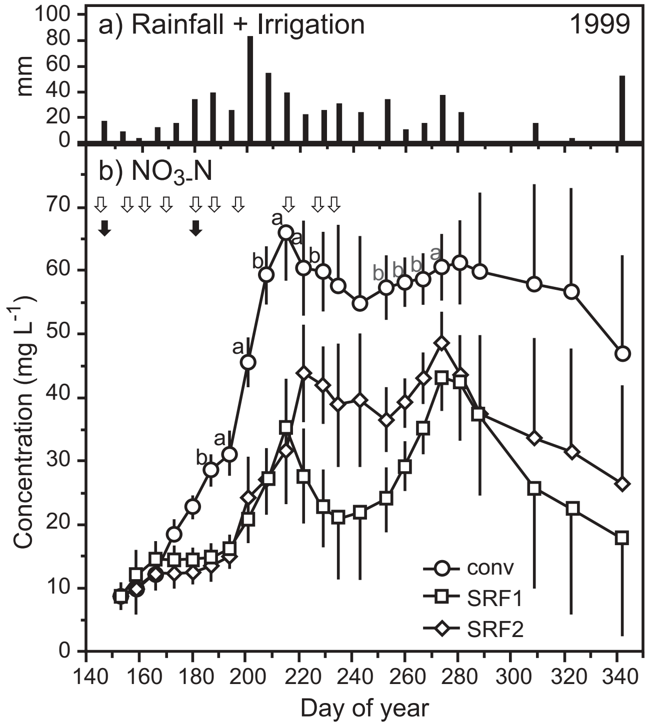

Figure 2—a) Rainfall and irrigation summed between sampling dates from May 1999 to December 1999. b) Average NO_3–N soil water leachate concentrations at 1-m (3-ft) depth for 1999. Filled and open arrows represent slow release and conventional fertilizer applications, respectively.

There were no treatment differences ($P < 0.05$) in leachate cation (K^+, Ca^{2+}, Mg^{2+}) concentrations during the 1999 or 2000 growing season (Figures 4 and 5). In all treatments, K^+ leachate concentrations were undetectable at the onset of the first growing season and then abruptly increased during late July. Following this abrupt increase, K^+ concentrations gradually decreased for the remainder of the first and throughout the second growing season. Calcium leachate concentrations for all treatments were greatest during the first growing season and remained relatively constant during both sampling periods (Figures 4 and 5). Contrary to Ca^{2+}, Mg^{2+} leachate concentrations for each treatment were greater during the second growing season and displayed the greatest variability among and within treatments (Figures 4 and 5). Although not significantly

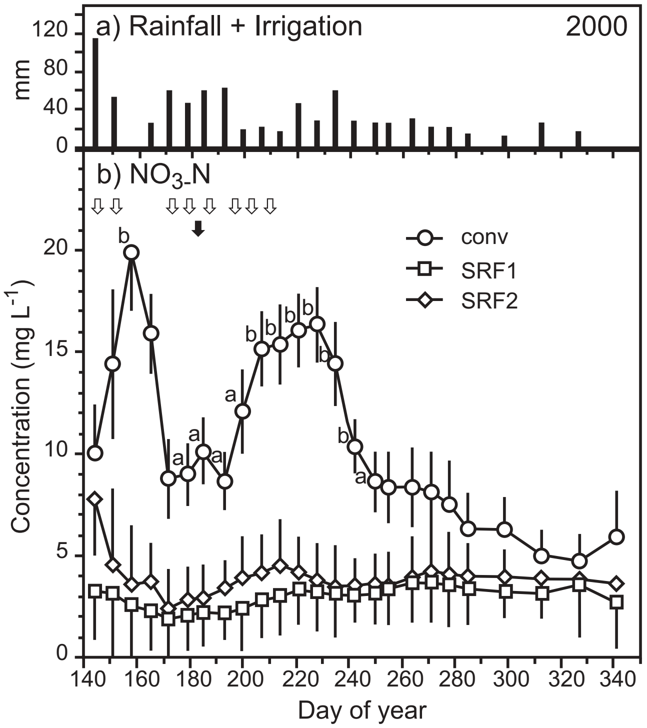

Figure 3—a) Rainfall and irrigation summed between sampling dates from May 2000 to December 2000. b) Average NO_3N soil water leachate concentrations at 1-m (3-ft) depth for 20a)00. Filled and open arrows represent slow release and conventional fertilizer applications, respectively.

greater, Mg^{2+} concentrations in the leachate of the SRF2 treatment were consistently greater than those observed in both Conv and SRF1 treatments during both the first and second growing seasons.

Leachate Correlations

During the first growing season, K^+ leachate concentrations were highly ($P < 0.01$) correlated (SRF1 $r = 0.62$; SRF2 $r = 0.70$; Conv $r = 0.72$) with NO_3–N leachate concentrations. The relationship between concentrations of NO_3–N and Ca^{2+} (SRF1 $r = –0.04$ [$P > 0.01$]; SRF2 $r = –0.02$ [$P > 0.01$]; Conv $r = 0.45$ [$P < 0.01$]) or Mg^{2+} (SRF1 $r = 0.16$ [$P > 0.01$]; SRF2 $r = 0.70$ [$P < 0.01$]; Conv $r = 0.37$ [$P < 0.01$]) was mixed. Nitrate-N leachate concentrations were weakly correlated to cation leachate concentrations during the second growing season, except for SRF2 NO_3–N and Mg^{2+} ($r = 0.55$ [$P < 0.01$]) and Conv NO_3–N and K^+ ($r = 0.47$ [$P < 0.01$]).

Nitrogen Loading

There was significantly greater N leached from Conv compared with SRF treatments in 1999 and 2000 (Table 2). Nitrogen loading to the ground water accounted for approximately half of the difference between N applied and plant N uptake in the Conv treatment during both 1999 and 2000.

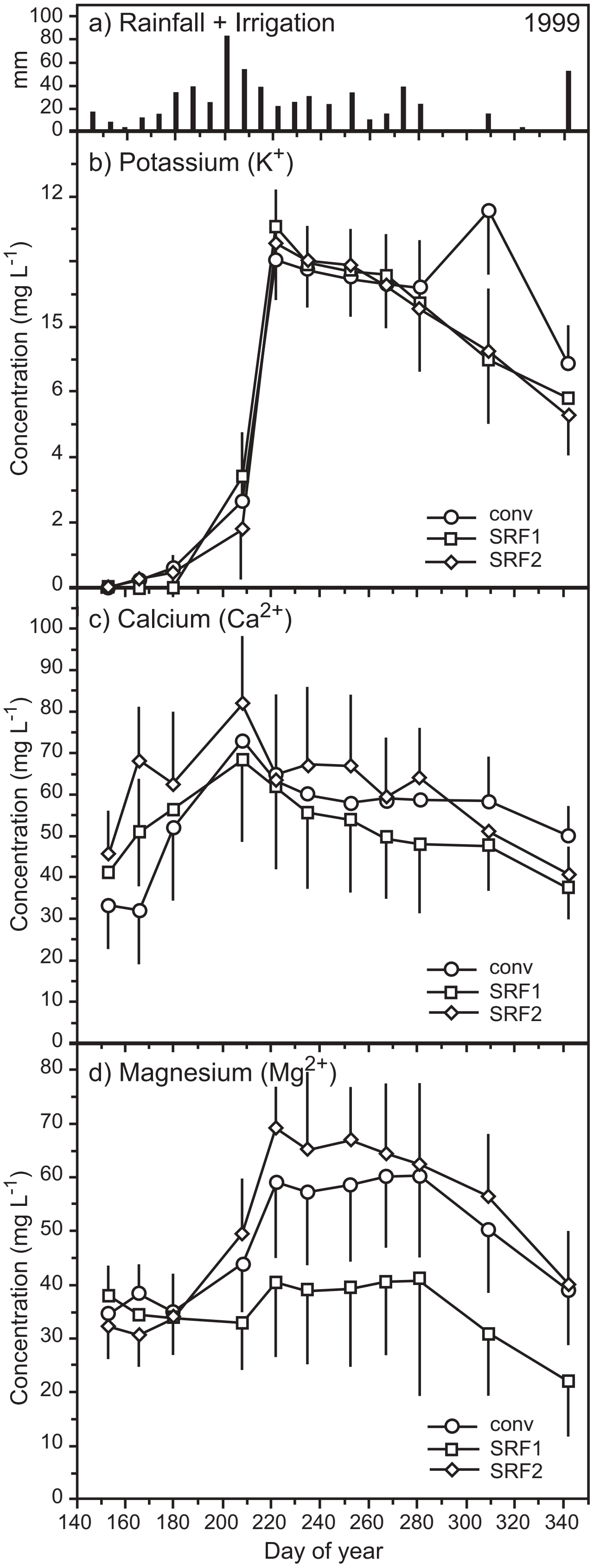

Figure 4—a) Rainfall and irrigation summed between sampling dates from May 1999 to December 1999. Average cation b) potassium, c) calcium, and d) magnesium soil water leachate concentrations for 1999.

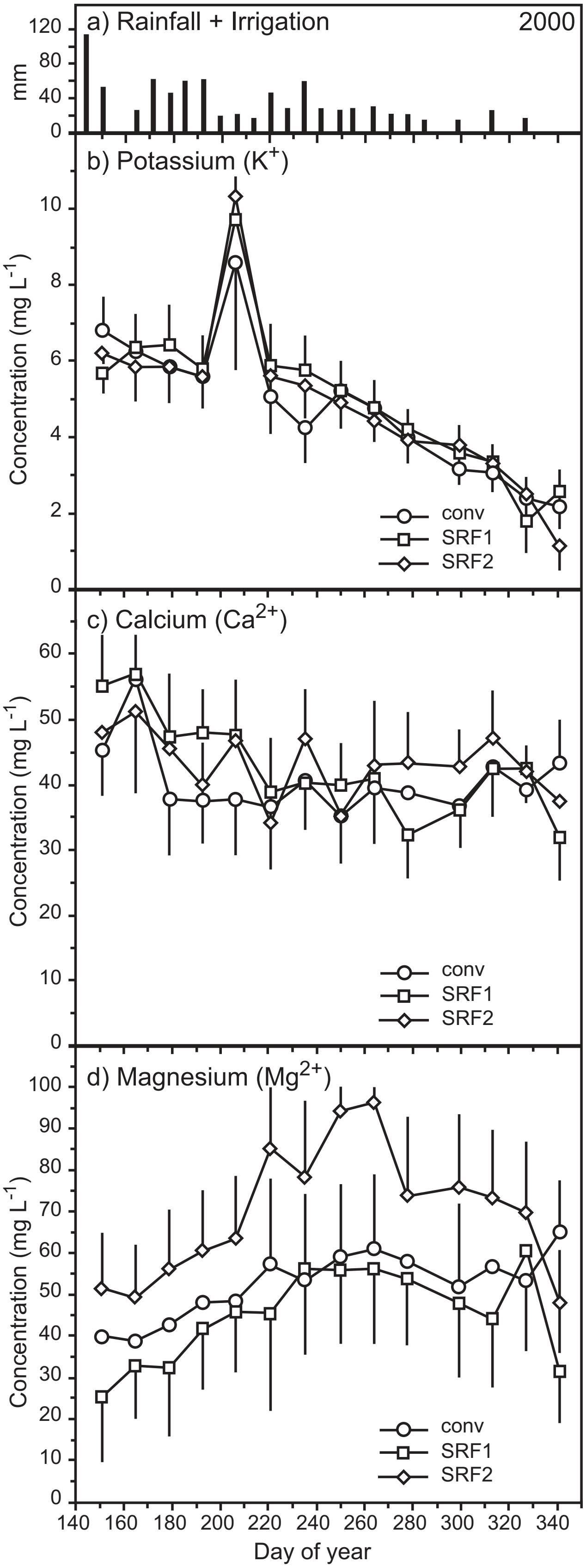

Figure 5—a) Rainfall and irrigation summed between sampling dates from May 2000 to December 2000. Average cation b) potassium, c) calcium, and d) magnesium soil water leachate concentrations for 2000.

Table 2—Nitrogen applied plant N uptake and estimated N leached for conventional (Conv), slow release 1 (SRF1), and slow release 2 (SRF2) fertilizer treatments over 2 growing seasons.

	N applied[a]	N uptake[b]	Estimated N leached[c,d]
		kg/ha	
1999			
Conv	180	19	73 a
SRF1	52	19	34 b
SRF2	52	19	40 b
2000			
Conv	180	80	52 a
SRF1	52	61	11 b
SRF2	52	62	15 b

[a] Total from May through August.
[b] Total from May through August.
[c] Total from May through December.
[d] Estimated N leached with the same letter are not significant at $P > 0.01$ within a year.

Nitrate-N loading for SRF treatments were greater than the difference between N applied and plant N uptake in both the first (–1 kg/ha [–0.9 lb/ac] SRF1; –10 kg/ha [–8.9 lb/ac] SRF2) and second (–20 kg/ha [–17.9 lb/ac] SRF1; –25 kg/ha [–22.3 lb/ac] SRF2) growing season (Table 2).

Soil

Before fertilizer application, soil pH, percent organic matter, available P, K^+, Ca^{2+}, and Mg^{2+} were similar ($P < 0.05$) among treatment plots (Table 3). At the end of the second growing season, soil pH in all 3 treatment groups increased (Table 3). As expected, soil organic matter decreased in all treatments after 2 growing seasons, but there were no differences among treatments (Table 3). Available phosphorus increased from the first to the second y in Conv, but remained the same in both SRF treatments. Potassium levels were greater ($P < 0.01$) after 2 years in the Conv treatment compared to SRF1 and SRF2 treatments. Calcium levels declined after 2 growing seasons in both SRF treatments; however, Ca increased in the Conv treatment, though not significantly ($P < 0.05$), with the addition of Ca applied as $CaNO_3$ in $15.5N:0P_2O_5:0K_2O$ (Table 3).

There were no differences ($P > 0.05$) in total soil N during the first or second growing season for all treatments (Table 4). In all treatments, average total soil N in the first growing season was greater in June than any other month of the year. During the second growing season, total N values were greatest during August for all 3 treatments. Soil NO_3^- values during the first season were numerically greater in the Conv treatment from May through August; however, the only significant ($P < 0.01$) difference between Conv and both SRFs was detected in June (Table 4). Though not significant, soil NO_3^- concentrations in the Conv treatment was numerically greater than soil NO_3^- concentrations in the SRF treatments during the early (May, June, and July) portion of the second season. Similar to total N, there were no differences ($P > 0.05$) in soil NH_4^+ concentrations observed during the first or second growing season. For all treatments, soil NH_4^+ concentrations were greatest in June

Table 3—Soil fertility characteristics sampled prior to project initiation (1999 May) and at end of second growing season (2000 September) for conventional (Conv), slow release 1 (SRF1), and slow release 2 (SRF2) fertilizer treatments.

Treatment	pH	Organic matter	P	$K^{+\,a}$	Ca^{2+}	Mg^{2+}
		percent	*kg/ha*	*kg/ha*	*cmol/kg*	*cmol/kg*
1999 May						
Conv	5.78	2.16	81	99	3.31	0.90
SRF1	5.82	2.33	91	113	3.52	.88
SRF2	5.77	2.24	84	113	3.48	.98
2000 September						
Conv	6.26	2.11	100	244 b†	3.56	1.04
SRF1	6.10	2.00	93	116 a	3.18	1.11
SRF2	6.18	2.05	91	164 a	2.97	1.07

[a] For K^+, data with the same letter are not significant at $P > 0.01$.

Table 4—Soil total N, NO_3^-, and NH_4^+ averaged monthly from May through October during the first (1999) and second (2000) growing season for conventional (Conv), slow release 1 (SRF1), and slow release 2 (SRF2) fertilizer treatments.

Month	Treatment	Total N		NO_3^-		NH_4^+	
		1999	2000	1999[a]	2000	1999	2000
		mg/L					
May							
	Conv	714	892	3.66	7.81	4.06	1.76
	SRF1	819	954	1.95	5.68	3.99	2.72
	SRF2	789	914	.86	3.03	4.19	2.20
June							
	Conv	1071	827	7.40 a	3.77	13.14	3.97
	SRF1	1052	866	2.60 b	.70	13.25	1.98
	SRF2	1027	851	3.28 b	1.12	12.18	1.59
July							
	Conv	962	835	7.44	1.98	7.80	5.33
	SRF1	998	886	5.45	1.42	6.93	4.26
	SRF2	945	884	7.31	1.23	7.32	5.30
August							
	Conv	957	1111	6.40	1.61	3.55	9.27
	SRF1	881	1038	4.55	2.18	3.84	10.08
	SRF2	913	1033	5.47	1.24	4.22	9.18
September[b]							
	Conv	—	1073	—	1.79	—	6.17
	SRF1	—	947	—	3.06	—	6.02
	SRF2	—	937	—	2.71	—	4.90
October							
	Conv	744	932	4.96	.75	6.09	2.14
	SRF1	727	882	5.46	.56	6.74	1.24
	SRF2	744	815	5.33	.51	6.57	2.50

[a] NO_3^- values for June 1999 with the same letter are not significant at $P > 0.01$.
[b] Data not available for 1999.

of the first growing season and August of the second growing season (Table 4).

Plant Tissue

There were no visual or qualitative differences in seedling appearance between treatments at the end of the first growing season (Figure 6). In late June to early August of the second growing season, the SRF-treated seedlings appeared slightly paler in color than the Conv-treated seedlings. However, by late August of the second growing season, there were no differences in seedling color between SRF and Conv-treated seedlings (Figure 7).

Dry mass, height, and diameter of *P. strobus* seedlings following the first growing season were similar ($P > 0.05$)

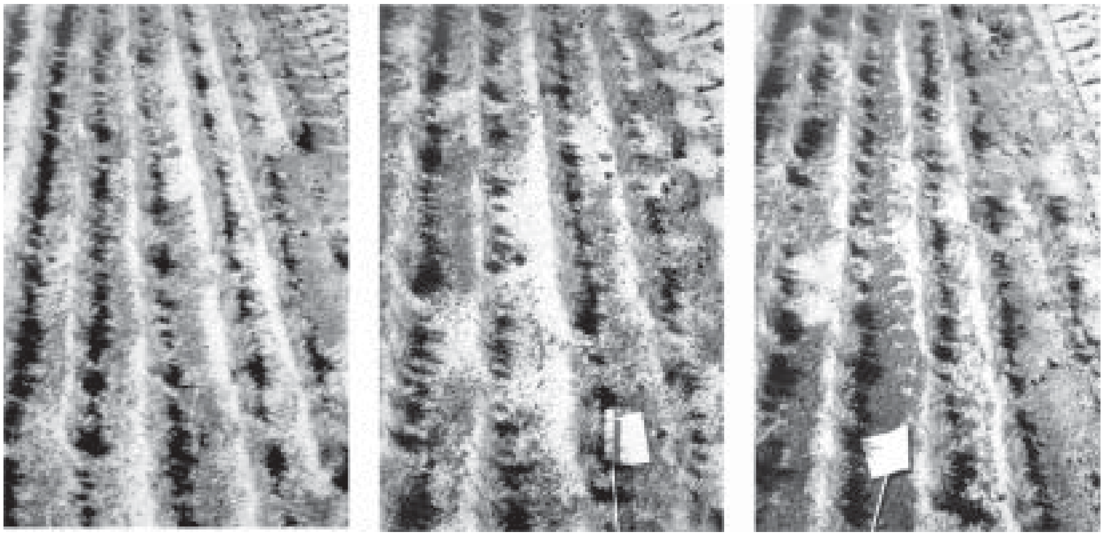

Figure 6—*Pinus strobus* (eastern white pine) seedlings after 1 growing season (late August 1999). From left to right, conventional (conv), slow release 1 (SRF1), and slow release 2 (SRF2) fertilizer treatments.

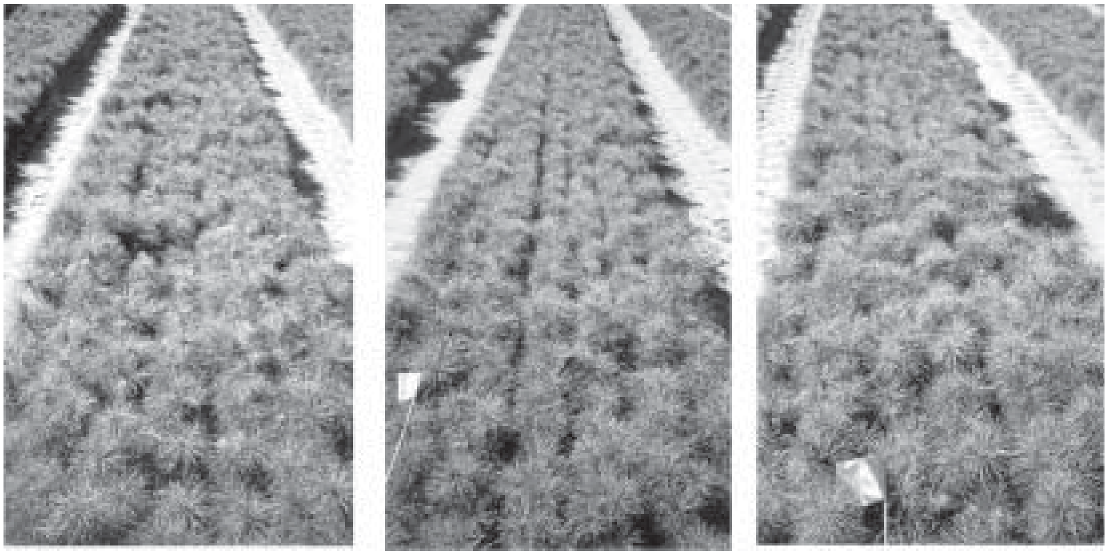

Figure 7—*Pinus strobus* (eastern white pine) seedlings after 2 growing seasons (late August 2000). From left to right, conventional (conv), slow release 1 (SRF1), and slow release 2 (SRF2) fertilizer treatments.

between treatments (Table 5). During the second growing season, the dry mass and heights were not different ($P > 0.05$); however, SRF2 seedling diameters were greater ($P < 0.05$) than both the Conv and SRF1 treatment seedlings. The diameter of the SRF2-treated seedlings increased an average of 92% from the first to the second season. In the Conv- and SRF1-treated seedlings, only a 6.2 and 16% mean increase in diameter was observed, respectively.

Plant uptake (g/kg) of total N and P did not differ between treatments during the first growing season (Table 6). The ratio of N uptake to N applied was ~10:1 for Conv compared to ~2.5:1 for both SRF1 and SRF2 (Table 2). Significantly lower ($P < 0.01$) concentrations of K^+ were observed in SRF1-treated seedlings compared to the Conv- and SRF2-treated seedlings. In addition, SRF2-treated seedlings displayed lower ($P < 0.05$) concentrations of Ca^{2+}, and SRF1-treated seedlings displayed lower concentrations of Mg^{2+} during the first growing season (Table 6).

Tissue analysis of seedlings sampled following the second growing season indicated that Conv-treated seedlings contained greater ($P < 0.05$) total N than either SRF1 or SRF2 treatments (Table 6). Nitrogen applied to N uptake ratios in each treatment group were: Conv (2.3:1), SRF1 (0.85:1), and SRF2 (0.84:1) (Table 2). Phosphorus, Ca^{2+}, and Mg^{2+} uptake

Table 5—Average morphological characteristics of *Pinus strobus* seedlings following the first and second growing season for conventional (Conv), slow release 1 (SRF1), and slow release 2 (SRF2) fertilizer treatments.

Treatment	Mass	Height[a]	Diameter[b]
	g/plant	*cm*	*mm*
1999			
Conv	0.29	6.11	2.59
SRF1	.28	6.10	2.33
SRF2	.30	6.05	1.56
2000			
Conv	2.01	19.3	2.75 b
SRF1	1.80	19.1	2.70 b
SRF2	1.84	18.6	3.00 a

[a] Root collar to tip of bud.
[b] Diameters for 2000 with the same letter are not significant at $P > 0.05$.

Table 6—Nutrient concentrations of *Pinus strobus* seedlings following the first and second growing season for conventional (Conv), slow release 1 (SRF1), and slow release 2 (SRF2) fertilizer treatments.

	Total Plant Uptake[a]				
Treatment	N[b]	P	K[c]	Ca[b]	Mg[b]
	g/kg				
1999					
Conv	44	9.1	28 a	13 a	7.7 b
SRF1	47	9.4	23 b	12 a	8.6 a
SRF2	44	8.6	27 a	11 b	7.6 b
2000					
Conv	33 a	6.5	21 a	8.1	5.2
SRF1	30 b	6.5	6.0 c	8.7	6.2
SRF2	30 b	6.4	19 b	9.4	5.8

[a] Root plus aboveground biomass.
[b] Values for total N in 2000, Ca and Mg in 1999 with the same letter are not significant at $P > 0.05$.
[c] Values for K with the same letter are not significant $P < 0.01$.

did not differ; however, K^+ uptake was different ($P < 0.01$) between each treatment.

Discussion

To our knowledge, this report is the first to provide an evaluation of NO_3–N leaching after conventional and SRF fertilization in bareroot tree production. These data clearly indicate that the use of SRFs was associated with a dramatic reduction in N loss to the environment without relinquishing seedling quality.

During the first growing season, the NO_3–N leachate concentrations collected 1 m (3 ft) below the surface illustrated a large disparity between the amount of N applied compared to the amount of N sequestered by tree seedlings. This difference existed in each treatment group; the disparity was especially pronounced in the Conv treatment. Second season NO_3–N leachate concentrations decreased substantially in all 3 treatment groups; however, the Conv treatment again showed consistently greater N leachate concentrations than either SRF treatments. The dramatic differences in NO_3–N concentrations during the first and second growing seasons are most likely the result of differences in seedling N demand. Seedlings were planted in fall of 1998 and germinated in spring of 1999. Since equal amounts of N (kg/ha) were applied during the first and second growing season, the young seedlings in the first season were evidently being overwhelmed with N from the fertilizers. Since NO_3–N losses are minimized when N fertilizer additions parallel plant N demand (Iyer 1988; Weed and Kanwar 1996), one may expect that NO_3–N losses would be reduced if bareroot tree nursery N additions were more closely tied to seedling N demand.

During the second growing season, the amount (kg/ha) of N sequestered by the SRF-treated seedlings was greater than the amount of N applied as fertilizer (Table 6). This suggests that a portion of the SRF-treated seedling N uptake was derived from other nonfertilizer inputs such as N mineralization from organic matter and N deposition from precipitation. Iyer (1988) has previously estimated that N input from precipitation is 5 kg/ha/yr (4.5 lb/ac/yr) and that the rate N mineralization from organic matter inputs occurs at a rate of 2%/y. Using these values, it is estimated that approximately 65 kg N/ha/yr (58 lb N/ac/yr) was derived from nonfertilizer sources during this study. By accounting for both N mineralization and N deposition from precipitation, the negative N budget (N applied—[seedling N uptake + N leached]) (Table 6) observed in the SRF treatments during both years one and two would be reduced. In the Conv treatment, approximately half the difference between N applied and seedling N uptake is estimated to be leached during both the first and second growing seasons (Table 2). The discrepancy between the N budget for both SRF (negative differences) and the Conv (positive difference) treatments may be caused by the tendency of porous cup samplers to measure resident soil water concentrations rather than flux concentrations (Brandi Dohrn and others 1996), or the difference in data measurement time periods (seedling N uptake [May through August]; N leached [May through December]).

Since the nutrient release rate of SRFs (specifically Polyon® polymer-coated SRF) is positively correlated to increases in temperature (Lunt and Oerteli 1962; Cabrera 1997), warm temperatures may be responsible for NO_3–N leachate concentration peaks observed in both SRF treatments during September (maximum temperatures averaged 25 °C (77 °F) in early September) of the first growing season. Furthermore, Kochba and others (1990) determined that the rate of nutrient release by SRFs was linearly related to the water vapor pressure varying with temperature. Thus, it is plausible that warm temperatures provided conditions for increased nutrient release concurrent with decreased N demand by the conifer seedlings. The slight deviation observed between SRF1 and SRF2 during both the first and second growing season is likely due to the smaller percentage of NO_3–N found within the fertilizer composition of SRF1 (9% NO_3–N and 10% NH_4–N) compared with SRF2 (12% NO_3–N) (Figures 2 and 3).

Large rainfall events preceded peaks in NO_3–N leachate concentrations in all 3 treatment groups, but the peaks were especially prominent within the Conv treatment. The close relationship observed between leachate NO_3–N concentrations and rainfall events in the Conv treatment may explain why NO_3–N leachate concentrations during the first growing season remained above 50 mg/L until December, even though the last fertilizer application was made on Julian day 232 (late Aug) (Figure 1). Examination of rainfall data indicates that very little precipitation occurred during this time period. On the other hand, the NO_3–N leaching pattern characteristic of the SRF treatments may be more closely related to seedling N demand or the timing of fertilizer release.

Similar to the pattern in NO_3–N leachate concentrations, peak concentrations of K^+ and Mg^{2+} are closely associated with rainfall events. Despite increased levels of soil Ca^{2+} in the Conv treatment because of the addition of Ca as $Ca(NO_3)_2$, there were no observed increases in Ca^{2+} leachate concentrations. Increases in Mg^{2+} leachate concentrations across all 3 treatments during the second growing season are likely attributed to Epsom salt ($MgSO_4$) applications.

The positive relationship previously noted between nutrient release of SRFs and temperature may explain the patterns observed in soil NO_3^- concentrations during first and second growing seasons. Soil NO_3^- concentrations in the SRF treatments remained below Conv treatment soil NO_3^- concentrations in the spring, when temperatures were cool, and increased during the warmer summer months of July and August. Likewise, the SRF nutrient release pattern likely contributed to the slower decline in soil NO_3^- concentrations in the SRF treatment relative to the Conv treatment during the months of September 2000 and October 1999. In addition, increases in SRF soil NO_3^- concentrations during the latter part of the first growing season are similar to the second SRF leachate NO_3–N concentration peak observed during this time. In October of 2000, the low soil NO_3^- concentrations in all treatments were also consistent with the leachate NO_3–N concentrations.

During the first growing season, soil total N and NH_4^+ concentrations were greatest in the month of June, which is approximately 30 days following the first fertilization and prior to an appreciable increase in seedling N demand. Similarly, second growing season average monthly soil total N and NH_4^+ concentrations were greatest in the month of August, again consistent with an expected decline in seedling N demand. The lower average monthly concentrations of NH_4^+ and greater NO_3^- concentrations observed at the beginning of the second growing season can likely be attributed to the conversion of NH_4^+ to NO_3^- during spring months (Cabrera 1997; Havlin and others 1999). Despite the presence of NH_4–N in the SRF1 fertilizer formulation, soil NH_4^+ concentrations were not significantly different in the first or second growing season compared to Conv and SRF2 soil NH_4^+ concentrations.

Data on seedling N uptake, together with the NO_3–N leachate concentrations and ratios of N applied to N uptake during the first growing season, suggest that all 3 fertilizer treatments supplied adequate amounts of N to meet seedling N demand. However, an analysis of second season SRF1 and SRF2 treatment results show a decrease in seedling N uptake, exceptionally low NO_3–N leachate concentrations, and ratios of N applied to N uptake of 0.85:1 (SRF1) and 0.84:1 (SRF2). These results suggest one or both of the following: 1) the rate of SRF nutrient release did not match the rate of seedling N uptake; 2) the quantity of N applied (kg/ha) in both SRF treatments did not meet seedling N demand. Since the rate of nutrient release did not appear detrimental in first year growth, it is likely that an increase in the quantity of SRF N applied may correct this perceived N deficiency. However, since the tissue N concentrations for all treatments were within prescribed seedling N concentration ranges established by Iyer and others (1989) for conifer seedlings grown in bareroot nurseries, it is possible that the increase in N uptake by Conv seedlings reflects luxury consumption. Furthermore, efforts to maximize seedling performance in the nursery may be unnecessarily overemhasized if adequate seedling nutrient content is present at outplanting (van den Driessche 1988).

The practical use of SRFs in bareroot nursery tree production is often dismissed due to the high cost of the SRF (Donald 1973; McNabb and Heser 1997). On average, the commercial price of SRF is usually about 3 to 7 times greater per unit N than standard conventional fertilizer. However, in order to maintain soil N levels, more applications of conventional fertilizer are required. A simple economic analysis of fertilizer expenses at the FG Wilson State Tree Nursery revealed that, contrary to popular belief, the final cost of slow release fertilizer was actually less than that of the conventional fertilizer (Vande Hey 2000). Moreover, the economic benefits of SRFs extend well beyond the initial costs of the fertilizer. When the additional expenses of fuel, labor, and environmental impact (for example, soil compaction and ground-water pollution) are also accounted for, the economic benefits of slow release fertilizers become even greater.

Conclusions

The use of slow release fertilizers in bareroot nursery tree production significantly reduced NO_3–N leachate concentrations compared to conventional, water-soluble fertilizers. However, first year seedling growth and nutrient concentrations were not affected by fertilizer treatment. The seedling N concentration of the SRF-treated seedlings after the second growing season was less than that of the Conv-treated seedlings; however, morphological characteristics such as height and diameter did not differ. The slow release fertilization did not alter concentrations of K^+, Ca^{2+}, or Mg^{2+} compared with conventional fertilization. Soil total N and NH_4^+ concentrations were likewise not affected by fertilizer treatment; the initial differences observed in soil NO_3^- concentrations were likely caused by the nutrient release patterns characteristic of the SRF. Overall, there was little difference in NO_3–N leachate concentrations, seedling morphology, seedling nutrient concentrations, and soil total N, NO_3^-, and NH_4^+ concentrations between SRF1 and SRF2.

Results of this research indicate that SRF can provide both economical and environmental benefits without sacrificing seedling quality. Research is needed to develop SRF formulations and application rates in order to further increase SRF efficiency and reduce NO_3–N leaching in bareroot nursery tree production. As demand for responsible stewardship of the environment increases, traditional fertilization practices will require revision. Slow release fertilization appears to provide a promising alternative.

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