Three-Year Response of Ponderosa Pine Seedlings to Controlled-Release Fertilizer Applied at Planting

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ABSTRACT: *Four controlled-release fertilizers (fast release [FR], moderate release [MR], slow release [SR] and slow release with micronutrients extended [ME]) were applied, at rates of 0, 5, 15 and 30 g/seedling, to ponderosa pine seedlings* (Pinus ponderosa Doug. ex Laws) *immediately after planting. Compared to the controls, the 5 and15 g/seedling of FR or ME fertilizer produced significantly greater caliper growth and the 5 and 15 g/seedling of ME fertilizer and 15 and 30 g of FR fertilizer produced significantly greater height growth after 3 yr. Mortality occurred mainly during the first growing season and varied substantially with fertilizer types and dosage. High dosage (30 g/seedling) generally caused more mortality than other dosage levels. Seventy-eight, 54, 51, and 36% of total nutrients had been released from the FR, MR, SR and ME products, respectively, by late August of the first growing season. Early in the second growing season, the FR product had released 98% of its total nutrients, and the MR, SR, and ME products had released over 90% of their nutrients. The best fertilizer treatment, 15 g of the ME product, produced a 21% diameter increase and a 30% height increase 3 yr after treatment. The relative magnitude of the growth responses is similar to those observed from other adjacent placement, controlled-release, seedling fertilization studies in the Northwest. West. J. Appl. For. 17(3):154–164.*

Key Words: Controlled-release fertilizer, ponderosa pine.

Fertilizing seedlings at or near the time of planting to enhance seedling growth and survival is an increasingly common practice. Fertilization experiments have shown that application of soluble inorganic fertilizers in new plantations generally results in increased growth (Ballard 1978). However, some fertilization experiments in conifer plantations also showed that soluble fertilizers increased mortality rates and did not improve early growth (White 1960, Sutton 1982). Increased mortality was primarily a consequence of the osmotic effect of high salt concentrations in the rooting zone. Poor seedling response to soluble fertilizers seemed related to the inability of newly planted seedling root systems to use large quantities of applied nutrients. Nutrient uptake by competing vegetation as well as the movement of the applied nutrients through the upper soil profile also contributed to poor response (Brockley 1988).

Controlled-release or organic fertilizers were used in some fertilization experiments (Arnott and Brett 1973) in order to overcome the disadvantages of soluble inorganic fertilizers. The release rate of controlled-release fertilizers is determined predominantly by the thickness and solubility characteristics of the coating materials as well as temperature during release. Tree growth response to controlled-release fertilizers varies with nutrient formulations, release characteristics, application rates, and fertilizer placement methods (Carlson and Preisig 1981). The three placement methods that have been commonly used with planting time fertilization are: planting hole application, adjacent application, and broadcast application. One problem with broadcast application of fertilizer is the possibility of stimulating growth of competing vegetation compared with either in-hole or adjacent placements. In New Zealand, fertilizers applied at planting are placed in a slit approximately 15 cm from the seedling to stimulate tree growth and simultaneously avoid vegetation competition (Ballard 1978). This placement method was used in our study.

Fertilization success with controlled-release fertilizers depends on factors such as nutrient formulations, release characteristics, application rates, placement methods and their interaction with seedling stock type, climate, and soil. Treatment effects have been measured in terms of tree growth, mortality, nutrient loss, weed competition, and economical and environmental feasibility. Extensive field tests of seedling fertilization with controlled-release fertilizer applied at planting are needed before appropriate prescriptions can be

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Table 1. Macronutrients and micronutrients, as percent by weight, provided by four controlled-release fertilizers used in the ponderosa pine seedling experiment.

	Controlled-release fertilizer			
Nutrient	Fast release (FR)	Moderate release (MR)	Slow release (SR)	Slow release with micronutrients extended (ME)
N	15	16	15	14
P	10	8	8	7
K	12	12	11	10
Ca	1.5	1.5	1.5	1.5
Mg	1	1	1	1
B	0.02	0.02	0.02	0.02
Cu	0.05	0.05	0.05	0.05
Zn	0.05	0.05	0.05	0.05
Fe	0.4	0.4	0.4	0.4
Mn	0.1	0.1	0.1	0.1
Mo	0.001	0.001	0.001	0.001

developed for inland Northwest forest conditions.

In 1996, a fertilization experiment was initiated at the time of planting ponderosa pine on the University of Idaho Experimental Forest using controlled-release fertilizers of various release characteristics and nutrient formulations (Table 1). The major objective of this study was to test the effects of adjacent placement of four fertilizer products at various application rates on ponderosa pine seedling survival, growth, and foliar nutrient concentration. A secondary objective was to determine the release characteristics of the fertilizer products under the environmental conditions at the experimental site.

Materials and Methods

Site Description

The experiment was located in Latah county in northern Idaho at 46°51′N and 116°50′W, elevation 950 m. The study site was clearcut in 1995 and slash-burned in the spring of 1996. It is characterized as Vassar Silt Loam soil which is 1.5 m deep. The habitat type is *Abies grandis/Clitonia uniflora* (Daubenmire and Daubenmire 1968). In winter, the average temperature is 0°C, and the average daily min. temperature is –4°C. In summer, the average temperature is 17°C, with an average daily max. temperature of 27°C. Located just out of the rain shadow of the Cascade Mountains, the summers begin moist and gradually turn dry by mid-July and continue mostly without appreciable rain through mid-September. October brings an increasing chance of rainfall. As autumn progresses into winter, the precipitation increases dramatically, falling as either snow or rain. The total annual precipitation is 763 mm. Of this, one-third usually falls in April through September (Osborne and Appelgren 1996).

Applying foliar active herbicide (Roundup) prior to planting and then twice more during the study period controlled competing vegetation. Vegetation control reduces extraneous variation in the experiment and is an increasingly common treatment during plantation establishment.

Experimental Design and Treatments

A randomized complete block design was used with six blocks per treatment on the 0.425 ha experimental site. Each block included 13 square plots of size 8 by 8 m, in which 36 trees were planted at 1.3 by 1.3 m spacing. All ponderosa pine seedlings (160/90 container stock type) planted for this study were raised the previous year (1996) at the University of Idaho Forest Research Nursery and were planted between May 22 and 24, 1996. Thirteen fertilization treatments, rates of 5, 15 and 30 g using four kinds of controlled-release fertilizers (Table 1) and one control (no controlled-release fertilizer applied), were randomly assigned to the 13 square plots. Release rates of the four products are controlled by their coating weights. Approximate nutrient release periods for fertilizers tested in our study are 9, 12, and 15 months for fast (FR), medium (MR), and slow (SR) release products, respectively. Actual release rates vary according to temperature and moisture conditions at the experimental site. A micronutrients extended (ME) product that has quickly released micronutrients outside the coating was also tested. The macronutrient release rate for the ME product was similar to the slowest release product in our study. The Scotts Company manufactured all fertilizers used in this experiment. Fertilizers were applied into a hole 15 cm deep and 8 cm away from the planting point on the uphill side immediately after planting.

To monitor fertilizer release rate, 15 g of the four fertilizer products were placed into sixty 25 by 5 cm fiberglass mesh bags. The bags were labeled and randomly placed into 15 cm deep slots midway on the sides of individual plots. Six bags from each fertilizer product were collected every 2 months for 2 yr and sent to Scotts Laboratories (Allentown, PA) for analysis of nutrient release.

Field Sampling and Measurements

The response variables of interest were diameter at the root collar, height, survival, and foliage nutrient concentrations. Seedling height and diameter were measured at planting and in late October of the 1996, 1997, and 1998 growing seasons. Survival was surveyed biweekly throughout the first growing season (1996) and was calculated for each plot as the percentage of live seedlings relative to the total number of seedlings planted. At the end of each growing season, three fascicles of fully matured needles located nearest the terminal bud were removed from each interior seedling of a plot. Needles were oven-dried at 70°C for 2 days and ground for chemical analysis. Scotts Laboratories completed analyses for N, P, K, Ca, Mg, B, Cu, Zn, Fe, Mn, and Mo, all of which were present in the controlled-release fertilizer products. Foliar N was determined using a standard mico-Kjeldahl procedure. Phosphorus, K, Ca, Mg, Mn, Fe, Cu, and Zn were determined by inductively coupled plasma (ICP) emission with digested plant tissue.

Soil moisture at 0–10, 11–20, and 21–40 cm and temperature at 10, 20, and 40 cm depths at six points distributed uniformly across the trial were also monitored biweekly throughout the first growing season to evaluate their potential impacts on seedling growth and mortality. In November of 1998, nine plots were selected systematically as sampling points for soil chemical analysis. Sample locations were selected such that they were unaffected by the fertilizers placed near the seedlings. In each plot, four 30 cm deep soil cores, one from each quadrant, were taken and composited for soil pH, NO_3^--N, extractable P, Mn, Cu, Zn, Fe, soil K, Ca, and Mg analyses. Soil pH was measured 1:1 in H_2O. Nitrate was extracted with calcium oxide and was determined using automated colorimetry. Extractable K, Ca, and Mg (1 N ammonium acetate, pH 3.0) were analyzed by ICP spetrometry. Phosphorus was determined on a 2 g subsample of soil extracted with 12 mL of Bray's solution (Bray and Kurtz, 1945). Manganese, Zn, Cu, and Fe were analyzed by atomic absorption. Holmes Analytical Laboratories at the University of Idaho conducted the soil chemical analyses.

Data Analysis

For growth response analysis, the average diameter and height, based on the 16 interior seedlings from each plot, were used for detecting fertilization effects. Plots with soil compaction and herbicide damage symptoms were not included so as to isolate nuisance error. Therefore, 49 plots (out of 78) were considered for data analysis; the replicates for each treatment were between three and six (mostly four). The resulting unbalanced experiment caused us to use a generalized linear mixed model (GLML) with repeated measures to analyze diameter and height response to various fertilization treatments:

$$Y_{ijk} = \mu + blk_i + trea_{ij} + blk_i \times trea_{ij} + t_k + trea_{ij} \times t_k + \varepsilon_{ijk}$$
$$(i = 1,...,6;\ j = 1,...,13;\ k = 1,...,4) \quad (1)$$

where Y_{ijk} is the average diameter or height for treatment *j* in block *i* and at time *k*, μ is the grand mean, blk_i is the random effect for block *i*, $trea_{ij}$ is the fixed effect for treatment *j* in block *i*, t_k is a fixed repeated factor for time *k*, where 1 represents the planting time in the spring of 1996 and 2, 3, and 4 represent 1996, 1997, and 1998 fall measurements, respectively, and ε_{ijk} is the random error for treatment *j* in block *i* at time *k*. In Equation (1) it is assumed that random effects, block and error, have a variance component covariance structure. The model resembles that of a randomized complete block repeated measures (split-plot in time), where the main plot error, $blk_i \times trea_{ij}$, is used to test for the fixed treatment effect, and the residual error, ε_{ijk}, is used to test for the fixed effects of time and time by treatment interaction. For foliar nutrient concentration data, the same model and covariance structure as (1) were employed except that *k* could take on values of 1, 2, or 3 (representing fall 1996, 1997, and 1998, respectively). Very few seedlings died on the experimental site during the second and third years. Therefore, only the first-year mortality was analyzed by using the model:

$$M_{ij} = \mu + blk_i + trea_{ij} + \varepsilon_{ij} \ (i = 1,..., 6;\ j = 1,...,13) \quad (2)$$

where M_{ij} is the percent mortality for treatment *j* in block *i,* and other parameters are as defined previously in Equation (1). First-year mortality within the upper 10 plots was unduly affected by soil compaction, thus masking treatment effects. These plots were not included (represented as missing values) in the analysis. Herbicide damage occurred to some additional plots during the second year of the experiment, and therefore the damage had no effect on first-year mortality. Consequently, each treatment had five or six replicates (blocks) available for mortality analysis. Our objective was to compare the effectiveness of various fertilizer products applied at different rates over time; therefore, we tested a set of orthogonal contrasts of the least square means for diameter, height, foliar nutrient concentration, and mortality. All statistical computations were performed using PROC MIXED of SAS (SAS® Institute Inc. 1995).

Results

Statistical analyses details, including significance levels and statistical estimates for factors in Equations (1) and (2), are provided in Tables 2 and 3. In addition, two orthogonal contrasts for the repeated factor were also employed to detect the temporal change in foliar nutrient concentration.

Table 2. Significance levels for fixed and random effects included in Equation (1) for diameter and height of ponderosa pine seedlings after 3 yr.

Fixed effect

	Caliper				Height	
Source	*NDF*	*DDF*	*F*	*Pr>F*	*F*	*Pr>F*
Trea	12	31	1.74	0.1109	2.56	0.0176
CTR vs. (FR+MR+SR+ME)	1	31	3.24	0.0716	2.78	0.1042
FR vs. (MR+SR+ME)	1	31	3.36	0.0690	2.44	0.1279
MR vs. (SR+ME)	1	31	1.39	0.3288	3.71	0.0644
SR vs. ME	1	31	2.21	0.1391	8.97	0.0053
Dose linear (DL)	1	31	4.01	0.0687	1.82	0.1915
Dose quadratic (DQ)	1	31	1.01	0.3040	1.72	0.1971
FR vs. (MR+SR+ME) × DL	1	31	0.45	0.5813	0.09	0.7732
FR vs. (MR+SR+ME) × DQ	1	31	0.05	0.9931	1.63	0.2154
MR vs. (SR+ME) × DL	1	31	0.22	0.7246	0.71	0.4087
MR vs. (SR+ME) × DQ	1	31	0.00	0.9427	0.05	0.8214
SR vs. ME × DL	1	31	6.67	0.0150	4.99	0.0333
SR vs. ME × DQ	1	31	1.73	0.2864	9.01	0.0054
T (year)	3	108	2,534.12	<0.0001	2,687.28	<0.0001
Trea × T	36	108	1.59	0.0355	2.70	<0.0001

Random effect

Variance	Diameter				Height			
component	Estimate	SE	*Z*	*Pr>/Z/*	Estimate	SE	*Z*	*Pr>/Z/*
Blk	0.1173	0.1471	0.80	0.2126	0.0402	0.5953	0.07	0.4730
Blk × Trea	0.6781	0.2224	3.05	0.0011	4.5257	1.6087	2.81	0.0025
Residual	1.3347	0.1557	8.57	<0.0001	10.9964	1.2826	8.57	<0.0001

Table 3. Significance levels for fixed and random effects included in Equation (2) for ponderosa pine seedling mortality during the first year.

Fixed effect				
Source	*NDF*	*DDF*	*F*	*Pr>F*
Trea	12	50	1.25	0.2800
CTR vs. (FR+MR+SR+ME)	1	50	0.18	0.6737
FR vs. (MR+SR+ME)	1	50	3.78	0.0574
MR vs. (SR+ME)	1	50	0.47	0.4984
SR vs. ME	1	50	3.25	0.0774
Dose linear	1	50	2.19	0.1456
Dose quadratic	1	50	1.99	0.1641
FR vs. (MR+SR+ME) × DL	1	50	0.56	0.4579
FR vs. (MR+SR+ME) × DQ	1	50	0.02	0.8992
MR vs. (SR+ME) × DL	1	50	0.69	0.4113
MR vs. (SR+ME) × DQ	1	50	1.06	0.3078
SR vs. ME × DL	1	50	0.03	0.8612
SR vs. ME × DQ	1	50	0.28	0.5995
Random effect				
Variance component	Estimate	SE	*Z*	*Pr>/Z/*
Blk	0.00048	0.00056	0.86	0.3893
Residual	0.00503	0.00091	5.55	0.0001

Soil Nutrient Concentrations, Moisture, and Temperature Regimes

Measured soil chemical and physical properties important for tree growth are shown in Table 4 and Figure 1. Soil Cu concentrations at the experimental site are low compared to those observed by Carlson and Preisig (1981). The experimental site experienced a very dry period from mid-July until late September. Soil moistures at the 11-40 cm depth during this period were below 25%, which may have slowed nutrient release from the fertilizer prills. Soil temperature at the three sampling depths remained at about 10° C throughout the sampling period.

Height and Diameter

Controlled-release fertilizers applied at planting tended to increase root-collar diameter and height growth of ponderosa pine seedlings (Figures 2 and 3) compared with the control (no fertilizer added); however, the statistical significance varied with different products and application rates over time. Fertilization had more effect on diameter ($P = 0.07$ for the contrast, "CTR vs. [FR+MR+SR+ME]") than on height ($P = 0.10$ for the same contrast) (Table 2). The FR product was more effective in increasing diameter growth than the overall effect of MR, SR, and ME products ($P = 0.07$ for the contrast, "FR vs. [MR+SR+ME]"). No statistical difference ($P > 0.05$) was found among MR, SR, and ME products ($P = 0.33$ and 0.14 for the contrasts, "MR vs. [SR+ME]" and "SR vs. ME", respectively). There was an overall dose linear trend ($P = 0.07$) and an interaction of "SR vs. ME × Dose linear trend" ($P = 0.02$) for diameter growth (Table 2). All dose levels of FR and the 5 and 15 g of ME product significantly improved diameter growth ($P < 0.05$) compared with the control (Figure 2).

For height growth, FR did not differ from the MR, SR, and ME products as a whole ($P = 0.13$ for the contrast, "FR vs. [MR+SR+ME]"). However, ME product was better than either the MR or SR products ($P = 0.01$ and 0.06 for the contrasts, "MR vs. [SR+ME]" and "SR vs. ME," respectively) (Table 2). Neither dose linear trend ($P = 0.19$) nor dose quadratic trend ($P = 0.20$) was significant across the whole experiment, even though the individual contrasts, "SR vs. ME × Dose linear trend" ($P = 0.03$) and "SR vs. ME × Dose quadratic trend" ($P = 0.01$) were statistically significant. All dose levels (5, 15, and 30 g) of FR, the 30 g of MR or SR, and the 5 and 15 g of ME products produced taller seedlings than the control ($P < 0.05$) (Figure 3).

Table 4. Chemical analysis of soil samples collected from 0–30 cm at the experimental site.

Attributes	Mean ± SD	Coefficient of variation (%)
Cation exchange capacity (CEC) (cmol/kg)	10.7 ± 1.1	10.1
PH	6.2 ± 0.4	7.0
NO_3^- -N (ppm)	3.0 ± 1.9	64.7
Extractable P (ppm)	54.9 ± 24.1	43.9
Extractable K (ppm)	150.1 ± 61.9	41.3
Extractable Ca (ppm)	1,345.7 ± 251.0	18.7
Extractable Mg (ppm)	110.3 ± 19.8	18.0
Extractable Mn (ppm)	9.3 ± 3.9	42.0
Extractable Cu (ppm)	0.46 ± 0.13	28.3
Extractable Zn (ppm)	1.66 ± 0.37	22.3
Extractable Fe (ppm)	92.0 ± 40.8	44.3

Mortality

The average mortality for the controls was 4.2%, but ranged from 1 to 12.8% for the fertilization treatments (Figure 4). There was no significant difference between the control and the fertilization treatments as a group ($P = 0.67$ for the contrast, "CTR vs. [FR+MR+SR+ME]"). The FR product resulted in higher mortality than MR, SR, and ME products as a group ($P = 0.06$ for the contrast, "FR vs. [MR+SR+ME]") (Table 3). The ME product had lower mortality than the SR product ($P = 0.77$ for the contrast, "SR vs. ME"). Although the linear and quadratic dosage trends for overall fertilizer types were not statistically significant, the dosage effect on mortality was evident for some individual fertilizer types such as FR and SR (Figure 4). Mortality appeared to increase with dosage for the

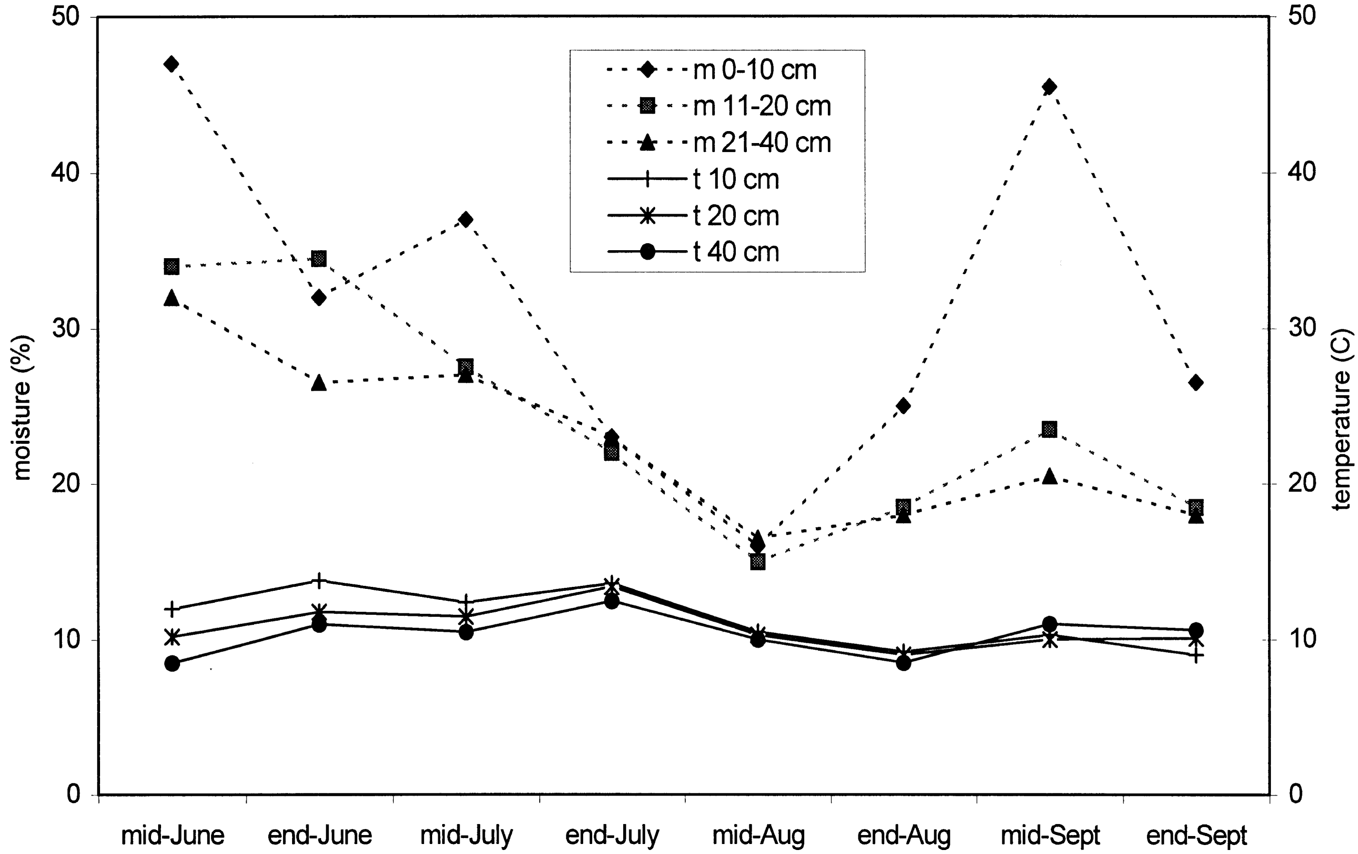

Figure 1. Observed soil moisture and temperature by Julian date at the experimental site in 1997 measured at three depths in the soil profile. M—moisture(%); t—temperature (°C).

ME fertilizer (Figure 4). During the first growing season, dead (brown) needle tips were observed for ponderosa pine seedlings treated with ME fertilizer, and the frequency of foliar damage was higher and symptoms more severe with higher dosages. No dead needle tips were observed on new growth in the second or third growing seasons. Only mortality associated with the 30 g of FR product (12.8%) statistically differed from the control ($P = 0.05$).

Foliar Nutrient Concentrations

Foliar K, Ca, Mg, B, and Zn concentrations showed significant overall treatment effects. Many pairwise comparisons were statistically significant ($P < 0.05$) for these elements. Foliar N, P, Fe, Cu, and Mn concentrations did not show significant treatment effects.

Temporal change in foliar nutrient concentration was observed for all nutrients except Fe. The yearly changes for foliar N, P, Mg, B, Cu, Zn and Mn concentrations were significant for both "first year vs. second year + third year" and "second year vs. third year" ($P < 0.05$); while for K and Ca the first contrast was not significant. Significant interactions of treatment by year were found for P, Ca, B, Cu, and Mn ($P < 0.05$).

The estimated least square mean for foliar N concentration decreased each sample year (Table 5). Foliar Ca and Cu concentrations decreased from 1996 to 1997 and then increased from 1997 to 1998. Foliar Fe concentration remained relatively unchanged over the years. Foliar K concentration in 1998 was lower than in 1996 and 1997. Foliar Mg concentration increased over years for most treatments. Foliar Mn concentration changed little from 1996 to 1997, but increased dramatically during 1998. Foliar macronutrient concentrations for all treatments in each sample year were well above critical levels (Powers 1983, Powers 1985). Foliar B, Cu, and Fe were deficient for most or all of the fertilization treatments based on the critical values suggested by Powers 1983, Powers 1985, and Boyer 1984 (unpublished). First year foliar B concentrations of ponderosa pine seedlings were extraordinarily increased by the ME fertilizer and reached concentrations over 250 ppm (Table 6).

Fertilizer Nutrient Release

Over the period from June 10 to August 26, 1996, approximately 78, 54, 51, and 36% of total nutrients had been released from the FR, MR, SR, and ME fertilizers, respectively. By October 26, 1996, the nutrients released from the FR, MR, SR, and ME fertilizers on average amounted to 86, 70, 55 and 39% of total nutrients. By July 8, 1997 (the 55th week after placement), the FR fertilizer released 98% of its total nutrients, and the MR, SR, and ME fertilizers released 90% of their nutrients (Figure 5).

Discussion

Overall, the fertilizer treatments produced larger seedlings than the controls after 3 yr (Figures 2 and 3). Several of the fertilizer treatments were also significantly different from each other after 3 yr. Based on final diameters and heights of ponderosa pine seedlings in this study, FR and ME fertilizers

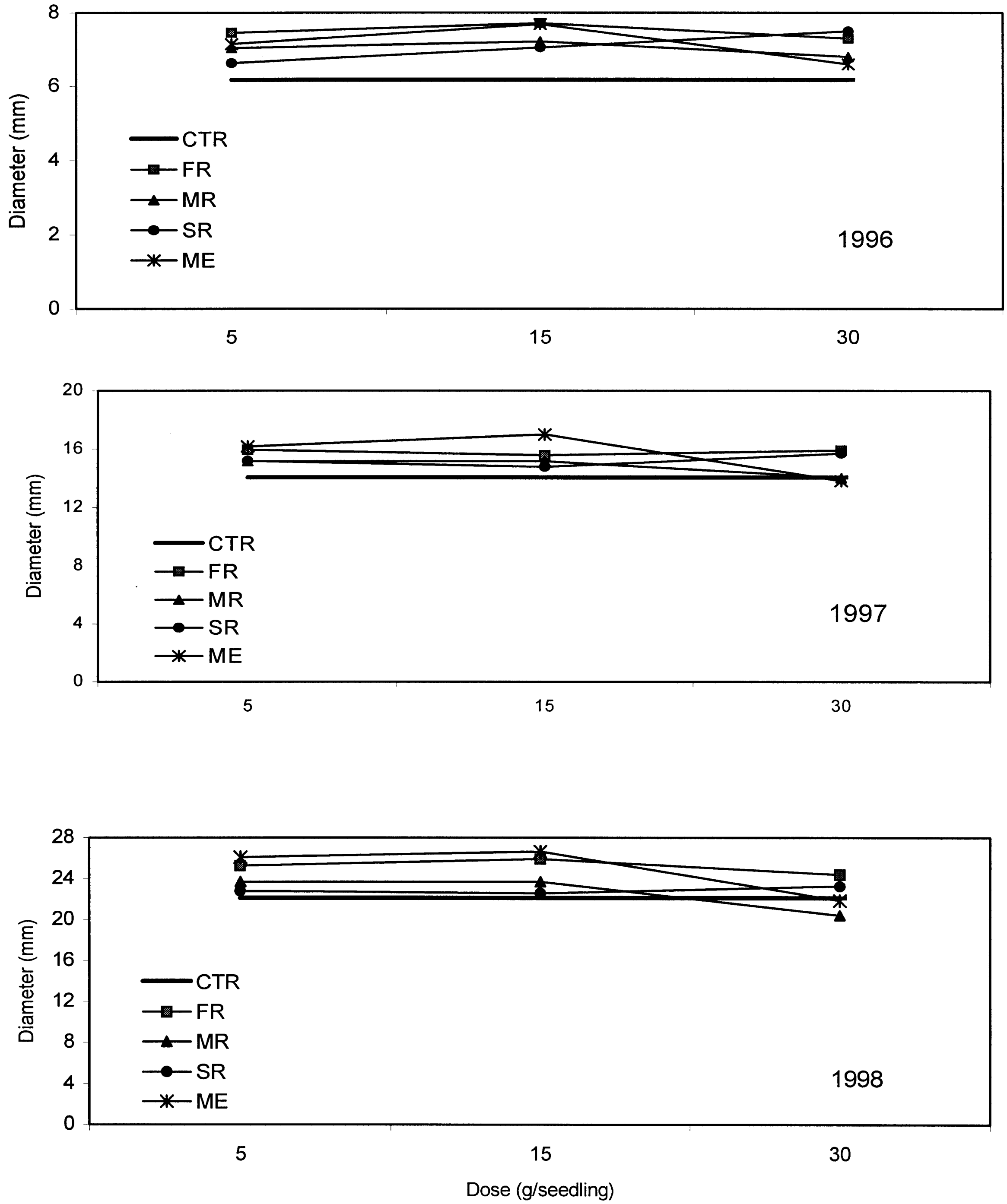

Figure 2. Caliper growth of ponderosa pine seedlings under various fertilization treatments at the experimental site for the first 3 yr. FR = fast release, MR = moderate release, SR = slow release, ME = slow release with micronutrients extended, CTR = the controls (no fertilizer added), and 5, 15, and 30 = g of fertilizer applied per tree.

were superior to MR and SR fertilizers. The 5 g and 15 g doses were generally better than the 30 g dose. The seedlings from the ME-15 treatment were largest, with an average diameter of 26.7 mm and height of 90.6 cm compared to control treatment diameter of 22.1 mm and height of 69.6 cm. The ME-15 treatment also had lower mortality than the control (Figure 4). The somewhat better performance of the ME fertilizer, at least for the two lower doses, may be related to the product's slower field release rate (Figure 5) perhaps resulting in greater nutrient availability during the second and possibly third growing season. However, this explanation is not reflected in foliar nutrient concentrations over the 3 yr period (Table 5).

Approximately 86, 70, 55, and 39% of the nutrients had been released from the FR, MR, SR, and ME products, respectively (Figure 5), by the end of the first growing season. By early in the second growing season, more than 90% of the nutrients had been released for all products. Thus, these products extend the nutrient release period by about a year for our experimental conditions compared to soluble inorganic fertilizers. However, substantial nutrient release, particularly from the ME and SR fertilizers, occurred during the snow-covered

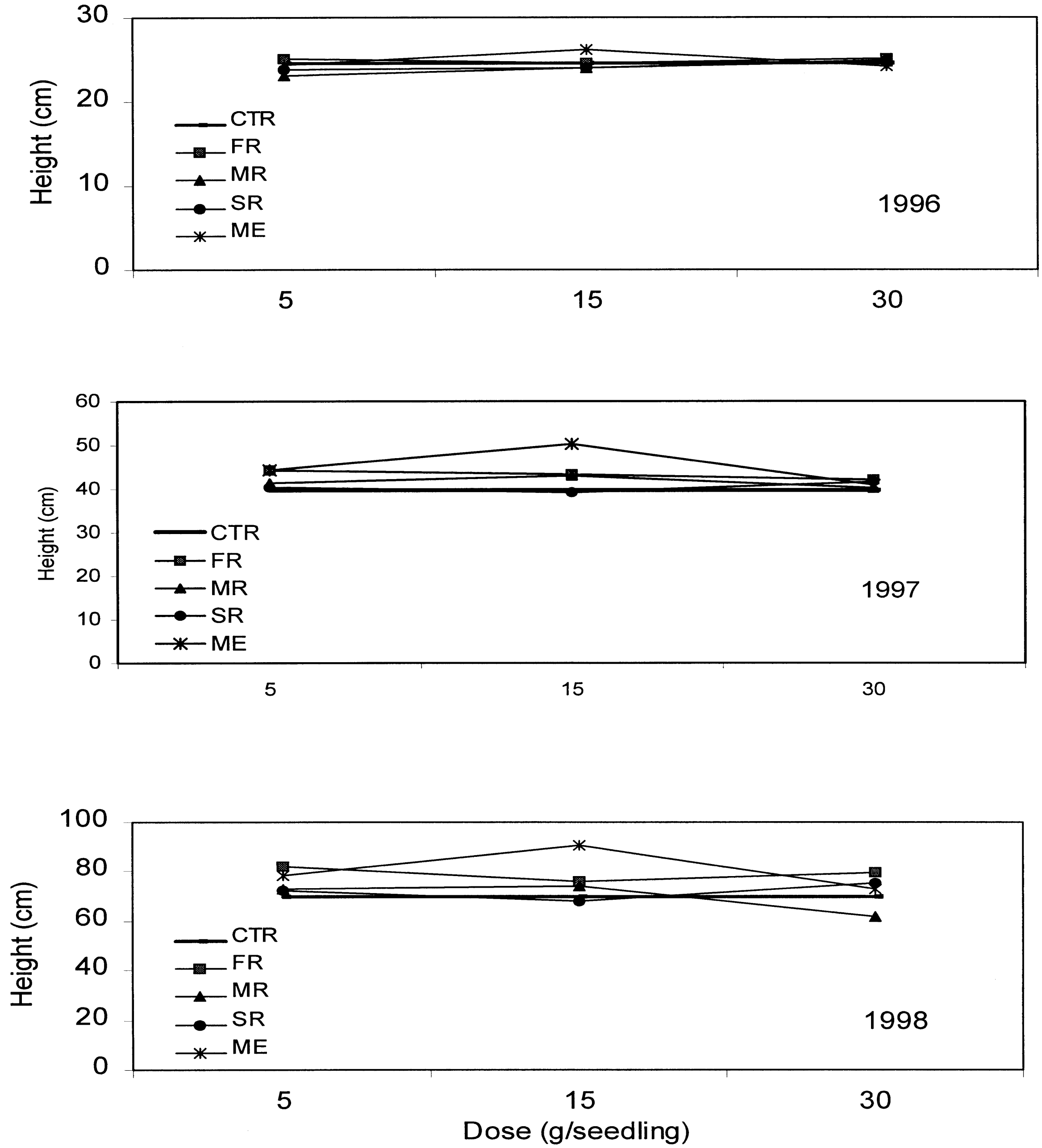

Figure 3. Height growth of ponderosa pine seedlings under various fertilization treatments at the experimental site for the first 3 yr. FR = fast release, MR = moderate release, SR = slow release, ME = slow release with micronutrients extended, CTR = the controls (no fertilizer added), and 5, 15, and 30 = g of fertilizer applied per tree.

winter (from week 24 to week 37), while trees were in dormancy. Thus, the nutrients may have leached lower in the soil profile and became unavailable to the seedling root systems.

Growth increases 3 yr following treatment were "noticeable" and statistically significant but not "dramatic." Close inspection of foliar nutrient concentrations may greatly explain our experimental results. All treatments, including the controls, had foliar concentrations well above critical levels for all nutrients except B, Cu, and Fe. The fertilizer treatments did not increase B, Cu, and Fe concentrations, except for elevated B concentrations following the ME treatments. Three alternative, or perhaps complementary, explanations suggest themselves from these data. The control seedlings had adequate nutrient supplies, particularly of the macronutrients; thus the fertilizer treatments did not produce substantial response. Our seedling quality was excellent and seedlings experienced "nutrient loading" in the nursery prior to planting. Seedling macronutrient foliar concentrations were still well above critical levels for the controls after 3 yr in the field. If seedling nutrient levels had been lower, fertilization response may have been higher than what we observed. Alternatively, B, Cu, and Fe concentrations were below critical levels, and the treatments failed to alleviate these deficiencies, except B for the ME product. Perhaps increased B levels explain the improved growth performance of ME-5 and 15 treated seedlings. Another explanation could be that little of the macro-nutrients delivered by the fertilizers were

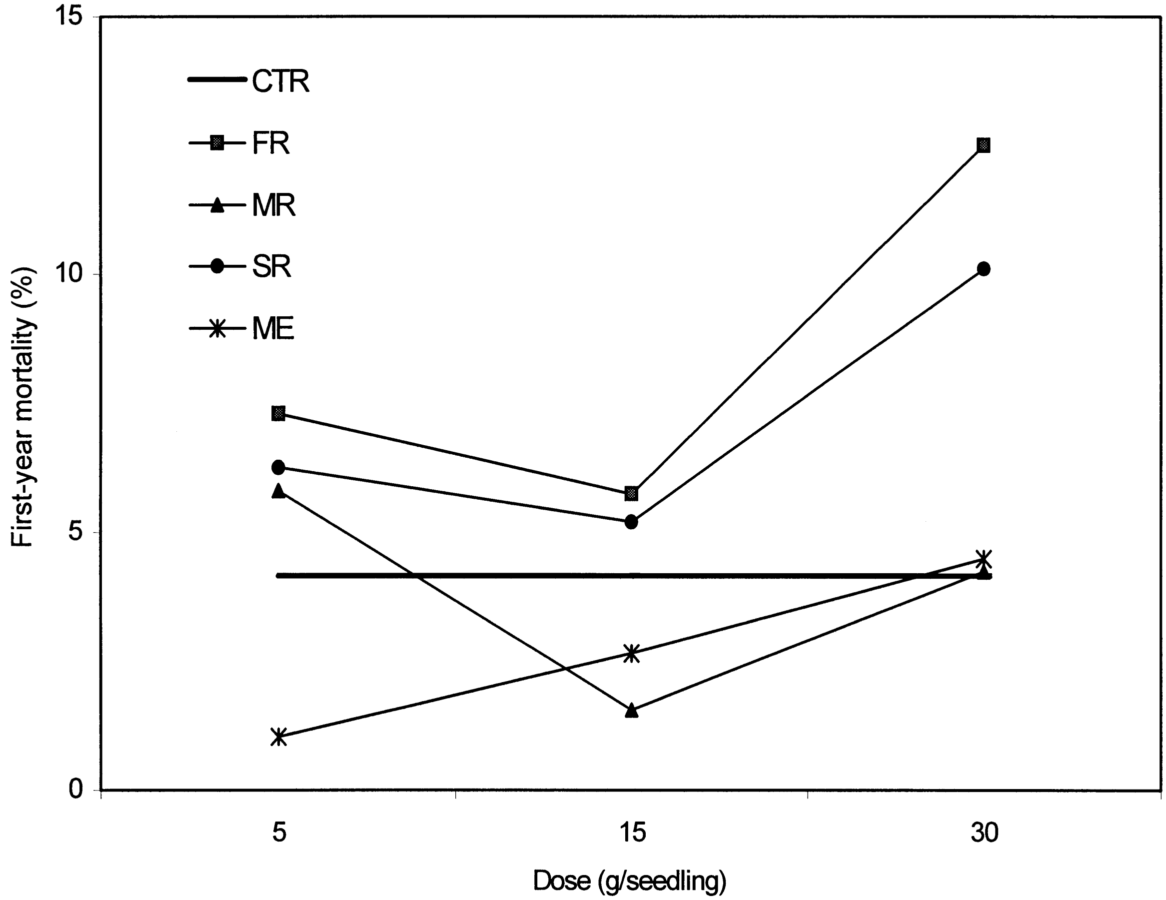

Figure 4. First-year mortality of ponderosa pine seedlings under various fertilization treatments at the experimental site.

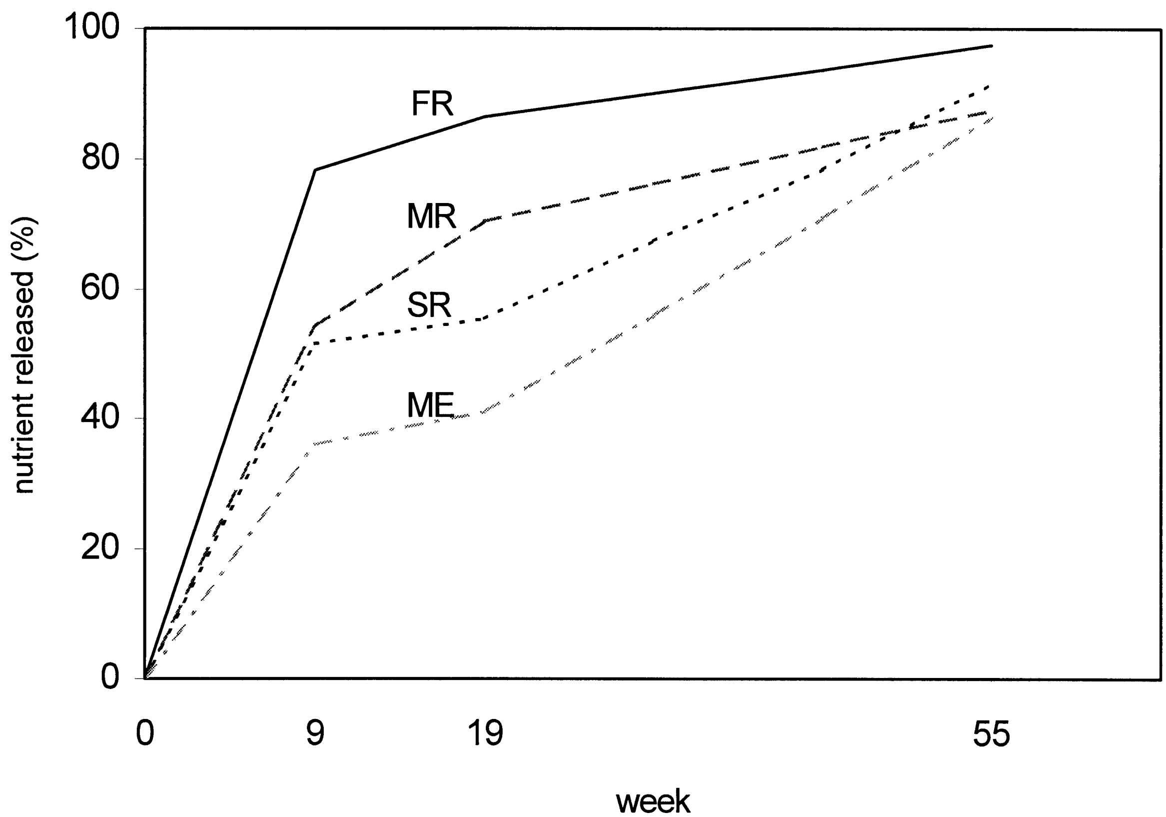

Figure 5. Nutrient release characteristics of four controlled-release fertilizers at the experimental site based on the fiberglass bag method.

Table 5. Least square means of ponderosa pine seedling foliar macronutrient concentrations for various fertilization treatments for 3 yr (FR = fast release; MR = moderate release; SR = slow release; ME = slow release minors extended; Three doses are 5, 15, and 30 g/seedling).

Treatment	Year	N	P	K	Ca	Mg
		(%)				
CTR	96	1.93	0.19	0.65	0.20	0.11
	97	1.54	0.16	0.68	0.20	0.12
	98	1.46	0.15	0.57	0.27	0.13
FR-5	96	1.94	0.19	0.62	0.21	0.10
	97	1.43	0.15	0.63	0.19	0.11
	98	1.33	0.15	0.59	0.23	0.12
FR-15	96	1.87	0.18	0.60	0.26	0.11
	97	1.58	0.18	0.62	0.25	0.13
	98	1.42	0.16	0.57	0.29	0.13
FR-30	96	1.97	0.18	0.62	0.26	0.10
	97	1.47	0.16	0.62	0.20	0.11
	98	1.42	0.16	0.59	0.27	0.14
MR-5	96	2.06	0.19	0.62	0.22	0.10
	97	1.43	0.15	0.68	0.21	0.12
	98	1.56	0.16	0.58	0.27	0.13
MR-15	96	1.98	0.19	0.62	0.25	0.10
	97	1.57	0.17	0.59	0.23	0.13
	98	1.35	0.15	0.59	0.25	0.14
MR-30	96	2.02	0.18	0.55	0.21	0.10
	97	1.58	0.17	0.76	0.17	0.10
	98	1.53	0.16	0.58	0.24	0.12
SR-5	96	1.98	0.19	0.64	0.22	0.11
	97	1.42	0.16	0.64	0.20	0.13
	98	1.35	0.16	0.61	0.24	0.13
SR-15	96	1.98	0.18	0.60	0.22	0.11
	97	1.46	0.15	0.65	0.20	0.12
	98	1.37	0.15	0.55	0.26	0.13
SR-30	96	1.99	0.18	0.61	0.25	0.10
	97	1.59	0.16	0.57	0.19	0.12
	98	1.37	0.15	0.66	0.30	0.14
ME-5	96	1.96	0.19	0.66	0.21	0.10
	97	1.47	0.16	0.66	0.20	0.11
	98	1.35	0.15	0.58	0.24	0.12
ME-15	96	1.87	0.18	0.66	0.23	0.11
	97	1.43	0.15	0.62	0.21	0.12
	98	1.35	0.15	0.60	0.22	0.11
ME-30	96	1.98	0.18	0.66	0.25	0.11
	97	1.41	0.16	0.68	0.18	0.10
	98	1.37	0.16	0.56	0.27	0.12
Critical value		1.10	0.08	0.48	0.05	0.05

actually taken up and used by the seedlings due to dry conditions during the first growing season.

Managers should be aware of one additional result produced by the ME product. Since the micronutrients are on the outside of the resin coating, they are rapidly released following treatment application. Seedling mortality increased with dosage increase of ME fertilizer (Figure 4) possibly due to boron toxicity. Foliar boron concentrations increased about tenfold by the end of the first growing season and reached over 250 ppm for the 30 g dose (Table 6). These ponderosa pine seedlings showed burned needle tips during the first growing season, one symptom of B toxicity. The frequency of foliar damage was higher and symptoms more severe with higher dosages. The 30 g dose seems too high for this product. In fact, the 30 g rate is probably too high for all of these fertilizers since mortality was higher for the FR and SR products, given this dose, while diameter and height for the MR product were smaller than the controls after three growing seasons.

Table 6. Least square means of ponderosa pine seedling foliar micronutrient concentrations for various fertilization treatments for 3 yr (FR = fast release; MR = moderate release; SR = slow release; ME = slow release minors extended; Three doses are 5, 15, and 30 g/seedling).

Treatment	Year	B	Cu	Zn	Fe	Mn
		(ppm)				
CTR	96	17	3.0	68	25	106
	97	25	2.5	52	25	107
	98	15	2.8	44	25	124
FR-5	96	19	3.2	88	26	114
	97	28	2.2	84	24	118
	98	13	2.6	42	25	202
FR-15	96	17	2.8	93	21	97
	97	24	2.2	88	25	131
	98	17	2.2	44	23	145
FR-30	96	23	3.3	54	24	105
	97	34	2.2	45	23	118
	98	16	3.3	49	28	258
MR-5	96	21	3.1	98	25	113
	97	23	2.4	53	26	122
	98	13	2.6	46	25	152
MR-15	96	18	3.2	104	24	110
	97	22	2.5	110	27	115
	98	15	2.6	46	26	139
MR-30	96	19	2.8	40	21	106
	97	20	2.1	35	24	117
	98	15	2.7	38	25	150
SR-5	96	22	3.3	60	25	114
	97	26	2.5	60	25	120
	98	15	2.6	41	24	126
SR-15	96	19	3.4	50	25	109
	97	25	2.3	67	25	121
	98	14	2.3	39	24	144
SR-30	96	21	3.1	85	25	106
	97	23	2.3	57	27	116
	98	14	2.5	43	25	169
ME-5	96	157	3.0	72	24	126
	97	25	2.4	47	40	118
	98	15	2.8	40	24	147
ME-15	96	216	2.8	47	24	136
	97	30	2.2	62	23	126
	98	16	2.4	41	25	161
ME-30	96	258	3.1	48	24	133
	97	39	2.3	66	26	114
	98	25	2.5	42	26	167
Critical value		20	3.0	30	50	60

The 30% height growth response produced after three growing seasons by our best treatment (ME-15) is surprisingly similar to relative height growth responses observed in other adjacent placement, controlled-release, seedling fertilization studies conducted in northwestern North America. For example, Carlson and Preisig (1981) showed about 42% height growth response after 2 yr for Douglas-fir in western Oregon, while Van den Driessche (1988) demonstrated a 31% height increase after 6 yr for Douglas-fir in coastal British Columbia. Adjacent placement of Osmocote produced a height increase of only 11% for western hemlock after two growing seasons in western Washington (Carlson 1981). However, placement of the same fertilizer in the planting hole resulted in a 30% height increase for hemlock in the same study. The above studies, including ours, represent a wide array of site conditions, tree species, and somewhat different fertilizer formulations and application rates. Therefore, the consistent seedling relative growth response is remarkable and perhaps comforting, although some managers may have higher expectations. A reasonable expectation for response seems to be about a 30% height growth increase following adjacent placement of controlled-release fertilizers after planting.

Conclusions

The best fertilizer treatment, 15 g of the ME product, produced a 21% diameter increase and a 30% height increase 3 yr after treatment. The relative magnitude of the growth responses is consistent with those observed from other adjacent placement, controlled-release, seedling fertilization studies in the Northwest. While the magnitude of response was statistically significant, the response may not be "operationally significant." Given the environmental conditions of our experiment, managers may not consider ponderosa pine seedling fertilization at the time of planting to be an attractive financial investment. We feel two factors, either singly or in combination, contributed to the lack of a more substantial growth response. First, macronutrient foliar concentrations for control ponderosa pine seedlings were well above critical levels for each of the 3 yr. Second, B, Cu, and Fe foliar concentrations were generally below critical levels during the study period, and the fertilizer treatments did not alleviate these deficiencies, except B for the ME product. The 30 g/seedling dose is too high for all the fertilizers we tested, given that we used 160/90 ponderosa pine container seedlings in our experiment.

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