GROWTH, BIOMASS ALLOCATION AND ROOT GROWTH POTENTIAL OF CONTAINER-GROWN PONDEROSA PINE SEEDLINGS WITH CONTROLLED-RELEASE FERTILIZER INCORPORATED IN THE ROOT PLUG

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Abstract

Prior to sowing seeds, three controlled-release fertilizers (fast release (FR), moderate release (MR) and slow release (SR)) were incorporated into the growing media at rates of 0.8, 1.6 or 3.2 grams as supplements to nursery supplied soluble fertilizer to grow ponderosa pine (*Pinus ponderosa Doug. ex Laws*) seedlings in the greenhouse. At lifting, the caliper, height and total dry weight of fertilized "160/90" seedlings ranged from 114 to 129%, 107 to 121% and 130 to 195% larger than those of the unfertilized seedlings, respectively. Needle biomass was affected more than stems or roots by the fertilization treatments. The 0.8 grams of FR or SR fertilizer treatments significantly increased ponderosa pine seedling root growth potential (RGP) compared to the controls. Toxicity from continuous nutrient release during cold storage resulted in much lower RGP for the 3.2 grams of MR or SR fertilizer treatments. The best dosage for caliper and height growth was 0.8 grams for FR fertilizer, 2.2 and 2.3 grams for MR fertilizer, and 1.9 and 2.0 grams for SR fertilizer, respectively. Lower application rates and shorter fertilizer release periods should be used with these small containers to prevent root damage when cold storage is required before outplanting.

Introduction

Tree seedling fertilization has been a topic of recent research interest in northwestern North America. Fertilization trials have been established to test not only fertilizer sources, application rate, application time and placement method but how these factors interact with stock type and cultural treatments such as site preparation and vegetation control to affect response magnitude and duration (Brockley 1988). Steady-state nutrition theory (Ingestad 1974,1977; Ingestad and Lund 1986; Ingestad and Agren 1988) suggests that seedling growth and nutrient uptake can be maximized and loss minimized by supplying small quantities of nutrients in proportion to requirements. Matching seedling growth with nutrient uptake using exponentially increasing application rates is important for maintaining steady-state nutrition and stable internal nutrient concentration in the plants. Short-term experiments with potted seedlings using nutrient-solution cultures by Imo and Timmer (1992) showed that exponentially based fertilization achieved steady-state nutrition and enhanced plant nutrient status, uptake and growth.

Factors contributing to loss of fertilizer efficiency are directly related to rapid dissolution and hydrolysis of the applied fertilizers. An efficient uptake rate and significant response could potentially be achieved by applying controlled-release fertilizers. Coating or encapsulating soluble compounds with materials that delay or slow the release rate achieves these controlled-release characteristics.

Several studies have reported on the effects of slow-release fertilizers on tree growth and/or soil chemical properties (Carlson 1981; Hunt 1989; Walker and Huntt 1992; Knowles et al. 1993; Walker and Kane 1997; Yanai et al. 1997; Catanzaro et al. 1998). Brockley (1988) summarized research results from Canada dealing with controlled-release fertilizers incorporated in container grown seedling root plugs. He felt that release rate and application rate were the key factors determining controlled-release fertilizer performance. Currently little information is available for conditions and species commonly grown in the inland Northwest of the United States. Therefore, the principal objective of our study was to investigate the effect of three controlled-release fertilizers with different release rates applied at three different rates on the growth, biomass allocation and root growth potential of ponderosa pine seedlings. Based on the results, we could estimate optimum fertilizer application rates to grow containerized ponderosa pine seedlings using the various products, and generally learn more about controlled-release fertilizers in container nurseries.

Materials and Methods

Treatments and experimental design

The Scotts Company provided the three types of controlled-release fertilizers (Table 1) tested in this study. Ponderosa pine seedlings were grown in 160/90 styroblocks (160 cavities per block, 90 cm^3 per cavity). For each type of the three controlled-release fertilizers, three application rates of 0.8, 1.6 and 3.2 grams per seedling were incorporated in the growing media prior to sowing the ponderosa pine seed. No controlled-release products were incorporated in the growing media for the control treatments. The study was conducted at the University of Idaho Forest Research Nursery from February 1996 until April 1997. A completely randomized design with 4 replicates was used to detect fertilizer effects. Controlled-release fertilizer was applied into a 50/50 percent peat-vermiculite growing medium (pH 4.2) and then cells were hand filled with the mixture. Ponderosa pine seeds were sown with a vacuum seeder and covered with about 0.6 cm of Target Forestry Sand®. Once sowing was complete, the containers were irrigated until the media was thoroughly moist. Phosphoric acid was injected into the irrigation water to adjust pH to around 6.0. The seed germination process was completed by March 22nd and cells were then thinned to one seedling when most seedlings shed their seed coats. During the growth phase (from March to June), day temperatures of 24-27 °C and night temperatures around 18 °C were maintained. Photoperiod was extended to 24 hours in the greenhouse. Wenny and Dumroese (1987) describe the growing regime for ponderosa pine in detail. The nursery based fertilization schedule they describe was in addition to the fertilization treatments included in our study.

Seedling measurements, biomass harvest and root growth potential test

At lifting on December 1, 1996, a random sample of thirty-two seedlings (eight seedlings per replication) for each treatment was harvested for seedling caliper, height and biomass measurements. Each seedling was cut at the root collar, and the roots extracted from the cells and hand washed. The shoot was separated into needle and stem components. The needle, stem and root samples were weighed after oven drying at 70 C for 48 hours. The needle weight ratio (NWR), stem weight ratio (SWR) and root weight ratio (RWR) were calculated as the ratio of the foliage, stem and roots, respectively, to total seedling dry weight. In addition, shoot (needle + stem)/root ratio was calculated for detecting fertilization treatment effects on biomass allocation between components.

The remaining seedlings from each treatment were wrapped with plastic after lifting and placed into polylined wax boxes for cold storage. The refrigerated storage was kept at 0.5 °C, with relative humidity near 100 percent. Before outplanting for a longer term field performance study in late April 1997, a random sample of thirty-two seedlings for each treatment was selected for root growth potential testing. Seedlings were placed in 3.78-liter pots filled with the 50/50 percent peat-vermiculite growing media, and grown in the same greenhouse environment as before. Seedlings were watered to maintain maximum water-holding potential for the media. The root growth potential experiment ended four weeks later after 80% of the buds had broken dormancy. Seedlings were extracted from the pots and medium washed carefully from the roots. Root growth potential index was evaluated based on the following criteria (Burdett 1979):

0----- no new root growth

1----- some new roots but none over 1 cm long

2----- 1-3 new roots over 1 cm long

3----- 4-10 new roots over 1 cm long

4----- 11-30 new roots over 1 cm long

5----- > 30 new roots over 1 cm long

Data analysis

Dunnett's single-step multiple comparison procedure using the Student's t statistic (Dunnett 1955,1964) was first employed to evaluate fertilization effects by comparing the difference in seedling caliper, height, needle, stem, root and total dry weight, and needle, stem and root dry weight ratios, and shoot (stem+needle)/root ratio between the nine fertilization treatments (3 fertilizer products × 3 dosages) and the control using the Type-I family error rate 0.05. Then two-way classification analysis of variance (ANOVA) was conducted with the nine fertilization treatments to detect the effect of fertilizer product and dosage on the aforementioned seedling responses. Pairwise contrasts between fertilizer products were conducted to rank the three fertilizer products if significant product effect

($p<0.10$) was found by ANOVA. Simple linear regression was used to quantify relationships between seedling biomass components and fertilizer application rates. Regression of caliper and height on fertilizer application rates was conducted using a parabolic model of the form:

$$Y = a_0 + a_1 X + a_2 X^2 + \varepsilon \qquad (1)$$

where Y is the seedling caliper (mm) or height (cm), X is the application rate, a_0, a_1 and a_2 are the regression parameters, and ε is the random error. The estimated application rate associated with maximum caliper and height for each fertilizer type was calculated via differentiation as follows:

$$\text{estimated application rate} = -\hat{a}_1 / 2\,\hat{a}_2 \qquad (2)$$

Statistical computations aforesaid were performed using the PROC GLM of SAS. Root growth potential data were analyzed using the PROC FREQ of SAS (SAS® Institute Inc. 1995). For simplicity and convenience in the following sections, we use CTR to represent the control (no controlled release fertilizer added), and FR-0.8, FR-1.6, and FR-3.2 to represent the 0.8, 1.6 and 3.2 grams per seedling of the FR fertilizer treatments. The moderate (MR) and slow (SR) release treatments are similarly designated.

Results

Caliper and height growth

Fertilization effect was evident in that most fertilization treatments produced significantly larger caliper and height (labeled by '+') than the control (Figure 1). The MR-0.8 and SR-0.8 treatments did not differ from the control with respect to seedling caliper. Similar results were observed for height except that another treatment, SR-3.2, also did not produce significantly larger height than the control. The two-way ANOVA including the nine fertilization treatments but excluding the control (Table 2) showed no detectable caliper differences attributable to fertilizer type, application rate or their interaction were found between fertilization treatments. However, significant fertilizer type effect on height was detected ($p=0.0614$) from the same analysis approach. Subsequent contrasts revealed that the FR fertilizer produced taller seedlings than the MR ($p=0.0368$) and SR ($p=0.0440$) fertilizers. But no statistically significant difference in height was found between the MR and SR fertilizers. Both caliper and height means of the 1.6 gm rate were the largest among the three application rates for both the MR and SR fertilizer types. Based on parabolic regression results of caliper and height on the application rates for the MR and SR fertilizer products (Table 3) and calculations from equation (2), the application rates which produced the maximum caliper and height growth were 2.2 grams for the MR product and 2.0 grams for the SR product, respectively. Residual analysis showed no detectable pattern when fitting equation (1) to the data and the lack-of-fit was non-significant. Since all rates of the FR product produced about the same average caliper and height, we did not estimate a "maximum response" application rate.

Biomass allocation

Fertilization effect on biomass allocation predominately derived from needle production differences, since five out of nine treatments, i.e., FR-0.8, FR-1.6, Mr-0.8, MR-1.6 and SR-1.6 produced significantly larger needle dry weight than the controls (Figure 2B). The average needle dry weight of a seedling for the controls was 0.94 gm while needle weights ranged from 1.39 to 2.23 gm, 48-137% larger than the controls, for the fertilization treatments. The average stem dry weight for the controls was 0.58 gm while fertilization treatments ranged from 0.78 to 1.15 g, 34-98% larger than the controls. However, the stem dry weight increase was not statistically significant (Figure 2C). Two treatments, FR-0.8 and MR-1.6, were significantly greater than the controls with respect to root dry weight. Average root dry weight for the fertilization treatments ranged from 0.81 to 1.22 g, 13-70 % larger than the control's mean of 0.72 g (Figure 2D). Only two fertilization treatments, FR-0.8 and MR-1.6, produced significantly larger total seedling dry weight than the controls (Figure 2A). At lifting, the average total seedling dry weight ranged from 3.01 to 4.6 g for the fertilization treatments an increase of 34-104% over the controls (2.25 g). Comparing only the nine treatments that included fertilizer (not the controls), no significant difference due to fertilizer type, application rate or their interaction was detected for total dry weight (Table 4).

Fertilizer treatments generally changed biomass allocation among components by increasing NWR and shoot/root ratio, but decreasing SWR and RWR compared to the controls (Figure 3). All fertilizer treatments, except for SR-0.8 and SR-1.6, produced significantly larger NWR than the controls. The NWR for the controls was 42% and fertilizer treatments ranged from 46 to 53 % (Figure 3A). The FR-1.6, SR-1.6, FR-3.2 and MR-3.2 treatments produced significantly lower RWR than the controls. The RWR for the controls was 31% and ranged from 23 to 28 % for fertilizer treatments (Figure 3C). The MR-0.8 and SR-3.2 treatments had significantly lower SWR compared to the controls. The SWR averaged 26% for the controls and ranged from 22 to 26.8% for the fertilizer treatments (Figure 3B). Only the FR-3.2 fertilizer treatment resulted in significantly larger shoot/root ratios than the controls. The shoot/root ratio for the controls was 220% and ranged from 260 to 370% for fertilizer treatments (Figure 3D).

Two-way ANOVA of the nine fertilizer treatments, excluding controls, further revealed that differences in NWR, RWR and shoot/root ratio were primarily attributable to application rate, while change in SWR was attributable to both application rate and the fertilizer type × application rate interaction (Figure 4). Shoot/root ratio and NWR increased while RWR decreased linearly with application rates for the three fertilizer products. The relationship between SWR and application rate depended on fertilizer types, since SWR increased linearly with application rates for the MR fertilizer and decreased with application rates for the SR fertilizer. No linear relationship existed between SWR and application rate for the FR fertilizer (Figure 5).

Root growth potential and nutrient release during cold storage

Root growth potential is the capacity for seedlings to initiate new roots under a favorable environment. After 5 months of cold storage, root growth potential of ponderosa pine seedlings was related to fertilization treatments, as indicated by the large number of dead root plugs (root growth potential index =0) for the MR-3.2 and SR-3.2 treatments compared to the control and all other fertilization treatments ($p<0.05$). Treatment FR-0.8 produced more seedlings with root growth potential indexes in categories 4 and 5 than other treatments; however, the differences were not statistically significant ($p=0.05$). Treatments MR-3.2 and SR-3.2 also had significantly lower root growth potential index than other treatments (Figure 4).

The fertilizer release test showed that nutrients were continuously released from the fertilizer pellets during cool storage. The amount of nutrients released from 3.2 grams of MR and SR fertilizer was 0.295 (9.21%) and 0.142 (4.43%) grams, respectively.

Discussion

Caliper and height growth

The FR fertilizer has a 9-month release period, which matches the 9-month greenhouse seedling production period (from March to November), nutrients were available early in the growing season to support the requirements for rapid seedling growth. Thus caliper and height of seedlings treated with this fertilizer type were significantly greater than the control. Treatment FR-0.8 seems best for height growth, while caliper growth did not respond to higher application rates of this fertilizer, likely due to the additional nutrients leaching out of the container early in the growing season before they were needed and could be absorbed by the seedlings.

The MR fertilizer has a 12 to 14-month release period, which is longer than the greenhouse seedling growth regime. Providing that larger caliper is desirable at lifting, the 0.8 gm per tree rate seems too low since caliper and height were not significantly increased from this treatment. However, a rate of 3.2 gm seems too high given the caliper and height growth decrease compared to the MR-1.6 treatment.

The SR fertilizer has the longest release period (16 to 20 months) among the three fertilizers. The slow nutrient release of this product probably caused inadequate nutrients to be available during the early growth period. The SR-0.8 treatment produced both insignificant caliper and height growth effects and the SR-3.2 treatment produced an insignificant height growth effect compared with the control. All these results indicate that both release rate and application rate should be carefully considered to achieve an optimum nutrient supply needed to grow larger seedlings with adequate nutrition. In addition, because of inherently different temporal growth patterns for height and caliper (height growth ceases at bud set in June while caliper growth continues nearly until lifting), the best application rate for each attribute was different when fertilizer release period was longer than the seedling production period such as the case for the MR and SR fertilizers. The estimated best application rates for caliper growth were slightly lower than for height growth. We suggest that the best application rates should be determined according to caliper growth because caliper is a better predictor than height in seedling quality assessment (Donald 1991). In our experiment, the best application rates for the FR, MR and SR fertilizer were 0.8, 2.2 and 1.9 g per tree respectively to achieve maximum caliper growth.

Biomass allocation

Carbohydrate allocation shifts to shoots under different fertility conditions have been reported by several researchers (Van Den Driessche 1988, Walker and Huntt 1992, Walker and Kane 1997). This phenomenon was also observed in our experiment. Most fertilizer treatments increased seedling needle weight and subsequently NWR and decreased RWR. However, root dry weight, RWR, SWR, shoot/root ratio and total seedling dry weight were only influenced by one or two fertilizer treatments. Fertilizer treatment effect on stem dry weight compared to the controls was not evident. Fertilizer application rate was the most important factor in our experiment since the highest rate hindered growth and produced unbalanced biomass allocation between different seedling components. In summary, our results suggest that controlled-release fertilizers can be used to increase seedling size without dramatically changing the ratios between individual organs, or combinations of organs, if fertilizer nutrient release characteristics and application rates are correctly selected.

Root growth potential

One problem with incorporating controlled-release fertilizers in container seedling root plugs is the continuous nutrient release during cold storage. This release subsequently causes high salinity buildup and toxicity, which in turn causes serious damage to seedling root systems (Brockley 1988). Results of our root growth potential test confirmed this point. The MR-3.2 and SR-3.2 treatments caused much lower root growth potential than the same rate of FR fertilizer. This result was probably related to longer release periods for the MR and SR fertilizers. Our release characteristics test of the MR and SR fertilizers during cold storage supports the idea that continuous nutrient release and subsequent salinity buildup in the root plug are the major reason for the lower root growth potential. This result suggests that for MR and SR fertilizers the 3.2 grams per seedling rate is too high. Therefore, given these small containers, lower application rates and shorter release periods should be used to prevent root damage when cold storage is required before outplanting. Longer fertilizer release periods may be appropriate if fall planting is used, thereby avoiding cold storage.

Conclusions

Controlled-release fertilizers significantly increased both caliper and height of ponderosa pine seedlings. All fertilizer treatments, except for MR-0.8, SR-0.8 and SR-3.2, produced significantly greater caliper and height than the controls. The dosage to achieve maximum caliper and height in the greenhouse was 2.2 and 2.3 grams per seedling for MR fertilizer and 1.9 and 2.0 g per seedling for SR fertilizer, respectively, while for FR fertilizer, the 0.8 g per seedling rate was best.

All treatments, except for FR-3.2, MR-3.2, SR-0.8 and SR-3.2, produced significantly greater needle dry weight than the controls. However, significant differences in root and total dry weights were found only for the FR-0.8 and MR-1.6 treatments and the controls. Fertilization effects on biomass allocation predominately resulted from the increase in needle dry weights, which in turn caused an increase in needle weight ratio, and the decrease in root weight ratio. Differences in NWR, RWR, and shoot/root ratio were attributable to fertilizer application rates alone, while SWR differences were mainly attributable to the interaction between fertilizer type and application rate. Shoot/root ratio and NWR were positively related to fertilizer application rates; however, RWR was negatively related to fertilizer application rates.

The MR-3.2 and SR-3.2 treatments resulted in much lower root growth potential probably due to toxicity caused by continuous nutrient release during cold storage. Many dead root plugs were found for these two treatments. The root damage was attributable to fertilizer type and application rate as well as their interaction. The release period of the fast release fertilizer better matched the length of the nursery's growing season than longer release products and it was therefore generally more effective in producing larger seedlings with well-balanced biomass components.

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Table 1. Percent by weight of macronutrients and micronutrients provided by three controlled release fertilizers used in the ponderosa pine experiment.

	Product		
Nutrient	Fast release (9 months)	Moderate release (12-14 months)	Slow release (16-20 months)
N	16	18	18
P (P_2O_5)	9	6	5
K (K_2O)	12	12	12
Ca	1.5	1.5	1.5
Mg	1	1	1
B	0.02	0.02	0.02
Cu	0.05	0.05	0.05
Zn	0.05	0.05	0.05
Fe	0.4	0.4	0.4
Mn	0.1	0.1	0.1
Mo	0.001	0.001	0.001

Table 2. Two-way classification analysis of variance results for caliper and height of the "160/90" ponderosa pine seedlings grown under different fertilization treatments in the greenhouse.

Response	Source	d.f.	Means of Squares	F	Pr>F
Caliper	Model	8	0.0632	1.62	0.12
	Fertilizer (F)	2	0.0110	0.95	0.39
	Rate (R)	2	0.1256	1.97	0.14
	F×R	4	0.0581	1.76	0.14
	Error	27	0.0744		
Height	Model	8	1.8109	2.11	0.07
	Fertilizer (F)	2	2.6545	3.10	0.06
	Rate (R)	2	1.9542	2.28	0.11
	F×R	4	1.3174	1.54	0.22
	Error	27	0.8563		
	Contrast				
	FR vs. MR	1	4.1334	4.83	0.04
	FR vs. SR	1	3.8240	4.47	0.04
	MR vs. SR	1	0.0060	0.01	0.93

Table 3. Regression summary for the caliper and height response of the "160/90" ponderosa pine seedlings versus fertilizer application rates at lifting in the greenhouse (The numbers in parentheses are the standard errors of the estimated coefficients).

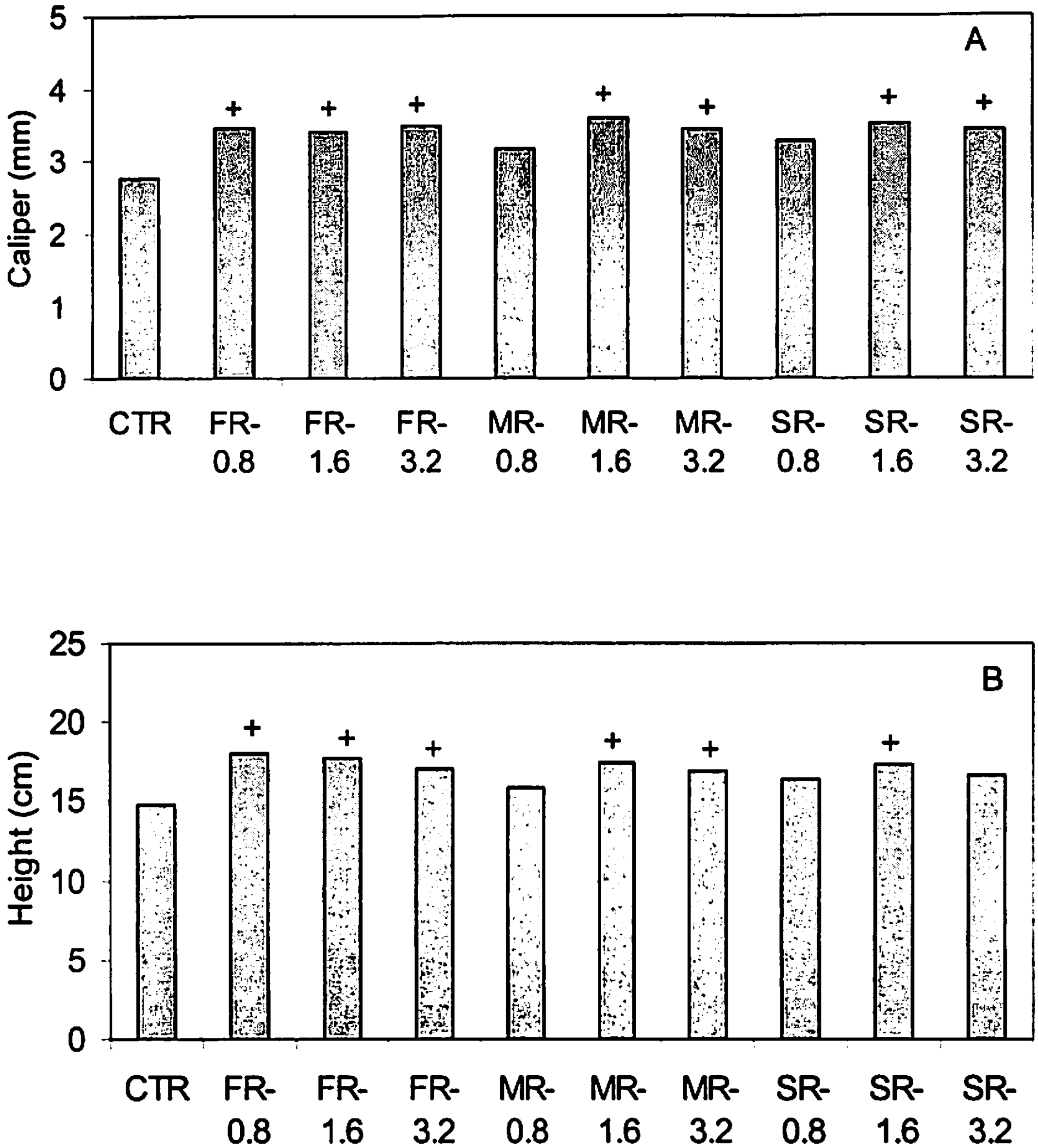
Fertilizer	Response	$\hat{a}_0$	$\hat{a}_1$	$\hat{a}_2$	Pr>F	R^2	$-\hat{a}_1/2\hat{a}_2$
MR	Caliper	2.747	0.756	-0.169	0.0053	0.5537	2.24
		(0.103)	(0.16)	(0.048)			
	Height	14.428	2.429	-0.530	0.0029	0.5932	2.29
		(0.395)	(0.63)	(0.185)			
SR	Caliper	2.780	0.786	-0.205	0.0009	0.5932	1.92
		(0.092)	(0.15)	(0.042)			
	Height	14.784	2.592	-0.636	0.0026	0.6004	2.04
		(0.413)	(0.66)	(0.190)			

Table 4. Two-way classification analysis of variance results for response characteristics for "ponderosa pine seedlings grown under different fertilization treatments in the greenhouse.

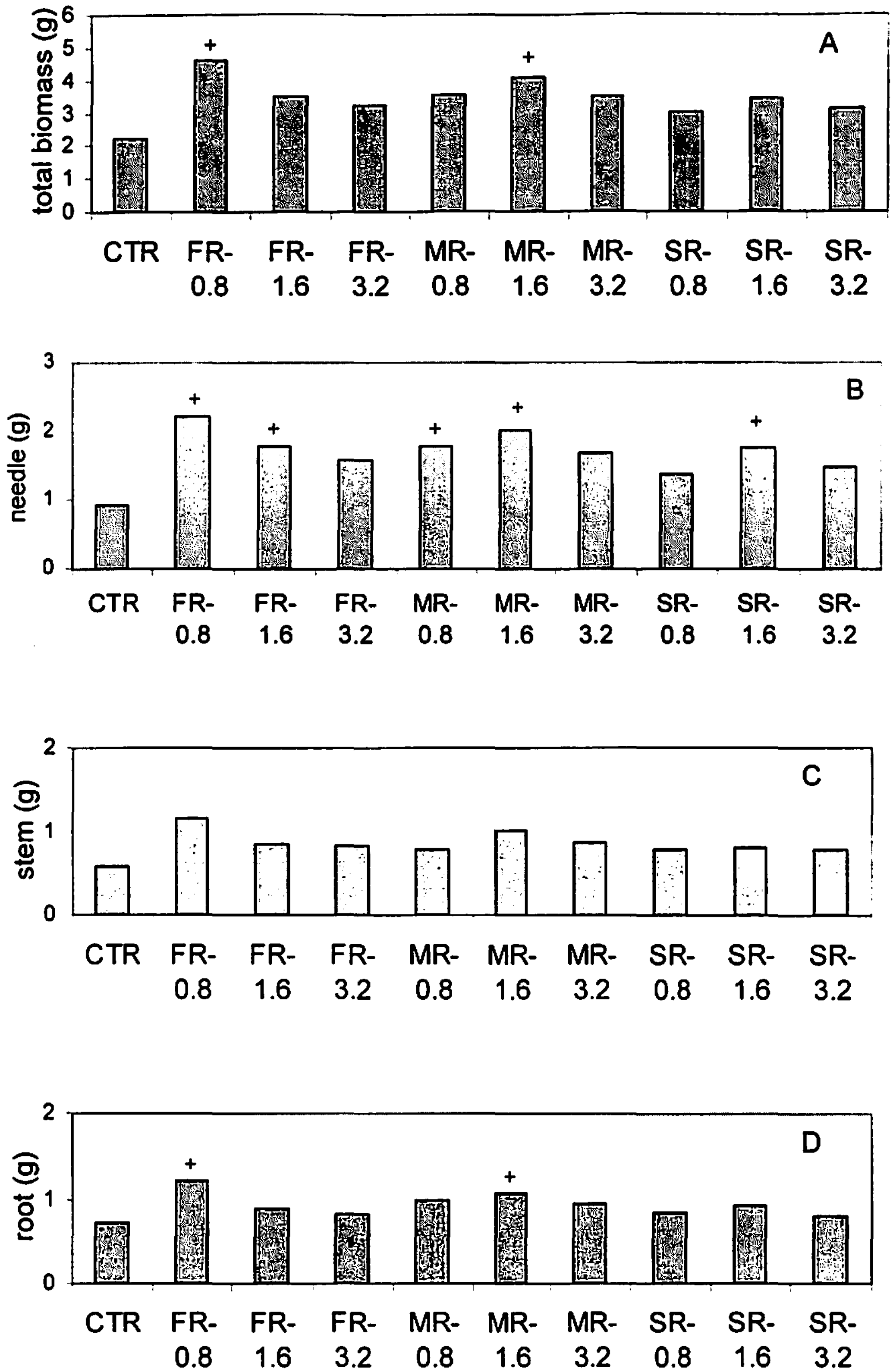
Response	Source	d.f.	Mean Squares	F	Pr>F
Total dry weight	Model	8	1.1926	1.38	0.25
	Fertilizer (F)	2	1.4789	1.72	0.20
	Rate (R)	2	0.7963	0.92	0.41
	F×R	4	1.2476	1.45	0.25
	Error	27	0.8613		
Needle weight	Model	8	0.3076	1.61	0.17
	Fertilizer (F)	2	0.4056	2.12	0.14
	Rate (R)	2	0.2801	1.46	0.25
	F×R	4	0.2724	1.42	0.25
	Error	27	0.1917		
Stem weight	Model	8	0.0875	0.97	0.48
	Fertilizer (F)	2	0.0992	1.10	0.35
	Rate (R)	2	0.0815	0.91	0.42
	F×R	4	0.0846	0.94	0.46
	Error	27	0.0898		
Root weight	Model	8	0.0771	1.57	0.18
	Fertilizer (F)	2	0.0827	1.69	0.20
	Rate (R)	2	0.0152	0.31	0.74
	F×R	4	0.1052	2.15	0.10
	Error	27	0.0490		
NWR	Model	8	0.0017	1.81	0.12
	Fertilizer (F)	2	0.0012	1.24	0.31
	Rate (R)	2	0.0040	4.08	0.03
	F×R	4	0.0009	0.93	0.46
	Error	27	0.0010		
SWR	Model	8	0.0010	3.77	0.00
	Fertilizer (F)	2	0.0003	1.03	0.37
	Rate (R)	2	0.0007	2.68	0.09
	F×R	4	0.0014	5.69	0.00
	Error	27	0.0003		
RWR	Model	8	0.0011	1.51	0.20
	Fertilizer (F)	2	0.0016	2.20	0.13
	Rate (R)	2	0.0023	3.22	0.06
	F×R	4	0.0002	0.31	0.87
	Error	27	0.0007		
(Needle+Stem)/Root	Model	8	0.3726	1.75	0.13
	Fertilizer (F)	2	0.4556	2.14	0.14
	Rate (R)	2	0.6674	3.13	0.06
	F×R	4	0.1837	0.86	0.50
	Error	27	0.2134		

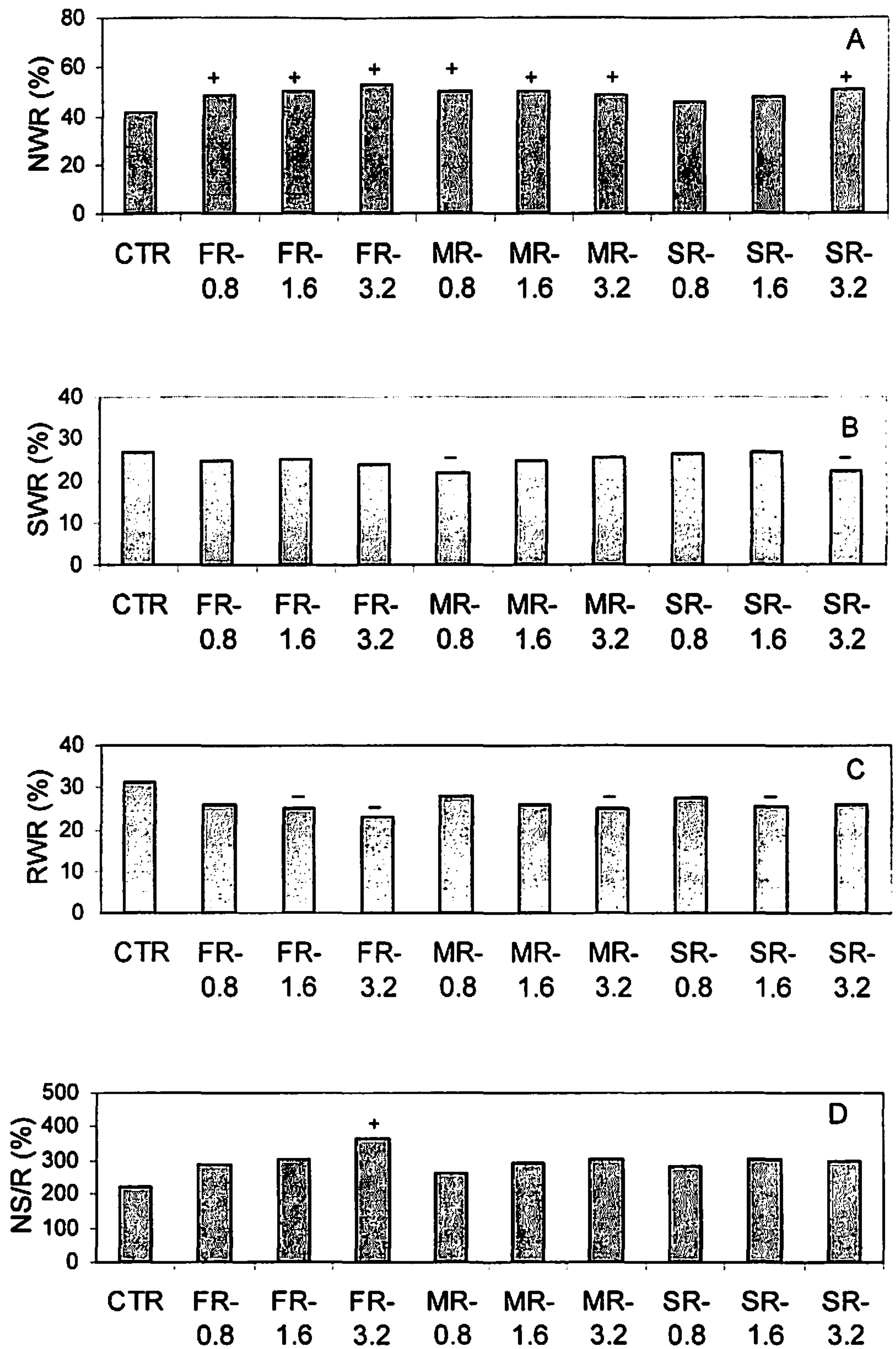
Table 5 Regression summary for the needle weight ratio (NWR), stem weight ratio (SWR), root weight ratio (RWR) and shoot/root ratio of ponderosa pine seedlings versus fertilizer application rates at lifting in the greenhouse (The number in parentheses are the standard errors of the estimated coefficients)

Fitted equations	R^2	Pr>F
NWR = 0.4673 + 0.0148 * application rate (0.0105) (0.0050)	0.5608	0.0202
RWR = 0.2780 + 0.0102 * application rate (0.0092) (0.0043)	0.4391	0.0518
Shoot/Root = 2.6395 + 0.1897 * application rate (0.1736) (0.0820)	0.4332	0.0539
FR: SWR = 0.2575 – 0.0054 * application rate (0.0075) (0.0035)	0.1879	0.1592
MR: SWR = 0.2200 + 0.0116 * application rate (0.0081) (0.0038)	0.4781	0.0128
SR: SWR = 0.2850 – 0.0183 * application rate (0.0133) (0.0063)	0.4605	0.0153



A
Caliper (mm)
0
1
2
3
4
5
CTR
FR-0.8
FR-1.6
FR-3.2
MR-0.8
MR-1.6
MR-3.2
SR-0.8
SR-1.6
SR-3.2
B
Height (cm)
0
5
10
15
20
25
CTR
FR-0.8
FR-1.6
FR-3.2
MR-0.8
MR-1.6
MR-3.2
SR-0.8
SR-1.6
SR-3.2


total biomass (g)
6
5
4
3
2
1
0
A
CTR
FR-0.8
FR-1.6
FR-3.2
MR-0.8
MR-1.6
MR-3.2
SR-0.8
SR-1.6
SR-3.2
needle (g)
3
2
1
0
B
stem (g)
2
1
0
C
root (g)
2
1
0
D



80
60
40
20
0
NWR (%)
A
+
CTR
FR-0.8
FR-1.6
FR-3.2
MR-0.8
MR-1.6
MR-3.2
SR-0.8
SR-1.6
SR-3.2
40
30
20
10
0
SWR (%)
B
–
CTR
FR-0.8
FR-1.6
FR-3.2
MR-0.8
MR-1.6
MR-3.2
SR-0.8
SR-1.6
SR-3.2
40
30
20
10
0
RWR (%)
C
–
CTR
FR-0.8
FR-1.6
FR-3.2
MR-0.8
MR-1.6
MR-3.2
SR-0.8
SR-1.6
SR-3.2
500
400
300
200
100
0
NS/R (%)
D
+
CTR
FR-0.8
FR-1.6
FR-3.2
MR-0.8
MR-1.6
MR-3.2
SR-0.8
SR-1.6
SR-3.2

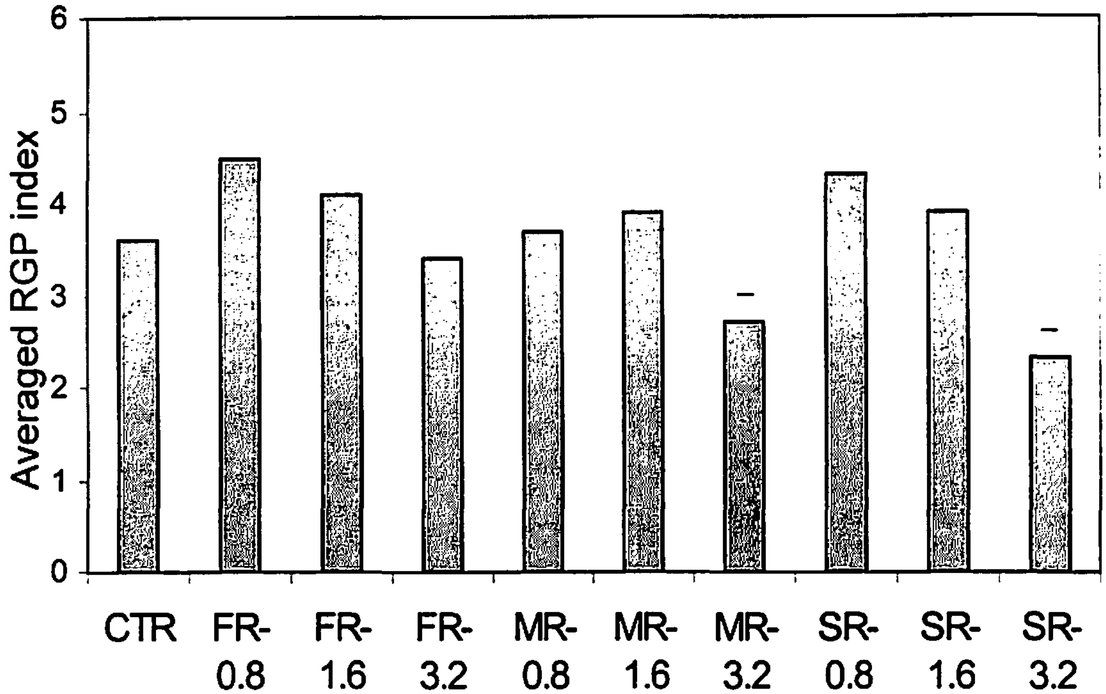

Averaged RGP index
0
1
2
3
4
5
6
CTR
FR-0.8
FR-1.6
FR-3.2
MR-0.8
MR-1.6
MR-3.2
SR-0.8
SR-1.6
SR-3.2

Figure 1. Caliper and height means of ponderosa pine seedlings under various fertilization treatments at lifting in the greenhouse (Panel A is caliper; Panel B is height; FR= fast release; MR= moderate release; SR= slow release fertilizer types; The numbers below fertilizer types are application rates (gram/seedling). '+' indicates treatments that are significantly larger than the controls $\alpha = 0.05$).

Figure 2. Needle, stem, root and total dry weights of ponderosa pine seedlings fertilized with different controlled-release fertilizers in the greenhouse measured in early December (at lifting) of 1996 (Panel A is total; Panel B is needles; Panel C is stems; Panel D is roots; FR= fast release; MR= moderate release; SR= slow release fertilizer types; The numbers below fertilizer types are application rates (gram/seedling). '+' indicates treatments that are significantly larger than the controls $\alpha = 0.05$).

Figure 3. Needle, stem, root dry weight, and (needle+stem)/root (NS/R) ratios of ponderosa pine seedlings fertilized with different controlled-release fertilizers in the greenhouse in early December (at lifting) of 1996 (Panel A is needle weight ratio (NWR); Panel B is stem weight ratio (SWR); Panel C is root weight ratio (RWR); Panel D is NS/R; FR= fast release; MR= moderate release; SR= slow release fertilizer types; The numbers below fertilizer types are application rates (gram/seedling). '+' and '-' indicate treatments that are significantly larger and smaller, respectively, than the controls $\alpha = 0.05$).

Figure 4. Average root growth potential index of ponderosa pine under various fertilizer treatments after 5 months of cold storage (FR= fast release; MR= moderate release; SR= slow release fertilizer types; The numbers below fertilizer types are application rates (gram/seedling). '-' indicates treatments that are significantly smaller than the controls α = 0.05).