Intermountain Forest Tree Nutrition Cooperative

Supplemental Report No.1

March 2000

Zhaofei Fan

James A. Moore

Bahman Shafii

EFFECT OF ROOT PLUG INCORPORATED CONTROLLED-RELEASE FERTILIZER UPON TWO-YEAR SURVIVAL, GROWTH AND NUTRIENT STATUS OF PLANTED PONDEROSA PINE SEEDLINGS

Submitted to Western Journal of Applied Forestry

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By:

Zhaofei Fan

James A. Moore

Department of Forest Resources

College of Natural Resources

and

Bahman Shafii

Statistical Programs

College of Agriculture

University of Idaho

Moscow, ID 83844-1133

Acknowledgments: The authors thank the Scott's Company and other members of the Intermountain Forest Tree Nutrition Cooperative for their support. We also thank Terry Shaw, Mariann Garrison and Mary Moore for their technical assistance.

EFFECT OF ROOT PLUG INCORPORATED CONTROLLED-RELEASE FERTILIZER UPON TWO-YEAR PERFORMANCE OF PLANTED PONDEROSA PINE SEEDLINGS

ABSTRACT

Three controlled-release fertilizers (fast release (FR), moderate release (MR) and slow release (SR)) were incorporated in the root plug at rates of 0.8, 1.6 or 3.2 grams per seedling at the time of sowing as supplements to nursery supplied soluble fertilizer. Effects on seedling growth, survival and foliar nutrient status of the "160/90" container ponderosa pine (*Pinus ponderosa Doug. ex Laws*) were evaluated after outplanting. At the end of the second growing season, fertilized seedlings had significantly greater caliper and height than unfertilized seedlings. Fertilization significantly increased relative height growth rate, but did not significantly increase relative caliper growth rate. Most treatments had lower caliper growth rates than the controls. The differences between the 3.2 grams of MR or SR fertilizer treatments and the controls were statistically significant. Height growth response was attributable to fertilizer doses rather than fertilizer types. The 3.2 grams of MR or SR fertilizer treatments produced significantly higher mortality (55 and 36 %, respectively) than the controls. The mortality was strongly correlated with root growth potential. Foliar N and Mo concentrations were significantly influenced by fertilization during the first growing season. During the second growing season, foliar Cu, Fe and K concentrations were found to be deficient or nearly deficient even after fertilization.

INTRODUCTION

Initial fertilizer toxicity and later deficiency in seedlings and most factors contributing to loss of efficiency in seedling fertilization are directly related to rapid dissolution and hydrolysis of the applied fertilizers. Controlled-release fertilizers may be considered as potential solutions to the problem because they provide a continuous supply of nutrients over an extended time period. Brockley (1988) discussed the potential for incorporating controlled-release fertilizers in the root plug of containerized seedlings for stimulating greenhouse and field growth performance and simplifying fertilizer operations. However, the reported results were not consistent. Few studies have explored the mechanisms behind the observed growth response. Fertilization research with controlled-release fertilizers is still empirical and in the stage of knowledge accumulation. Process-oriented research is needed to improve our understanding of mechanisms that control the response (Brockley 1988). The release characteristics, relative nutrient proportions and application rates of controlled-release fertilizers (Patel and Sharma 1977), and their interaction with stock type (Landis and Simonich 1984) were identified as priorities for future research.

We established a fertilization experiment with three controlled-release fertilizers characterized by various release rates and nutrient proportions in the production of container-grown ponderosa pine seedlings. Seedlings were then planted on the University of Idaho Experimental Forest in April of 1997. The study's objective was to evaluate the effect of three controlled-release fertilizers and several application rates on ponderosa pine seedling survival, growth and nutrient status. Specifically, the study addressed the following questions:

(1) What are the differences in growth and survival between fertilized and unfertilized ponderosa pine seedlings?

(2) How are growth and survival affected by fertilizer types and dosage?

(3) What effect does fertilization have on seedling foliar nutrient status and how is foliar nutrition related to growth and survival? and

(4) What effect does fertilization have on seedling root growth potential (RGP) and how is RGP related to growth and survival?

Based on the answers to the questions above, we make recommendations on fertilizer products and dosages to achieve maximum growth response and balanced seedling nutrition.

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 Vassar Silt Loam soil at the site 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 minimum temperature is –4 °C. In summer, the average temperature is 17 °C, and the average daily maximum temperature is 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 has 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, 267 mm, or 35 percent, usually falls in April through September (Osborne and Appelgren 1996). The study site was clearcut in 1995 and the slash burned in the spring of 1996.

Experimental design and treatments

The experiment was arranged as a randomized complete block design with six blocks on a one-acre trial. In each block, thirty-six ponderosa pine seedlings from each treatment were assigned randomly to a square plot of size 8 by 8 m with trees planted at 1.3 by 1.3 m spacing. All ponderosa pine seedlings planted for this study were grown the previous year (1996) at the University of Idaho Forest Research Nursery. Seedlings were stored at 0.5 °C, with relative humidity near 100 percent for 5 months (from December of the previous year to April) before outplanting. The controlled-release fertilizers (Table 1) were applied into the planting medium prior to sowing so they were incorporated in the root plugs of "160/90" containerized ponderosa pine seedlings. The fertilization treatments were the control (no controlled-release fertilizer), and 0.8, 1.6 and 3.2 grams per seedling of three controlled-release products: fast release, moderate release and slow release, a total of 10 treatments. All seedlings were planted on April 20th through 22nd, 1997.

Prior to planting, thirty-two seedlings for each treatment were randomly selected for root growth potential (RGP) testing. These 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 the maximum water-holding potential for the media. The RGP experiment ended four weeks later after 80% of the buds had broken dormancy. Roots were extracted from the pots and washed carefully from the medium. RGP index was evaluated based on the following criteria (Burdett 1979):

0----- no new roots 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

Field sampling and measurements

The potential variation in soil, seedling quality and the amount of fertilizer incorporated in the root plug was considered in the design. Thus we used square plots as sampling units rather than individual seedlings to investigate seedling response to fertilization treatments. The response variables of interest are mean caliper (diameter at the root collar), height, survival and foliage nutrient concentrations. Seedling height and caliper were measured at planting and at the end of each growing season (November). Relative caliper and height growth rates (RGR) were calculated for each plot by:

$$RGR = \frac{\ln Y_2 - \ln Y_1}{T_2 - T_1} \qquad (1)$$

Where Y_1 and Y_2 are the seedling's mean caliper or height for each plot at two points in time (T_1 and T_2). Survival was surveyed bi-weekly throughout the first growing season and was calculated for each plot as the percentage of living seedlings of the total number of planted seedlings. At the end of each growing season, three needle fascicles surrounding the apical bud were picked from each interior seedling in a plot. Needles were oven-dried at 70°C for 2 days and ground for chemical analysis. The following nutrients were analyzed: N, P, K, Ca, Mg, B, Cu, Zn, Fe, Mn and Mo, which were all included in the controlled-release fertilizers products. Foliar nitrogen 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 from digested plant tissue. Scotts Laboratories in Allentown, PA completed both procedures. Soil moisture and temperature at 10, 20 and 40 cm depths, at six points distributed uniformly across the trial were also monitored bi-weekly throughout the first growing season. These data were used to evaluate impacts on seedling growth and mortality. At the end of the second growing season, sixteen plots were systematically selected as sampling points for soil chemical analysis. Sample locations were selected such that they were unaffected by fertilizers contained in the seedling root plugs. In each plot, four 30cm deep soil cores, one from each quadrant, were taken and composited for soil pH, NO_3^--N, available P, Mn, Cu, Zn, Fe and exchangeable K, Ca and Mg analyses. Soil pH was measured 1:1 in H_2O. Nitrate was extracted with calcium oxide and determined using automated colorimetry. Exchangeable K, Ca and Mg (1 N ammonium acetate, pH 3.0) were analyzed by ICP spectrometry. Available P (for soil with pH< 7.2) was determined on a 2-g sub-sample of soil extracted with 12 mL of Bray's solution (Bray and Kurtz 1945). Available Mn, Zn, Cu and Fe were determined by atomic absorption.

Data analysis

Average caliper and height based on the sixteen interior seedlings from each plot were used in the statistical analysis. Caliper and height relative growth rates were also used as response variables. Dunnett's multiple comparison test (Kirk 1995) was conducted to test for differences in first and second-year survival, foliar nutrient concentrations, caliper, height and relative growth rates at the end of the second growing season (1998) between the nine fertilization treatments and the control. We tested the effects of fertilizer types and dosage on the final caliper and height of ponderosa pine seedlings using analysis of covariance (with caliper and height at planting as covariates). Analysis of variance (ANOVA) was conducted to test fertilization effects on caliper and height growth rates and foliar nutrient concentrations. Regression analysis of second-year caliper and height as related to fertilizer dosage was performed using a parabolic model of the form:

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

where Y is the seedling caliper (mm) or height (cm), X is the application rate (gram per seedling), a_0, a_1 and a_2 are the regression coefficients, and ε is the random error term under standard linear regression assumptions. The estimated fertilizer dosage associated with maximum caliper and height for each type of fertilizer was calculated via differentiation:

$$\text{estimated application rate} = -\hat{a}_1 / 2\,\hat{a}_2 \qquad (3)$$

Pearson's correlation coefficients were calculated to determine relationships between foliar nutrient concentrations and growth. Duncan's multiple-range test was used to compare differences in RGP between fertilizer treatments. The statistical computations were performed using the General Linear Model (GLM) procedure of SAS (SAS® Institute Inc. 1995).

RESULTS

Soil nutrient concentrations, moisture and temperature regimes

Mean values for soil chemical and physical properties are shown in Table 2 and Figure 1. Soil nitrate and Cu concentrations at the experimental site were very low. The experimental site experienced a dry period from mid-July until late September. The soil moisture between 11-40 cm deep during this period was less than 25%. Such low soil moisture can reduce nutrient release and tree growth. Soil temperatures remained moderate for fertilizer release during the period.

Caliper and height growth

At the end of the second growing season, all fertilization treatments except the 3.2 grams per seedling of moderate-release (MR) and slow-release (SR) fertilizer treatments produced significantly (p=0.0001) larger calipers than the control (Figure 2a). These two treatments had lower caliper growth rates than the control (Figure 2b). All treatments produced taller seedlings than the control at the end of the second growing season, except for the SR -0.8 treatment (Figure 3a). Relative height growth rates did not significantly increase (p>0.05) for the 0.8 rate for all fertilizer types and the 3.2 SR treatment (Figure 3b).

Both ANCOVA and ANOVA results (Table 3) show that dose rather than fertilizer release rate accounts for most of the variation in caliper and height growth. The interaction of fertilizer by dose significantly affected relative caliper growth rate, while there was no significant interaction effect on final caliper, final height or relative height growth rate. Regression summary for the parabolic model given in equation (2) is provided in Table 4. The model fit the data well and residual analysis showed no detectable trend. Based on the parabolic fit, the dose for achieving the maximum caliper at the end of the second growing season solving equation (3) was 1.96, 1.84 and 1.84 grams for FR, MR and SR products respectively, and 1.86, 2.02 and 2.06 grams for FR, MR and SR products respectively produced the maximum height response.

Survival and root growth potential (RGP)

Seedling survival varied significantly between fertilization treatments primarily due to the 3.2 MR or SR treatments that had much lower survival than the controls for the first two years (Figure 4). Fertilizer types, doses, and their interactions produced this result (Table 5). There were no survival differences between the other fertilization treatments (Figure 4). Seedling death mainly occurred within the first two months after planting and only 3.7% of the seedlings died after that time. Overall mortality at the end of the first growing season was 14 % (Figure 5). Very few seedlings (1.4%) died during the second growing season. Ponderosa pine treated with both fast and moderate-release fertilizers had similar survival patterns after one year. Mortality rate increased as rate increased from 0.8 to 1.6 grams and then decreased as rate further increased from 1.6 to 3.2 grams. The treatments differed in that survival dropped sharply with doses (from 1.6 to 3.2 grams) for MR fertilizer, but decreased only slightly for the same doses of FR fertilizer. Survival of ponderosa pine treated with SR fertilizer decreased with increasing dosage, particularly for the 3.2 grams per seedling rate (Figure 4).

Seedling mortality mainly resulted from dead root plugs (73.6%). The 3.2 grams of MR or SR fertilizer treatments produced most of the dead root plugs. Root growth potential tests showed that these two treatments resulted in significantly lower RGP than the controls and other fertilizer treatments (Figure 6). The 0.8 grams of FR or SR fertilizer treatments produced significantly higher RGP than the controls. No significant RGP difference was found between other treatments (Figure 6). Field mortality decreased exponentially with increasing seedling RGP index (Figure 7).

Foliar nutrients

Treatments MR-3.2, SR-1.6 and SR-3.2 produced lower foliar Mo concentrations and treatments FR-1.6, MR-0.8, MR-3.2, SR-1.6 and SR-3.2 resulted in lower foliar N concentrations than the control at the end of the first growing season ($p<0.05$). No treatments were different from the control for other nutrients. At the end of the second growing season, the FR-0.8 treatment produced higher foliar Cu concentration, SR-3.2 lower foliar N concentration, and FR-1.6 and MR-0.8 higher foliar P concentrations than the control ($P=0.05$). No difference was found after the second year for other treatments and nutrients (Table 6).

ANOVA showed that foliar N, B, Cu and Mo concentrations at the end of the first growing season were significantly accounted for by fertilizer types ($P<0.1$); however, foliar Mg varied significantly by doses rather than fertilizer types ($P<0.005$). The FR fertilizer produced the highest foliar N, B, Cu and Mo concentrations, while the SR fertilizer was lowest and the MR fertilizer was intermediate. At the end of the second growing season, differences in foliar Ca and Zn resulted from fertilizer doses applied ($P<0.05$), foliar Cu from both dose and the interaction of dose by fertilizer type ($P<0.01$) and foliar P concentration from fertilizer type ($P<0.01$).

Based on the critical foliar nutrient concentrations for ponderosa pine (Powers 1983, Powers et al. 1985, Boyer 1984 (unpublished)), Fe was deficient for the first two years and Cu was deficient for the first year. Foliar Cu and K for the second year were only slightly higher than their respective critical values and were possibly deficient (Table 6). Based on the non-species-specific critical and optimal nutrient ratios (Van den Driessche 1974), our K/N ratio was below the critical ratio and the ratios of P/N and Mg/N were slightly over the critical ratios but were lower than the optimal ratios. The Ca/N ratio was above the optimal ratio but all other ratios were below optimal (Table 7).

The relationship between foliar nutrient status, growth and survival.

During the first growing season, caliper growth rate was positively related to foliar N, Ca and B concentrations, and negatively related to foliar K concentration and the P/N, K/N, and Mg/N, ratios (Table 8). Height growth rate was positively related to foliar P, Mg and Mn concentrations, and negatively related to foliar Cu concentration. During the second growing season, caliper growth rate was positively related to foliar N concentration and negatively related to the concentration ratios of all macronutrients to N. Height growth was positively related to foliar Mn concentration and negatively related to foliar B concentration. The negative relationship can be interpreted as either growth dilution or deficiency. However, based on the results presented in Table 6, except for the Cu deficiency, all negative relationships are assumed to reflect growth dilution. Significant correlation between relative growth rate and foliar nutrient concentration and concentration ratios were observed more frequently for caliper than for height suggesting that caliper growth was more affected by foliar nutrient status than was height growth. First year mortality was negatively related to foliar N, Mg, B, Mn and Mo concentrations, but positively related to the P/N ratio. Foliar concentrations of P, K, Ca, Mg, Cu, Fe, and Mo in 1998 were not significantly correlated with any response variables and therefore were not included in Table 8.

DISSCUSION

Caliper and height growth

There is no evidence that fertilization increased caliper growth rate two years after field planting. Of the nine fertilization treatments, six treatments were lower and three treatments were slightly greater than the control with respect to caliper growth rate after planting. Therefore, when compared to the unfertilized seedlings, the significantly larger caliper of fertilized ponderosa pine measured after two years was mainly due to their size differences at the time of planting rather than subsequently greater field growth rate. The 3.2 grams of MR or SR fertilizer treatments greatly reduced caliper growth, while the 3.2 grams of FR fertilizer treatment increased caliper growth. The 1.6 grams of MR fertilizer achieved maximum field caliper growth rate (Figure 2b).

Fertilization significantly increased ponderosa pine seedling height at the end of the second growing season. The taller seedlings resulted from both their larger initial size resulting from treatment effects while in the greenhouse as well as higher growth rate after planting (Figure 3b and Table 3). Differences in height and height growth rate among the fertilized seedlings resulted from dosage differences rather than fertilizer types or the interaction of fertilizer type by dosage (Table 3). Neither 0.8 grams of FR, MR or SR fertilizer nor 3.2 grams of SR fertilizer produced significantly greater height growth rate than the control (Figure 3b). Field height growth was more affected by fertilization treatments than was caliper growth. As suggested by the parabolic fit (Table 4), the best dosage for both caliper and height growth should be between 1.8 and 2.1 grams per seedling.

The relationship between mortality and fertilizer release rate

Brockley's (1988) finding that continuous nutrient release and extremely high salinity buildup and toxicity during cold storage likely explained our dead root plugs. Root growth potential tests showed that incorporating high doses of controlled-release fertilizers in the containers resulted in lower root growth potential. Many dead root plugs were found with the 3.2 grams of MR or SR fertilizer treatments. The strong association between RGP and field mortality (Figure 7) suggests that high mortality was attributable to low seedling RGP.

Unbalanced physiological and morphological characteristics of the seedlings such as nutrient imbalance within plant organs and high shoot/root ratios were the probable factors leading to ponderosa pine mortality. Necrotic needle tips were observed within two weeks of planting for the 3.2 grams of MR or SR fertilizer treatments. Moisture content in the top 40 cm of soil was greater than 30 % before the end June (Figure 1) by which time 83.2% of the overall mortality had occurred. Low soil moisture per se did not contribute to high seedling mortality.

Some of the MR and SR fertilizers still remained in the root plugs when the seedlings were placed in cold storage, while most FR fertilizer had already been released. This is evidenced by the much better survival for the FR-3.2 treatment compared to the same rate of MR or SR fertilizers (Figure 4). These results suggest that dosage should be lower for fertilizers whose release periods are longer than the nursery's production cycle to avoid seedling damage caused by continuous release and salinity buildup in the root plug during cold storage before planting. Results may have been very different if the seedlings had been fall planted rather than placed in cold storage waiting for spring planting.

Foliar nutrient status and seedling growth.

In our study, foliar nutrients were generally poorly correlated with soil nutrients. No significant associations were found for all nutrients other than P. For example, foliar Fe and K were diagnosed as deficient and nearly deficient even though soil available Fe and K were high (Table 2). Foliar Cu was deficient for the first year and only slightly above its critical value for the second year and soil available Cu was also deficient. Since we fertilized the seedlings rather than the site, lower soil nutrient availability was not the only reason for foliar nutrient deficiency. The deficiency of foliar micronutrients, such as Cu, Zn and Fe, may be caused by application of high levels of N and P rather than low soil nutrient availability (Miller and Cooper 1973, Teng and Timmer 1990). We believe that foliar Fe and K deficiency in our study was related to the high level of foliar N. No matter the reason, foliar nutrient deficiency may be corrected by increasing the nutrient proportion in the fertilizer, particularly, the proportions of K, Fe and Cu.

Because of the complexity of nutrient remobilization and translocation between the plant and soil, and the interaction between nutrients, many fertilization practices have been based on both soil and plant tissue (mostly the foliage) analysis. The relationship between foliar nutrient status and tree growth has usually been obscured in the absence of biomass and nutrient uptake information (Imo and Timmer 1996). To minimize this problem, we used relative growth rate rather than absolute size of ponderosa pine seedlings to do correlation analyses and conducted these analyses not only for the same time period but for different time periods, i.e. the correlation between second-year's relative growth rate and first-year's foliar nutrient concentrations and nutrient ratios. This analysis approach clarifies that caliper growth was mainly attributable to foliar N concentration, particularly during the second dosage for achieving maximum caliper and height should be 1.7 and 1.93 gram per seedling, respectively.

Ponderosa pine mortality mainly occurred within the first two months after planting. Incorporating 3.2 grams of MR or SR fertilizer in the root plug produced significantly higher mortality (54 and 36 %, respectively), which resulted from lower RGP caused by nutrient toxicity due to the continuous nutrient release for these two fertilizers during cold storage.

None of the fertilization treatments applied in the root plug prior to the container nursery-growing regime were entirely effective in stimulating seedling growth after planting. We feel the key for future improvement is extension of the product release time period past seedling cold storage into the first growing season after spring planting. Another possibility would be to test fall planting with the higher rates of slower release fertilizers.

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Table 1. Percent by weight of nutrients 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. Chemical analysis of soil samples collected from 0-30 cm at the experimental site.

Attributes	Mean ± standard deviation	Coefficient of variation (%)
Cation exchangable 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
Available P (ppm)	54.9 ± 24.1	43.9
Exchangeable K (ppm)	150.1 ± 61.9	41.3
Exchangeable Ca (ppm)	1345.7 ± 251.0	18.7
Exchangeable Mg (ppm)	110.3 ± 19.8	18.0
Available Mn (ppm)	9.3 ± 3.9	42.0
Available Cu (ppm)	0.46 ± 0.13	28.3
Available Zn (ppm)	1.66 ± 0.37	22.3
Available Fe (ppm)	92.0 ± 40.8	44.3

Table 3. Two-way analysis of covariance of second-year caliper and height and analysis of variance for relative caliper and height growth rate for the ponderosa pine seedlings at the experimental site.

Source	Second-year caliper				Second-year height			
	df	SS	F	P	df	SS	F	P
Covariate	1	8.8	4.81	0.2391	1	120.2	12.45	0.0011
Block	5	40.8	4.45	0.0027	5	367.6	7.62	0.0001
Fertilizer(F)	2	7.4	2.02	0.1464	2	20.6	1.07	0.3544
Dose (D)	2	22.1	6.02	0.0053	2	146.3	7.58	0.0017
F×D	4	5.3	0.72	0.5843	4	28.0	0.72	0.5805
Error	39	71.5			39	376.4		
	Caliper growth rate (%)				Height growth rate (%)			
	df	SS	F	P	df	SS	F	P
Block	5	0.030	3.18	0.0166	5	0.049	7.85	0.0001
Fertilizer(F)	2	0.008	2.14	0.1309	2	0.002	0.85	0.4360
Dose (D)	2	0.019	5.11	0.0105	2	0.015	5.93	0.0055
F×D	4	0.026	3.38	0.0178	4	0.004	0.83	0.5151
Error	40	0.076			40	0.050		

Table 4. Parabolic regression of second-year caliper and height versus doses for three controlled-release fertilizers for ponderosa pine. (FR = fast-release; MR= moderate-release; SR= slow-release. The numbers in parentheses are the standard errors of estimated coefficients).

Fertilizer Type	Dependent Variable	$\hat{a}_0$	$\hat{a}_1$	$\hat{a}_2$	Pr>F	R^2	Dose for maximizing Caliper or height ($-\hat{a}_1/2\hat{a}_2$)
FR	Caliper	16.65	4.20	-1.06	0.0012	0.48	1.96
		(0.64)	(1.01)	(0.29)			
	Height	43.76	14.03	-3.78	0.0001	0.57	1.86
		(1.69)	(2.68)	(0.78)			
MR	Caliper	16.74	4.57	-1.24	0.0040	0.40	1.84
		(0.76)	(1.20)	(0.35)			
	Height	43.52	11.95	-2.96	0.0005	0.52	2.02
		(1.70)	(2.69)	(0.78)			
SR	Caliper	16.69	3.99	-1.09	0.0020	0.45	1.84
		(0.61)	(0.97)	(0.28)			
	Height	42.76	11.69	-2.84	0.0001	0.59	2.06
		(1.46)	(2.31)	(0.67)			

Table 5. Analysis of variance for first two-year survival of fertilized ponderosa pine at the experimental site.

Sources	First-year survival				Second-year survival			
	d.f.	SS	F	P	d.f.	SS	F	P
Block	5	0.138	3.44	0.0112	5	0.118	2.67	0.0354
Fertilizer (F)	2	0.261	16.19	0.0001	2	0.230	13.07	0.0001
Dose (D)	2	1.047	65.05	0.0001	2	1.109	62.94	0.0001
F×D	4	0.292	9.08	0.0001	4	0.242	6.87	0.0001
Error	40	0.322			40	0.352		

Table 6. Mean foliar nutrient concentrations of ponderosa pine seedlings for various fertilization treatments at the end of the 1997 and 1998 growing seasons (The critical values for P, K, Ca and Mg are from Powers (1983), the value for N from Powers et al. (1985) and values for B, Cu, Zn, Fe and Mn are from Boyer (1984, unpublished). The critical value for Mo is not available. '+' and '-' indicate treatments that were significantly higher and lower than the control, respectively. FR= fast release; MR= moderate release; SR= slow release; Three doses are 0.8, 1.6 and 3.2 grams per seedling, respectively).

Nutrient	Year	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	
N (%)	97	2.10	1.99	1.77 -	1.82	1.78 -	1.98	1.76 -	1.80	1.67 -	1.69 -	
	98	1.96	1.89	1.84	1.88	1.87	1.96	1.87	1.90	1.86	1.74 -	
P (%)	97	0.18	0.18	0.17	0.18	0.18	0.18	0.18	0.18	0.18	0.18	
	98	0.17	0.18	0.19 +	0.18	0.19 +	0.18	0.18	0.17	0.18	0.17	
K (%)	97	0.71	0.71	0.71	0.73	0.73	0.72	0.76	0.72	0.75	0.77	
	98	0.52	0.50	0.52	0.52	0.54	0.51	0.52	0.49	0.49	0.52	
Ca (%)	97	0.21	0.24	0.23	0.22	0.22	0.23	0.21	0.23	0.22	0.22	
	98	0.29	0.33	0.31	0.30	0.33	0.32	0.29	0.33	0.31	0.30	
Mg (%)	97	0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.11	0.11	0.10	
	98	0.12	0.14	0.14	0.12	0.14	0.14	0.13	0.13	0.13	0.13	
B (ppm)	97	22.4	23.2	23.5	22.3	23.8	23.1	21.3	22.4	20.8	20.6	
	98	31.2	31.2	29.2	28.0	28.9	29.4	30.0	26.3	29.2	29.5	
Cu (ppm)	97	2.96	2.80	2.79	2.92	2.65	2.81	2.72	2.69	2.53	2.60	
	98	3.30	3.78 +	3.25	3.14	3.32	3.24	3.44	3.32	3.31	3.38	
Zn (ppm)	97	67.3	62.7	60.3	50.7	56.3	52.5	53.6	71.1	52.5	54.5	
	98	53.8	56.4	57.2	49.6	54.9	53.4	51.0	59.4	55.5	54.2	
Fe (ppm)	97	28.4	27.0	27.6	26.9	27.5	27.6	27.0	26.1	28.3	26.0	
	98	25.0	25.8	26.1	26.0	26.7	25.9	26.5	24.0	26.5	26.8	
Mn (ppm)	97	98	106	112	104	111	114	108	129	113	101	
	98	125	119	133	124	132	132	129	128	119	131	
Mo (ppm)	97	0.45	0.40	0.47	0.43	0.33	0.31	0.25 -	0.35	0.28 -	0.22 -	
	98	0.50	0.58	0.60	0.66	0.62	0.56	0.61	0.50	0.57	0.56	
Percent difference from critical values												Critical Values (%)
N	97	91	81	61	65	62	80	60	64	52	54	1.10
	98	78	72	67	71	70	78	70	73	69	58	
P	97	125	125	113	125	125	125	125	125	125	125	0.08
	98	113	125	138	125	138	125	125	113	125	113	
K	97	48	48	48	52	52	50	58	50	56	60	0.48
	98	8	4	8	8	13	6	8	2	2	8	
Ca	97	320	380	360	340	340	360	320	360	340	340	0.05
	98	480	560	520	500	560	540	480	560	520	500	
Mg	97	100	100	100	80	100	100	100	120	120	100	0.05
	98	140	180	180	140	180	180	160	160	160	160	
B	97	12	16	18	12	19	16	7	12	4	3	20.0
	98	56	56	46	40	45	47	50	32	46	48	
Cu	97	-1	-7	-7	-3	-12	-6	-6	-10	-16	-13	3.0
	98	10	26	8	5	11	8	15	11	10	13	
Zn	97	124	109	101	69	88	75	79	137	75	82	30.0
	98	79	88	91	65	83	78	70	98	85	81	
Fe	97	-43	-46	-45	-46	-45	-45	-46	-48	-43	-48	50.0
	98	-50	-48	-48	-46	-45	-45	-46	-52	-47	-46	
Mn	97	63	76	87	73	84	90	80	116	89	68	60.0
	98	108	98	122	107	120	119	114	114	99	118	

Table 7. Foliar nutrient concentration ratios of ponderosa pine seedlings under various fertilization treatments for the 1997 and 1998 growing seasons (FR= fast release; MR= moderate release; SR= slow release; Three doses are 0.8, 1.6 and 3.2 grams per seedling, respectively. Critical and optimal ratios are from Van den Driessche (1974)).

Nutrient-ratio		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	Critical or optimal ratio
P/N	97	0.09	0.09	0.10	0.10	0.10	0.09	0.10	0.10	0.11	0.10	
	98	0.09	0.09	0.10	0.10	0.10	0.09	0.09	0.09	0.10	0.10	
K/N	97	0.34	0.36	0.43	0.41	0.41	0.37	0.44	0.41	0.46	0.46	
	98	0.27	0.27	0.29	0.28	0.29	0.26	0.28	0.26	0.27	0.30	
Ca/N	97	0.10	0.12	0.13	0.12	0.13	0.12	0.12	0.13	0.14	0.13	
	98	0.15	0.18	0.17	0.16	0.18	0.16	0.16	0.17	0.16	0.17	
Mg/N	97	0.05	0.05	0.06	0.05	0.06	0.05	0.05	0.06	0.07	0.06	
	98	0.06	0.07	0.07	0.07	0.08	0.07	0.07	0.07	0.07	0.08	
---Percent difference from the critical ratio---												
P/N	97	13	13	25	25	25	13	25	25	38	25	0.08
	98	13	13	25	25	25	13	13	13	25	25	
K/N	97	-32	-28	-14	-10	-10	-26	-12	-10	-8	-8	0.50
	98	-46	-46	-42	-44	-42	-48	-44	-48	-46	-40	
Ca/N	97	100	140	160	140	160	140	140	160	180	160	0.05
	98	200	260	240	220	260	220	220	240	220	240	
Mg/N	97	0	0	20	0	20	0	0	20	40	20	0.05
	98	20	40	40	40	60	40	40	40	40	60	
---Percent difference from the optimal ratio---												
P/N	97	-40	-40	-33	-33	-33	-40	-33	-33	-27	-33	0.15
	98	-40	-40	-33	-33	-33	-40	-40	-40	-33	-33	
K/N	97	-48	-45	-34	-37	-37	-43	-32	-37	-29	-29	0.65
	98	-58	-58	-55	-57	-55	-60	-57	-60	-58	-54	
Ca/N	97	0	20	30	20	30	20	20	30	40	30	0.10
	98	50	80	70	60	80	60	60	70	60	70	
Mg/N	97	-50	-50	-40	-50	-40	-50	-50	-40	-30	-40	0.10
	98	-40	-30	-30	-30	-20	-30	-30	-30	-30	-20	

Table 8. Pearson's first moment correlation coefficients between foliar nutrient concentrations, nutrient ratios and relative growth rates and survival of ponderosa pine treated with controlled-release fertilizers. Foliage concentrations and ratios for 1997 are tested against attributes for both years, while 1998 values are tested only against 1998 attributes. (* denotes 0.05< P<0.1, ** denotes 0.01<P<0.05 , and *** denotes P<0.01).

	Nutrient	Caliper growth rate (%)		Height growth rate (%)		Mortality (%)
Year		1997	1998	1997	1998	1997
1997	N	0.22 *				-0.25 *
	P		0.30 **	0.28 **	0.32 **	
	K	-0.39 ***				
	Ca	0.31 **				
	Mg		0.23 *	0.42 ***	0.28 **	-0.38 ***
	B	0.24 *				-0.26 **
	Cu			-0.27 **		
	Fe		0.29 **			
	Mn			0.23 *		-0.29 **
	Mo		0.24 *			-0.41 ***
	P/N	-0.23 *				0.22 *
	K/N	-0.36 ***				
	Ca/N					
	Mg/N	-0.25 ***	0.24 *			
1998	N		0.46 ***			
	B				-0.22 *	
	Mn				0.40 ***	
	P/N		-0.49 ***			
	K/N		-0.42 ***			
	Ca/N		-0.23 *			
	Mg/N		-0.35 ***			

Figure 1. Observed soil moisture and temperature at the experimental site in 1997.

m = moisture (%)   t = temperature (°C)

Figure 2. Caliper (panel a) and caliper growth rate (panel b) of ponderosa pine seedlings following various fertilization treatments after two growing seasons (1998). '+' indicates treatments that are significantly greater than the control and '-' indicates treatments that are significantly lower than the control.

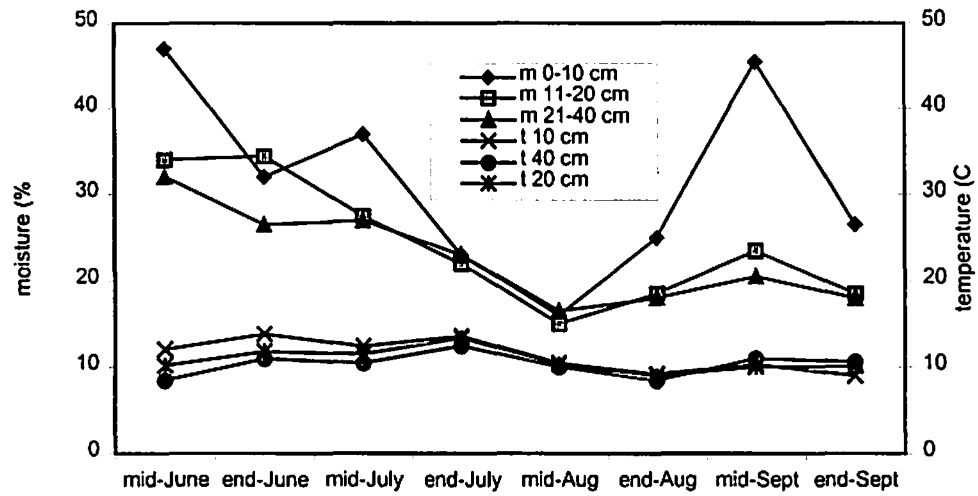
Figure 3. Height (panel a) and height growth rate (panel b) of ponderosa pine seedlings following various fertilization treatments after two growing seasons (1998). '+' indicates treatments that are significantly greater than the control.

Figure 4. First two-years survival of ponderosa pine by fertilization treatments ('-' indicates the treatments that had significantly lower survival than the control).

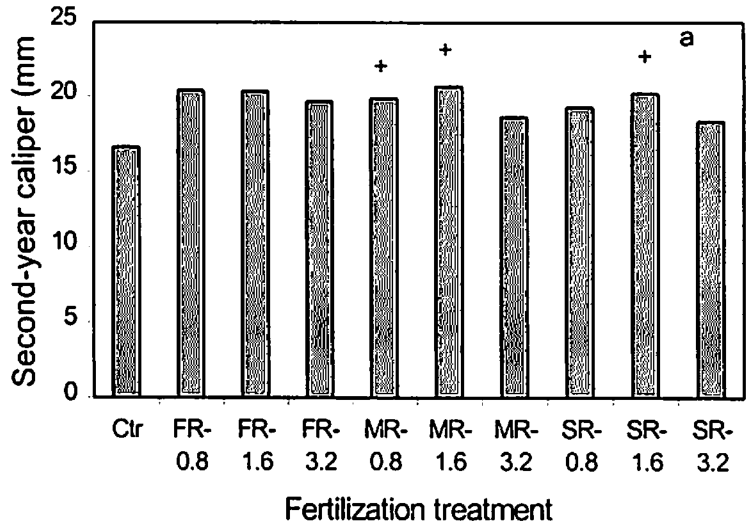
Figure 5. Overall field mortality of ponderosa pine by month during the first year after outplanting.

Figure 6. Root growth potential of ponderosa pine under various fertilizer treatments after 5 months of cold storage. Bars labeled with the same letter are not significantly different ($p=0.05$).

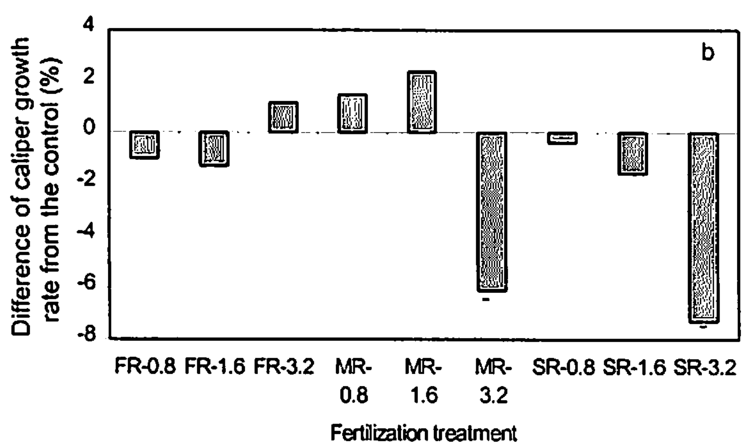
Figure 7. The relationship between two-year field mortality and root growth potential of ponderosa pine (The numbers in parentheses are the standard errors of estimated coefficients).



50
40
30
20
10
0
moisture (%
temperature (C
m 0-10 cm
m 11-20 cm
m 21-40 cm
t 10 cm
t 40 cm
t 20 cm
mid-June
end-June
mid-July
end-July
mid-Aug
end-Aug
mid-Sept
end-Sept

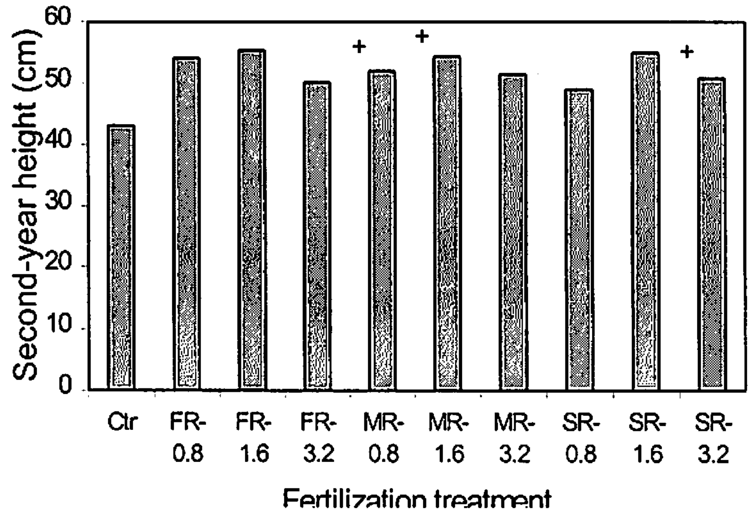


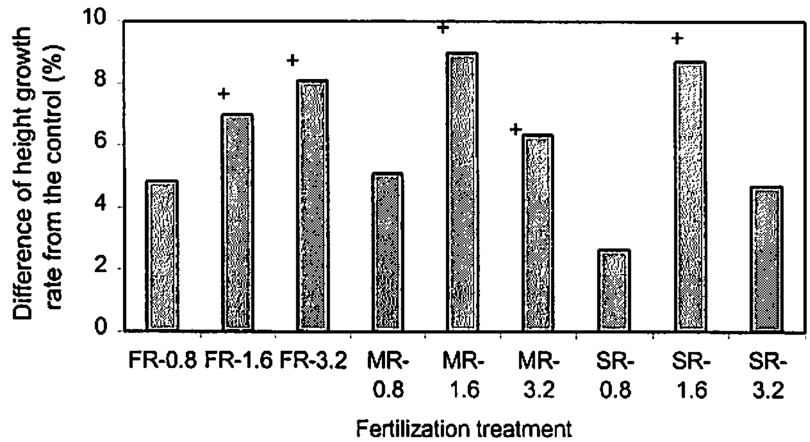
(a) caliper



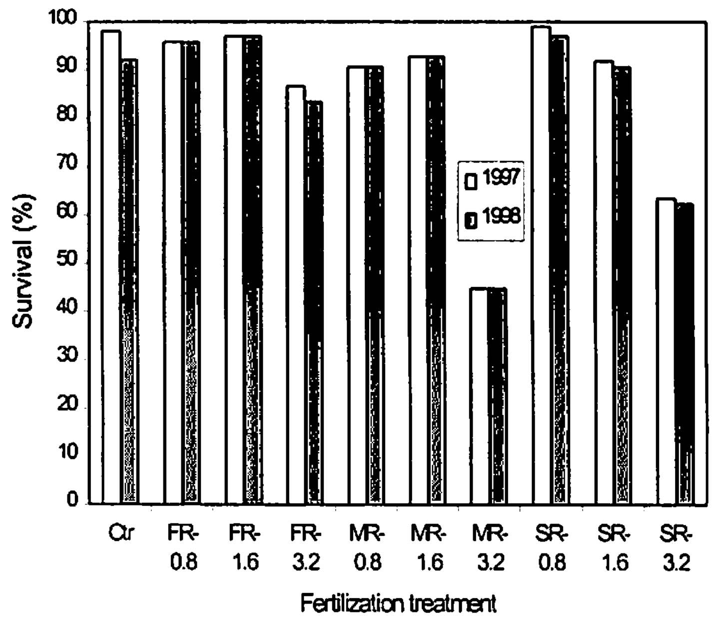
(b) caliper growth

(a) height

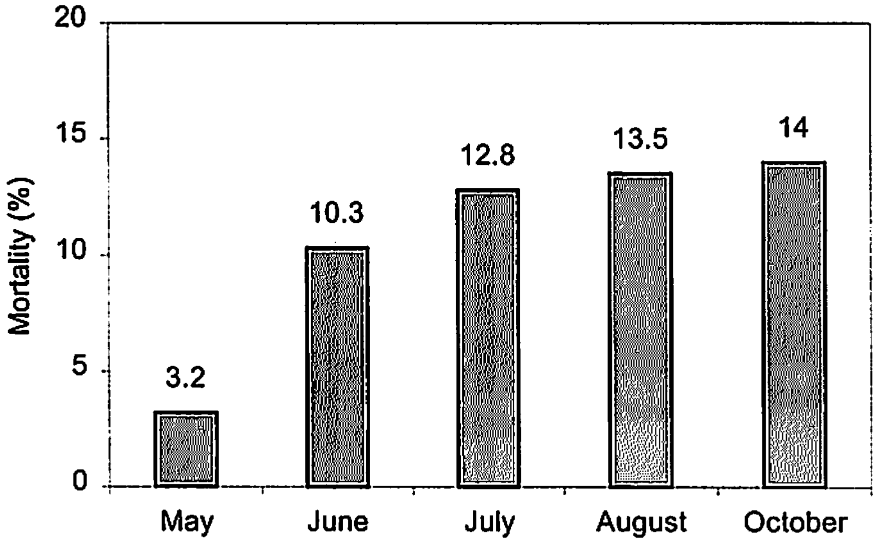


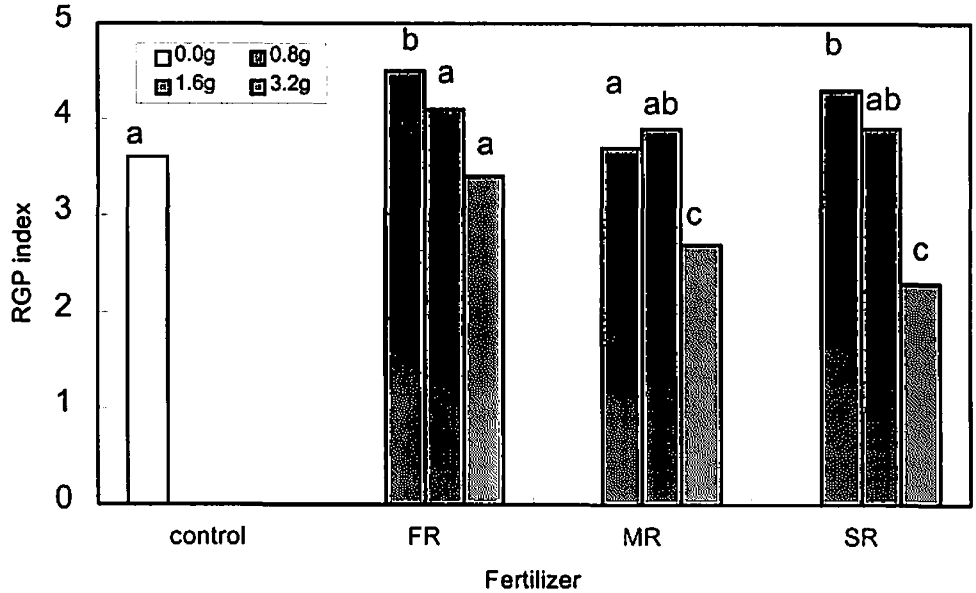


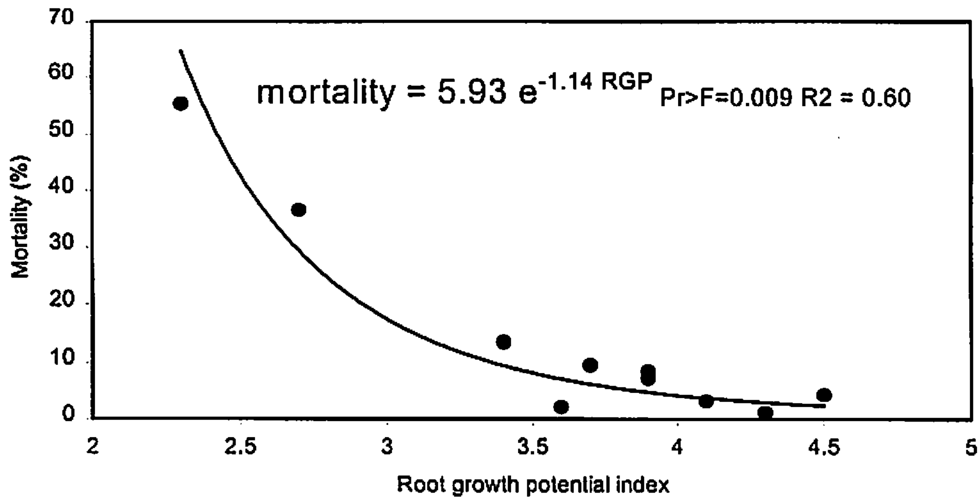
(b) height growth



100
90
80
70
60
50
40
30
20
10
0
Survival (%)
1997
1998
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
Fertilization treatment


20
15
10
5
0
Mortality (%)
3.2
10.3
12.8
13.5
14
May
June
July
August
October


5
4
3
2
1
0
RGP index
0.0g
0.8g
1.6g
3.2g
a
b
a
a
a
ab
c
b
ab
c
control
FR
MR
SR
Fertilizer


mortality = 5.93 e-1.14 RGP Pr>F=0.009 R2 = 0.60
Mortality (%)
70
60
50
40
30
20
10
0
2
2.5
3
3.5
4
4.5
5
Root growth potential index