Response of planted ponderosa pine trees to slow release fertilizers

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Introduction

Nutrient availability has long been recognized as a limiting factor to plant growth (Luxmoore et al. 1993). In the Pacific Northwest, of the elements needed for tree growth, nitrogen is the only one that is consistently deficient in the forests of the Northwest (Cole, et al., 1992). Foliage samples collected from 90 fertilizer trials in Douglas-fir scattered across eastern Washington, northeastern Oregon, Idaho and western Montana showed nitrogen concentrations of unfertilized trees to be quite low throughout the area (Mika and Moore, 1990). Foliar analysis has also shown severe to very severe nitrogen deficiencies to be common in lodgepole pine stands throughout the interior of British Columbia (Ballard, 1986) and in many ponderosa pine (Powers et al. 1988) and true fir (Powers, 1981) stands in California and Oregon. No other nutrients have been found generally lacking over such large areas and wide range of conditions. Since early work by the College of Forestry, University of Washington, in the1950's, wide-scale testing with nitrogen has been used to develop response predictions. Currently, however, most information on application rates has been based on broadcast application of soluble nitrogen sources. Very little or no information is available on effects of slow release sources on growth of ponderosa pine, especially using a dibble technique. Therefore, the objectives of this study are:

1) to determine the optimum rate of a complete fertilizer to assure rapid tree establishment and early development during the first four years following outplanting;

2) to evaluate the effects of different nutrient release characteristics on plant performance, especially on the root system and

3) to determine correlation of nutrient concentrations from tissue analysis with nutrient application rate and seedling growth rates.

The experiment, if successful, will provide a practically economic and efficient fertilization method to ensure rapid growth and a higher nutrient uptake rates of after planting ponderosa pine.

Experimental design

1. **Trial description:**

Location: University of Idaho Experimental Forest, Flat Creek Unit, Section 19, half mile from Idaho highway #9

Topography: Elevation: 3200 feet ASL

Aspect: NE 27

Slope: 28%

Position: mid-slope

Soil: Vassar silt loam, 60 inches deep.

Habitat series: Grand fir habitat.

2. **Trial design :**

There are two trials for the field fertilization test, one established in 1996, and the other in 1997. The two field trials are laid out in a randomized block design. The total area of each trial is about 1 acre. In the 1996 experiment, trees were fertilized at the time of planting (May 10^{th}, 1996). In the 1997 experiment, trees were fertilized in the greenhouse in the previous year (March 1^{st}, 1996). Thirteen treatments, their plot code and designs as well as a tree's position within each plot are shown in Tables 1 and 2 and Figures1 and 2.

Table 1. Treatments and corresponding plot codes for the 1997 ponderosa pine plantation

Treatments			Plot code					
Fertilizer code		rates (g/tree)	Block I	Block II	Block III	Block IV	Block V	Block VI
CB2-95	fast release	0.8	104	209	305	407	502	605
CB3-95	medium release	0.8	101	204	313	406	510	612
IOP	slow release	0.8	108	210	304	412	508	609
CB2-95	fast release	1.6	113	202	309	402	512	604
CB3-95	medium release	1.6	110	208	301	409	505	602
IOP	slow release	1.6	103	205	310	401	501	610
CB2-95	fast release	3.2	107	213	306	408	504	608
CB3-95	medium release	3.2	112	201	303	405	503	601
IOP	slow release	3.2	109	203	311	410	513	613
IOP	slow release *	3.2	105	211	302	411	507	607
CB1-95 NH7.8	(not treated)		102	212	307	404	509	603
IOP 6 CSC	(not treated)		106	206	312	413	506	606
CONTROL		0	112	207	308	403	511	611

* Trees were grown in 45/345 (# of cells per tray/cell volume (ml)) trays.

Table 2. Treatments and corresponding plot codes for the 1996 ponderosa pine plantation

Treatments			Plot code					
Fertilizer code		rates (g/tree)	Block I	Block II	Block III	Block IV	Block V	Block VI
15-10-12	fast release	5	110	209	309	401	502	605
16-08-12	medium release	5	102	204	308	408	510	612
15-08-11	slow release	5	106	203	304	410	508	609
14-07-10	minors external	5	103	210	313	402	512	604
15-10-12	fast release	15	109	208	302	407	505	602
16-08-12	medium release	15	101	212	310	406	501	610
15-08-11	slow release	15	111	205	301	409	504	608
14-07-10	minors external	15	104	207	307	403	503	601
15-10-12	fast release	30	112	202	305	411	513	613
16-08-12	medium release	30	105	211	303	412	507	607
15-08-11	slow release	30	108	206	311	405	509	603
14-07-10	minors external	30	113	201	312	413	506	606
CONTROL		0	107	213	306	404	511	611

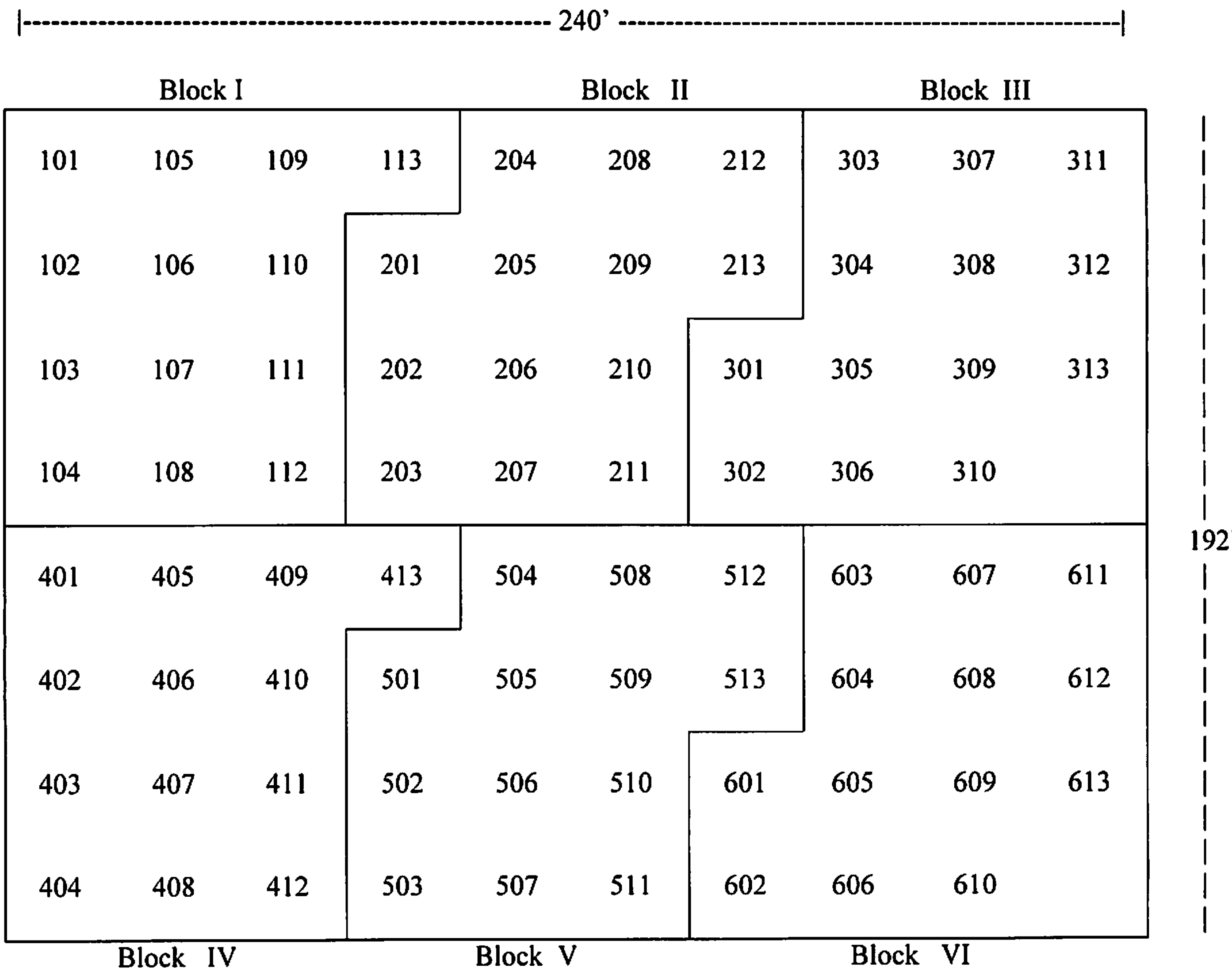

Figure 1. The randomized block design diagram for the 1996 and 1996 field trails.

|---------------------24'---------------------|

O	O	O	O	O	O
O	X	X	X	X	O
O	X	X	X	X	O
O	X	X	X	X	O
O	X	X	X	X	O
O	O	O	O	O	O

24'

O border trees
X interior trees

4 X 4 spacing

Figure 2. Planting points in a single plot (experimental unit).

3. Observation items and sampling methods

For the 1997 plantation, tree height and caliper were measured at planting and at the end of the growing season. Also, mortality was surveyed every two weeks. For the 1996 plantation, caliper and height were measured at the end of the growing season. Foliage samples were collected from all healthy interior trees within each plot at the end of the growing season for nutrient analysis. Three needles around the top buds were picked in three directions.

Relative caliper and height growth rates were calculated based on the formula:

$$\text{relative growth rate(\%)} = \frac{\ln(\text{caliper or height at time } t_2) - \ln(\text{caliper or height at time } t_1)}{t_2 - t_1}$$

where $t_2 - t_1 = 1$ year. For the 1997 plantation, relative growth rates are the difference between the natural logarithm of the caliper or height at the end of the growing season and at planting. For the 1996 plantation, relative growth rates in 1997 are the difference between the natural logarithm of the caliper or height at the end of the growing season of 1997 and 1996.

Mortality was computed as the percentage of dead trees to the total number of trees for the plot and averaged over the treatments.

Root growth potential tests were conducted in the UI Research Nursery in May, 1997. Tested trees were grown in one-gallon pots. A completely random design with four replications was employed. Each replication included 7 to 9 trees. Trees were watered to keep the maximum water-hold potential for the media. The experiment ended when 80% of the buds broke dormancy. Then roots were washed carefully from the media and root growth potential were evaluated based on the following criteria for each category:

0--- no new roots growth

1--- some new roots but none over 2 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

Photosynthesis and conductance were measured for the 1996 plantation on June 13th and September 14th of 1997, respectively. On June 13th , foliage sample were also collected for nutrient analysis in order to investigate the relationships between photosynthesis and foliage nutrient concentrations.

In addition, soil moisture and temperature were monitored at 10, 20 and 40 cm depths. Air temperature extremes at 30 and 70 cm heights above the ground in the two plantations were monitored every two weeks through the whole growing season to evaluate the potential impacts of these environmental factors on tree growth.

4. Data analysis

For growth and nutrient data, ANOVA, MANOVA, multiple comparison of means, covariance analysis and multiple linear regression respectively were employed to investigate treatment effects on growth and nutrient allocation, and the association between growth and foliage nutrient concentrations.

RESULTS

I. 1997 plantation

1. Mortality

(1) The average mortality for the whole plantation

Burned needles were observed in the middle of May, two weeks after planting in the 1997 plantation (Figure 1). By late May, 15.2% (146 trees) of the trees showed burned needles. By the middle of July, 63% (92 trees) of them had died, however, 31% (45 trees) of them had recovered normally. After that time, no evident burned-needles were observed through the whole growing season. For the whole plantation, tree death mainly occurred before the middle of July (Figure 2), after that time, mortality increased slowly. By the end of the growing season, the average mortality for the whole plantation was about 14.06%.

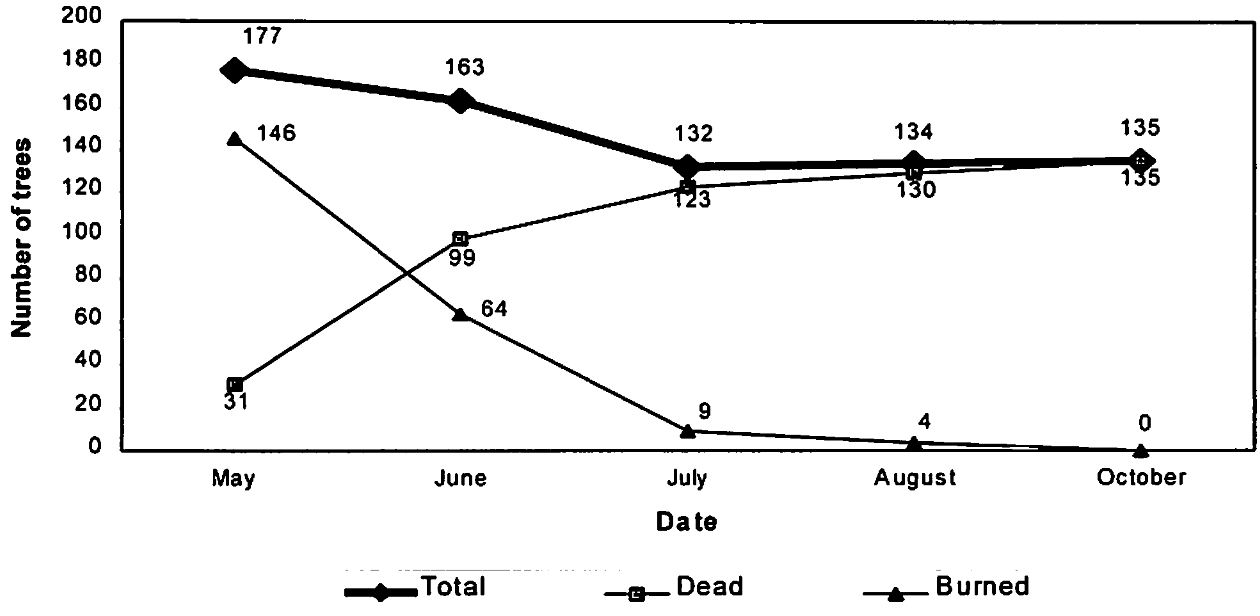

Figure 1. Transformation between dead trees and burned trees in the 1997 ponderosa pine plantation during the first growing season

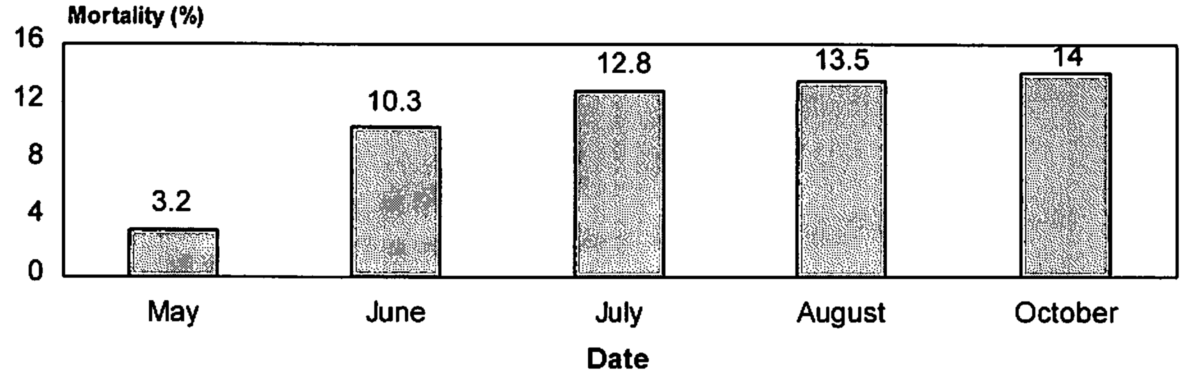

Figure 2. Mortality pattern during the first growing season for the 1997 ponderosa pine plantation.

(2) Tree mortality for various fertilization treatments

Analysis of variance shows that mortality differs significantly between treatments (pr>F=0.0001). High application rates (3.2 grams per tree) of the fast and medium release products produced 55.21% and 36.46% mortality, respectively (Figure 3 and table1). High application rates of the slow release product only slightly increased mortality (13.54%) compared to the low (0.8 grams per tree) and middle (1.6 grams per tree) rates of the same product. Tree mortality for the control (no fertilization) was 2.08%. The mortality rates for both low and middle application rates of all three products were all below 10%.

Multiple comparisons of mortality means show that compared with the control, only high application rates of the fast and medium release products caused significantly higher mortality (Bon-p=0.0001) (Table2). No significant difference in mortality rates existed between low and middle application rates of the fast and medium release products, and the three application rates of the slow release product. Effects of fertilizer sources on mortality were detected only for high application rates, with the result that the fast and medium release products caused higher mortality than the slow release product (Bon-p=0.0001 and 0.0255, respectively), but there was no difference between the fast and medium release products.

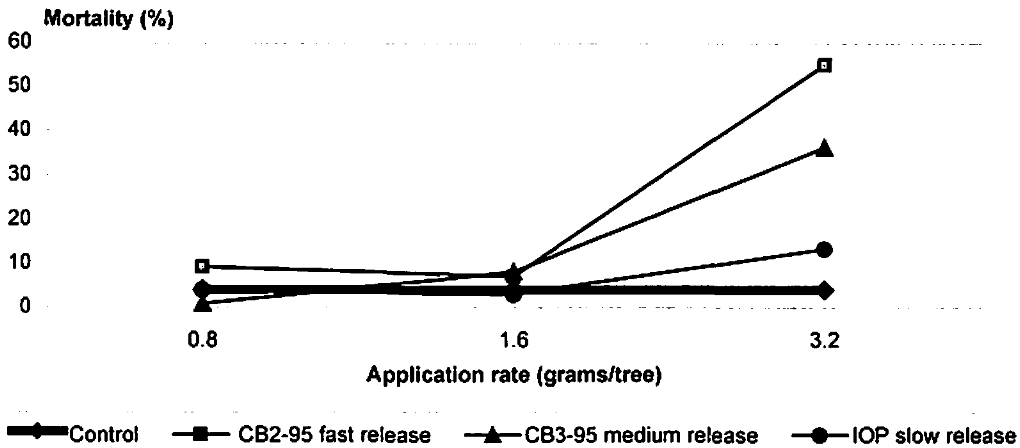

Figure 3. Mortality pattern of various fertalization treatments in the 1997 ponderosa pine plantation at the end of the first growing season

Table 1. The average percentage of dead and burned trees for various fertilization treatments in 97' ponderosa pine plantation during the first growing season

Treatment		May		June		July		August		October	
Code	Rate(g/tree)	Dead	Burned	Dead	Burned	Dead	Burned	Dead	Burned	Dead	Burned
FR	0.8	1.04	2.08	5.21	0	6.25	1.04	7.29	1.04	9.38	0
FR	1.6	2.08	3.13	6.25	0	7.29	0	7.29	0	7.29	0
FR	3.2	15.63	68.75	39.58	38.54	51.04	3.13	54.17	2.08	55.21	0
MR	0.8	0	0	0	1.04	0	1.04	0	1.04	1.04	0
MR	1.6	3.13	5.21	8.33	0	8.33	0	8.33	0	8.33	0
MR	3.2	6.25	59.38	31.25	20.83	35.42	3.13	36.46	0	36.46	0
SR	0.8	0	1.04	3.13	1.04	4.17	0	4.17	0	4.17	0
SR	1.6	1.04	0	1.04	1.04	1.04	0	2.08	0	3.13	0
SR	3.2	2.08	12.50	7.29	4.17	12.50	1.04	13.54	0	13.54	0
CONTROL	0	1.04	0	1.04	0	2.08	0	2.08	0	2.08	0
Total		3.23	32.44	10.31	6.67	12.81	0.94	13.54	0.42	14.06	0

Table 2. Multiple test results of mortality for various treatments for the 1997 ponderosa pine plantation at the end of the first growing season .

Contrast significance	Contrast	Raw-P	Bon-P
	FR 0.8 vs. Control	0.3877	1.0000
Contrast between nine	FR 1.6 vs. Control	0.6034	1.0000
Fertilization treatments	FR 3.2 vs. Control	**0.0001**	**0.0001**
And control	MR 0.8 vs. Control	0.4889	1.0000
	MR 1.6 vs. Control	**0.0001**	1.0000
	MR 3.2 vs. Control	1.0000	**0.0001**
	SR 0.8 vs. Control	0.8623	1.0000
	SR 1.6 vs. Control	0.1230	1.0000
	SR 3.2 vs. Control	0.7289	1.0000
Contrast between three	0.8 vs. 1.6	0.7289	1.0000
Application rates of	0.8 vs. 3.2	**0.0001**	**0.0001**
FR	1.6 vs. 3.2	**0.0001**	**0.0001**
Contrast between three	0.8 vs. 1.6	0.2282	1.0000
Application rates of	0.8 vs. 3.2	**0.0001**	**0.0015**
MR	1.6 vs. 3.2	**0.0001**	**0.0001**
Contrast between three	0.8 vs. 1.6	0.8623	1.0000
Application rates of	0.8 vs. 3.2	0.0875	1.0000
SR	1.6 vs. 3.2	0.1230	1.0000
Contrast between three	FR vs. MR	0.1694	1.0000
Kinds of fertilizers of the	FR vs. SR	0.3877	1.0000
same application rate---	MR vs. SR	0.6043	1.0000
0.8g/tree			
Contrast between three	FR vs. MR	0.8623	1.0000
Kinds of fertilizers of the	FR vs. SR	0.4889	1.0000
same application rate---	MR vs. SR	0.3877	1.0000
1.6g/tree			
Contrast between three	FR vs. MR	**0.0029**	0.1986
Kinds of fertilizers of the	FR vs. SR	**0.0001**	**0.0001**
same application rate---	MR vs. SR	**0.0004**	**0.0255**
3.2g/tree			

(3) The relationship between mortality and root growth potential (RGP)

Root growth potential of the seedlings as conducted at the UI Forest Research Nursery relates to the field mortality pattern very well. The Pearson correlation coefficient between mortality and RGP is –0.8540 (p=0.0017). Analysis of variance shows a significant difference in RGP between fertilization treatments. The difference was caused by the extremely low RGP of high application rates of the fast and medium release products (Table 3) which results in higher mortality rates in the field. A slight discrepancy exists between RGP and mortality rankings of high application rates of the fast and medium release products. The fast release product causes relatively higher mortality than the medium release product, but its RGP value is slightly lower than that of the medium release product. This discrepancy may be caused by differences in environmental conditions. It should be noted that even under such super experimental conditions(without limitation of moisture, temperature, etc) there are still some trees without new roots initiated from the root plug at the end of the experiment. A large proportion of dead trees in the field before the middle of July were found to have no new roots initiated from the root plug even one and half months after the planting date. The 1/RGP plot (Figure 4) is visually very similar to field mortality plot (Figure 3). For this experiment, RGP can be used as an index to predict field mortality.

Table 3. The average class value of root growth potential for various fertilization treatments for the 1997 ponderosa pine plantation.

Fertilizer sources	Application rates(grams/tree)			Class:
	0.8	1.6	3.2	
Control	3.6	3.6	3.6	0—No new roots growth
FR	3.7	3.9	2.7*	1—Some new roots but none over 2cm long
MR	4.3	3.9	2.3*	2—1-3 new roots over 1 cm
SR	4.5	4.1	3.4	3—4-10 new root over 1 cm
				4—11-30 new root over 1 cm
				5—30+ new root over 1 cm long

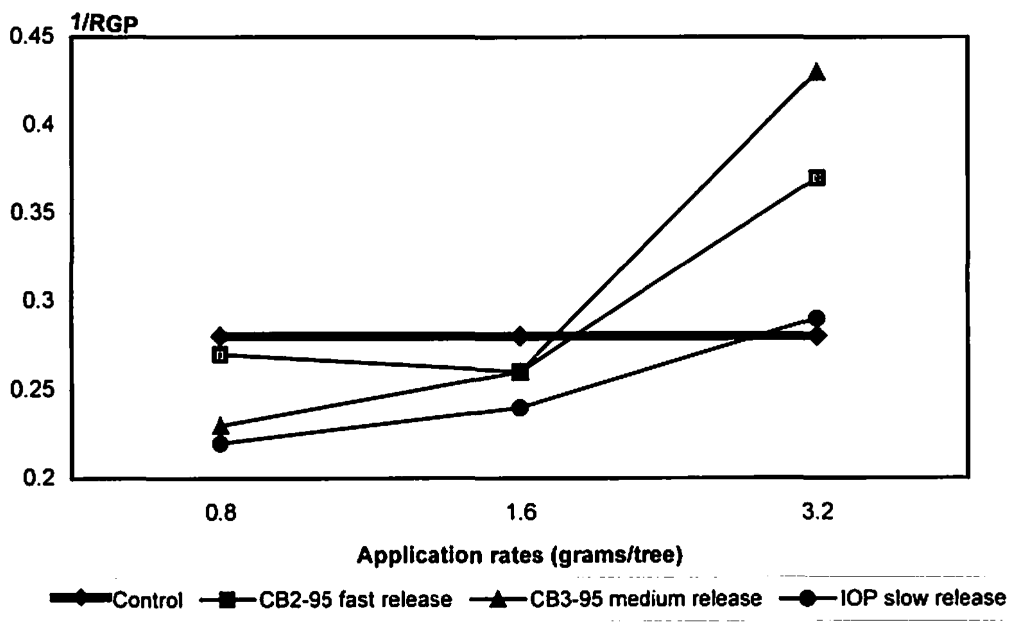

Figure 4. The 1/RGP values for various treatments for the 1997 ponderosa pine plantation.

2. Caliper and height

MANOVA shows that fertilization has significant influences on both relative caliper increment and relative height increment (Pr>F=0.0001). More variation in relative caliper increment is accounted for by blocks (pr>F=0.0001) than by treatments (pr>F=0.0106). For relative height increment, however, differences caused by fertilization (pr>F=0.0001) are larger then block effects (pr>F=0.0714). This indicates that height growth was affected more strongly by fertilization then caliper growth.

For caliper growth, the1.6 grams per tree rate achieved the highest growth rate for both the fast and medium release products. However, the highest growth rate was achieved at 3.2 grams per tree for the slow release product (Figure 5). Based on raw p values, 0.8 and 1.6 grams per tree of the fast release product and 1.6 and 3.2 grams per tree of the slow release product produced a higher caliper growth than the control at p=0.05 level (Table 4). Except for the treatments of the 1.6 and 3.2 grams per tree of the fast release product, no significant difference was detected between fertilization treatments. Among all treatments, 1.6 grams per tree of the fast release product produced the best results, while 3.2 grams per tree produced the poorest. The bonferoni p values for all contrasts are greater than 0.05.

For height growth, the 1.6 grams per tree rate achieved the highest growth rate for both the medium and slow release products. However, the highest growth rate was achieved at 0.8 grams per tree for the fast release product (Figure 6). Based on raw p values, 0.8 and 1.6 grams per tree for the fast and slow release products and all three levels of the medium release product produced greater height growth than the controls. For a particular fertilizer source, both 0.8 and 1.6 grams per tree of the fast release product have greater height growth than 3.2 grams per tree. The medium release product applied at a rate of 0.8 grams per tree of produced greater height growth than 1.6 and 3.2 grams per tree. There were no differences detected for the other fertilization treatments. It should be noted here that 0.8 grams per tree of the fast release product (Bon-p=0.0195), 1.6 grams per tree of the medium release product (Bon-p=0.0004) and the slow release product (Bon-p=0.0322) produced significantly greater height growth than the control based on the bonferroni p values.

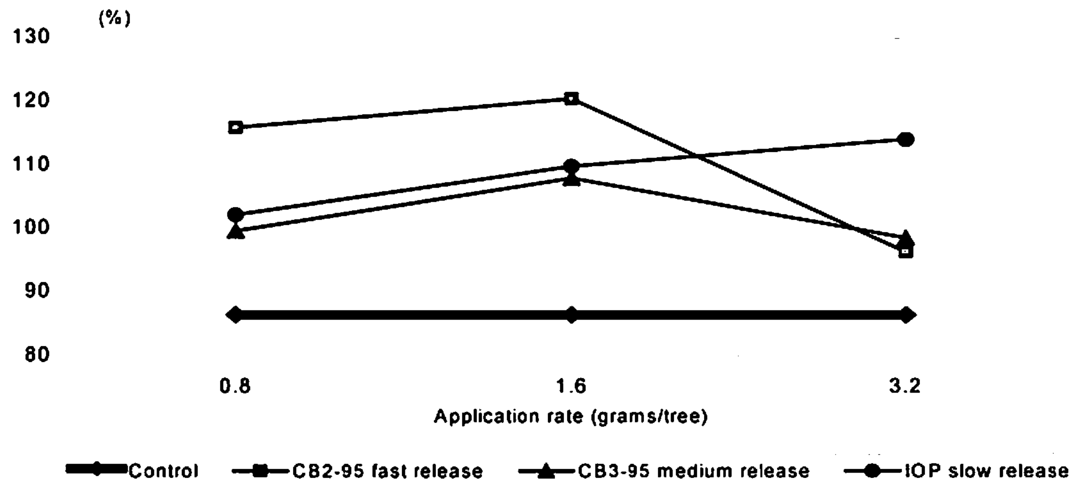

Figure 5. Relative caliper increment of various fertilization treatments in the 1997 ponderosa pine plantation at the end of the first growing season

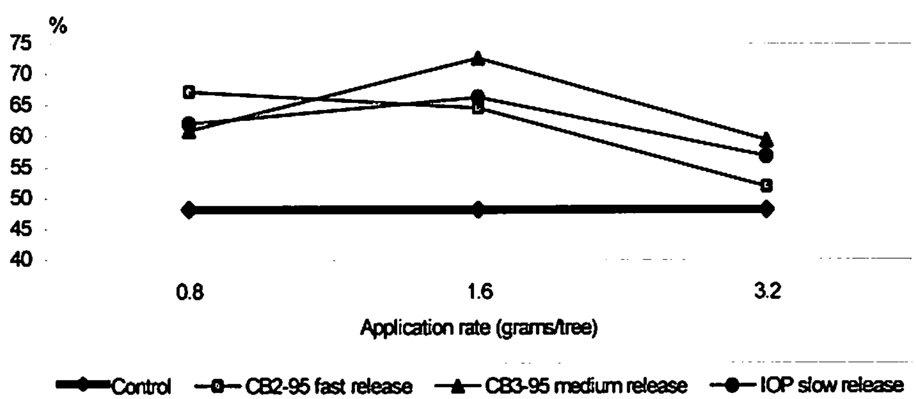

Figure 6. Relative height increment of various fertilization treatments in the 1997 ponderosa pine plantation at the end of the first growing season.

Table 4. Multiple test results of relative increment of caliper and height for various fertilization treatments in the 1997ponderosa pine plantation at the end of the first growing season.

Contrast significance	Contrast	Relative caliper increment		Relative height increment	
		Raw-P	Bon-P	Raw-P	Bon-p
	FR 0.8 vs. Control	**0.0119**	0.7414	**0.0003**	**0.0195**
Contrast between nine	FR 1.6 vs. Control	**0.0040**	0.2709	**0.0013**	0.0932
Fertilization treatments	FR 3.2 vs. Control	0.3829	1.0000	0.4361	1.0000
And control	MR 0.8 vs. Control	0.2472	1.0000	**0.0112**	0.7192
	MR 1.6 vs. Control	0.0624	1.0000	**0.0001**	**0.0004**
	MR 3.2 vs. Control	0.2885	1.0000	**0.0236**	1.0000
	SR 0.8 vs. Control	0.1699	1.0000	**0.0061**	0.4058
	SR 1.6 vs. Control	**0.0433**	1.0000	**0.0005**	**0.0322**
	SR 3.2 vs. Control	**0.0180**	1.0000	0.0782	1.0000
Contrast between three	0.8 vs. 1.6	0.6884	1.0000	0.6032	1.0000
Application rates of	0.8 vs. 3.2	0.0898	1.0000	**0.0029**	0.1968
FR	1.6 vs. 3.2	**0.0378**	1.0000	**0.0118**	0.7414
Contrast between three	0.8 vs. 1.6	0.4657	1.0000	**0.0184**	1.0000
Application rates of	0.8 vs. 3.2	0.4087	1.0000	**0.0086**	0.5603
MR	1.6 vs. 3.2	0.9222	1.0000	0.7670	1.0000
Contrast between three	0.8 vs. 1.6	0.4990	1.0000	0.3757	1.0000
Application rates of	0.8 vs. 3.2	0.7115	1.0000	0.0560	1.0000
SR	1.6 vs. 3.2	0.2974	1.0000	0.2928	1.0000
Contrast between three	FR vs. MR	0.1562	1.0000	0.2029	1.0000
Kinds of fertilizers of the	FR vs. SR	0.2290	1.0000	0.2933	1.0000
same application rate---	MR vs. SR	0.8255	1.0000	0.8204	1.0000
0.8g/tree					
Contrast between three	FR vs. MR	0.2732	1.0000	0.1013	1.0000
Kinds of fertilizers of the	FR vs. SR	0.3561	1.0000	0.7242	1.0000
same application rate---	MR vs. SR	0.8676	1.0000	0.1947	1.0000
1.6g/tree					
Contrast between three	FR vs. MR	0.8482	1.0000	0.1275	1.0000
Kinds of fertilizers of the	FR vs. SR	0.1238	1.0000	0.3161	1.0000
same application rate---	MR vs. SR	0.1759	1.0000	0.5937	1.0000
3.2g/tree					

3. Comparison between the control and 3.2 grams per tree of the slow release product for trees grown in the "45/435 (# of cells in a tray/volume (ml.) of a cell)" tray in the greenhouse.

For ponderosa pine trees grown in large containers, the high application rate of the slow release product increased caliper growth (pr>F=0.0182) at 0.05 significance level, but had no significant effect on height growth (pr>F=0.2783). Fertilization had no effect on mortality for these larger seedlings. No burned needles were observed for fertilized trees. At the end of the growing season, only one of the fertilized trees died for reasons that are unclear. Table 5 provides summary statistics for caliper and height growth.

Table 5. Average size of larger seedlings fertilized with 3.2grams of slow release product and those without fertilization.

	3.2 grams of slow release product				without fertilization			
	At planting	At late October	Increment	Relative growth rate(%)	At planting	At late October	Increment	Relative growth rate(%)
Caliper (mm)	6.65±1.34	11.53±1.87	4.89±1.15	80.33±18.53	5.68± 1.10	9.22±1.58	3.54±0.86	70.58±15.32
Height(cm)	18.33±4.95	37.83±6.30	19.50±5.60	106.96±29.16	16.44±3.27	32.78±7.01	16.33±6.46	98.82±33.46

4. Foliage nutrient concentrations

MNOVA shows that nutrient concentrations among fertilization treatments differs significantly at 0.05 significance level. ANOVA further demonstrates that differences mainly exist between Al, Mg, K, Mo, N, Mn and Fe. The p-values of ANOVA for each nutrient are given in Table 6.

Table 6. The p values for ANOVA of foliage nutrient concentration.

	Pr > F		
Nutrient	Total SS	Treatment SS	Block SS
Al	0.0001	**0.0281**	**0.0001**
Mg	0.0001	0.0779	**0.0001**
K	0.0001	0.4468	**0.0001**
Mo	0.0010	**0.0002**	0.3678
N	0.0191	**0.0066**	0.4741
Mn	0.0236	0.3679	**0.0036**
Fe	0.0389	0.5929	**0.0035**
Cu	0.0796	0.2097	0.0573
P	0.2000	0.6139	**0.0495**
B	0.2186	0.2433	0.2572
Ca	0.4489	0.8159	0.1238
Na	0.5162	0.6905	0.2538
Zn	0.7780	0.7886	0.5353

It is obvious from Table 6 that fertilization significantly influences the concentration of Al, Mo and N at the 0.05 significance level. But for Al, block effects are more significant. Differences in Mg, K, Mn and Fe were mainly caused by variation between blocks, not by fertilization. Because the p value for the effect of fertilization on Mg is very close to 0.05, fertilization also had some effect on its concentration. Also, there is some variation in Cu and P concentration between blocks. Table 7 more clearly demonstrates variation in needle nutrient concentration. Treatments significantly differing from the control at p=0.05 level in nutrient concentration are highlighted and underlined. Based on tables 6 and 7, it can be concluded that fertilization affected N and Mo in needles.

Table 7. Foliage nutrient concentrations for various fertilization treatments in the 1997 ponderosa pine plantation.

Treatment	N %	P %	K %	B	Cu	Zn	Fe
Control	1.988 ± 0.169	0.183 ± 0.012	0.718 ± 0.119	21.839 ± 2.876	2.862 ± 0.251	65.417 ± 16.568	28.633 ± 3.118
SR-0.8	1.987 ± 0.187	0.177 ± 0.004	0.709 ± 0.134	23.233 ± 2.707	2.796 ± 0.245	62.667 ± 15.186	27.033 ± 1.880
SR-1.6	<u>**1.768**</u> ± 0.290	0.174 ± 0.014	0.714 ± 0.174	23.450 ± 2.130	2.793 ± 0.235	60.250 ± 15.603	27.550 ± 1.712
SR-3.2	<u>**1.820**</u> ± 0.149	0.181 ± 0.008	0.735 ± 0.114	22.283 ± 2.299	2.920 ± 0.308	50.650 ± 17.865	26.900 ± 3.240
FR 0.8	<u>**1.780**</u> ± 0.123	0.183 ± 0.007	0.727 ± 0.124	23.750 ± 2.913	2.652 ± 0.202	56.283 ± 19.219	27.517 ± 1.487
FR 1.6	1.977 ± 0.237	0.183 ± 0.006	0.724 ± 0.128	23.083 ± 1.604	2.807 ± 0.350	52.500 ± 12.525	27.550 ± 1.701
FR 3.2	<u>**1.758**</u> ± 0.126	0.182 ± 0.016	0.760 ± 0.141	21.283 ± 3.712	2.720 ± 0.306	53.583 ± 16.054	26.983 ± 4.131
MR 0.8	<u>**1.797**</u> ± 0.201	0.177 ± 0.005	0.722 ± 0.115	22.383 ± 3.156	2.690 ± 0.461	71.133 ± 47.520	26.067 ± 2.648
MR 1.6	<u>**1.670**</u> ± 0.242	0.184 ± 0.011	0.749 ± 0.123	20.783 ± 2.629	<u>**2.533**</u> ± 0.202	52.516 ± 11.353	28.267 ± 1.242
MR 3.2	<u>**1.690**</u> ± 0.175	0.175 ± 0.014	0.766 ± 0.117	19.950 ± 2.866	<u>**2.600**</u> ± 0.238	54.467 ± 13.940	25.983 ± 2.113
SR 3.2*	1.735 ± 0.096	0.169 ± 0.007	0.700 ± 0.131	22.683 ± 1.776	2.438 ± 0.169	50.900 ± 11.782	26.017 ± 2.485
Control*	1.760 ± 0.197	0.167 ± 0.007	0.749 ± 0.151	20.200 ± 4.950	2.670 ± 0.325	43.200 ± 0.707	26.550 ± 0.495

(continue from table 7)

Treatment	Ca %	Mg %	Mn	Mo	Na	Al
Control	0.208 ± 0.025	0.095 ± 0.009	103.006 ± 26.577	0.469 ± 0.123	36.178 ± 17.451	51.811 ± 16.562
SR-0.8	0.226 ± 0.028	0.104 ± 0.012	112.250 ± 17.231	0.475 ± 0.106	39.617 ± 16.876	71.417 ± 34.731
SR-1.6	0.225 ± 0.025	0.094 ± 0.008	103.567 ± 22.402	0.434 ± 0.168	26.250 ± 5.592	62.450 ± 39.652
SR-3.2	0.216 ± 0.017	0.101 ± 0.008	112.683 ± 20.850	0.396 ± 0.066	29.267 ± 4.982	60.367 ± 25.521
FR 0.8	0.223 ± 0.030	0.101 ± 0.006	110.600 ± 21.047	<u>**0.330**</u> ± 0.056	34.400 ± 16.121	63.700 ± 26.619
FR 1.6	0.228 ± 0.019	0.105 ± 0.008	113.917 ± 27.977	<u>**0.311**</u> ± 0.081	28.917 ± 8.018	68.600 ± 35.593
FR 3.2	0.215 ± 0.044	0.096 ± 0.018	108.117 ± 25.558	<u>**0.246**</u> ± 0.056	27.117 ± 5.921	<u>**83.033**</u> ± 42.078
MR 0.8	0.230 ± 0.028	0.106 ± 0.008	<u>**129.350**</u> ± 36.800	0.349 ± 0.097	34.317 ± 14.999	57.083 ± 21.453
MR 1.6	0.224 ± 0.017	0.108 ± 0.013	113.117 ± 18.885	<u>**0.281**</u> ± 0.030	34.233 ± 11.875	<u>**87.267**</u> ± 19.293
MR 3.2	0.220 ± 0.021	0.096 ± 0.018	100.550 ± 18.143	<u>**0.223**</u> ± 0.075	43.933 ± 26.726	58.550 ± 25.115
SR 3.2*	0.216 ± 0.017	0.101 ± 0.008	112.683 ± 20.850	0.396 ± 0.065	29.267 ± 4.982	60.367 ± 25.521
Control*	0.182 ± 0.007	0.109 ± 0.008	104.800 ± 27.153	0.748 ± 0.034	26.100 ± 1.414	54.800 ± 22.486

5. The relationship between growth and foliage nutrient concentration

Tree growth depends on various factors including nutrients. It is difficult, sometimes impossible to study the effect of nutrients on growth without considering other factors. However, it is interesting to discuss the general trend of nutrient effects on growth based on the available data. First, simple correlations between nutrient concentrations and growth were analyzed (table 8). Because of the correlation and interaction between nutrients, it is impossible to identify the effects of a particular nutrient on growth from this experiment, but we still can see the composite effects of a group of nutrients. Table 8 shows that caliper growth is positively related to Ca and B, and negatively related to K and Fe. Height growth is positively related to Al, Mg, P and Mn, and negatively related to Cu. Mortality is negatively related to B, Mg, Mn, Mo and N. In order to detect the relationships between growth and nutrient concentrations, Canonical correlation analysis was employed. The results are summarized in table 9.

Table 8. Pearson correlation coefficients between needle nutrient concentration and ponderosa pine seedling growth

Nutrient	Caliper growth (%)	Height growth (%)	Mortality (%)
Al	-0.18287 (0.1620)	0.33223 (**0.0095**)	-0.00574 (0.9653)
B	0.24133 (**0.0632**)	0.00472 (0.9715)	-0.25860 (**0.0460**)
Ca	0.31280 (**0.0150**)	0.10634 (0.4187)	-0.13844 (0.2915)
Cu	0.15245 (0.2449)	-0.26514 (**0.0406**)	-0.01262 (0.9238)
Fe	-0.38500 (**0.0024**)	0.17001 (0.1941)	-0.21008 (0.1072)
K	-0.39293 (**0.0019**)	-0.08673 (0.5099)	0.01370 (0.9173)
Mg	-0.06233 (0.6361)	0.42152 (**0.0008**)	-0.37768 (**0.0029**)
Mn	-0.14481 (0.2696)	0.23136 (**0.0753**)	-0.29209 (**0.0235**)
Mo	-0.04194 (0.7504)	0.03714 (0.7782)	-0.40857 (**0.0012**)
N	0.21964 (0.0918)	-0.12969 (0.3233)	-0.24969 (**0.0544**)
Na	0.07649 (0.5613)	0.01705 (0.8971)	-0.05317 (0.6866)
P	0.06838 (0.6037)	0.27500 (**0.0335**)	-0.03551 (0.7877)
Zn	-0.00377 (0.9772)	-0.15319 (0.2426)	-0.07847 (0.5512)

In table 9, parts (1), (2), (3) and (4) show that the correlations between the three pairs of canonical variables (growth (v's) vs. nutrient (w's)) are significant (Pr>F< 0.05). The squared canonical correlation coefficients for the first, second and third pair of canonical variables are 0.614458, 0.427334 and 0.328836, respectively. The first pair (V1 and W1) contributes 56.32% of variation in the data set. The second pair (V2 and W2) contributes 26.37% of variation in the data set. And the third pair (V3 and W3) interprets 17.31% of information in the data set. Parts (5) and (6) demonstrate the structure of the three pairs of canonical variables and their correlations with their composites. Canonical variables (growth) V1, V2 and V3 were dominated by mortality, relative height growth and relative caliper growth, respectively. W1, W2 and W3 (nutrient) are dominated by Fe, Mg, Mn, and Mo, and Al, Mg, P and N, and B, Ca, Fe, K and N, respectively. Part (7) shows the correlations between growth variables and canonical variables of nutrients, and nutrient variables and canonical variables of growth. From part (7), it is clear that mortality is mainly negatively related to Fe, Mg, Mn and Mo. Relative height growth is positively related to Al, Cu, Mg and P, and relative caliper growth is positively related to B, Ca and N, and negatively related to Fe and K. The results are nearly the same as those of simple correlation analysis.

Table 9. SAS printout for cannonical correlation analysis on ponderosa pine growth and foliage nutrient concentration

(1)

	Canonical Correlation	Adjusted Canonical Correlation	Approx Standard Error	Squared Canonical Correlation
1	0.783874	0.717041	0.050193	0.614458
2	0.653708	0.552480	0.074555	0.427334
3	0.573442	0.524248	0.087378	0.328836

(2) **Eigenvalues of INV(E)*H = CanRsq/(1-CanRsq)**

	Eigenvalue	Difference	Proportion	Cumulative
1	1.5938	0.8475	0.5632	0.5632
2	0.7462	0.2563	0.2637	0.8269
3	0.4899	.	0.1731	1.0000

(3) **Test of H0: The canonical correlations in the current row and all that follow are zero**

	Likelihood Ratio	Approx F	Num DF	Den DF	Pr > F
1	0.14818379	3.0427	39	131.0413	0.0001
2	0.38435232	2.2988	24	90	0.0025
3	0.67116373	2.0489	11	46	0.0448

4) **Multivariate Statistics and F Approximations**
S=3 M=4.5 N=21

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.14818379	3.0427	39	131.0413	0.0001
Pillai's Trace	1.37062920	2.9766	39	138	0.0001
Hotelling-Lawley Trace	2.82992352	3.0960	39	128	0.0001
Roy's Greatest Root	1.59375404	5.6394	13	46	0.0001

NOTE: F Statistic for Roy's Greatest Root is an upper bound.

(5) **Standardized Canonical Coefficients for the 'VAR' Variables**

	V1	V2	V3
RCAL	-0.5697	0.0669	0.8516
RHEI	0.2936	1.0350	-0.0870
RMORT	-0.8040	0.5533	-0.4441

Standardized Canonical Coefficients for the 'WITH' Variables

W1 W2 W3

AL	-0.7436	0.3962	0.0299
B	0.0404	0.1324	0.4384
CA	-0.2403	0.0091	0.1197
CU	-0.8390	-0.1874	-0.1806
FE	0.5955	0.1382	-0.5609
K	-0.0621	-0.7493	-0.3442
MG	0.8137	0.3200	0.1873
MN	0.1128	-0.2159	0.0321
MO	0.3369	-0.2893	0.3403
N	0.2413	-0.5681	0.2802
NA	0.0468	0.2680	0.1759
P	-0.1070	0.3589	0.2200
ZN	0.1287	-0.2439	-0.0238

(6) Correlations Between the 'VAR' Variables and Their Canonical Variables

	V1	V2	V3
RCAL	-0.3758	0.1830	0.9084
RHEI	0.4575	0.8565	0.2388
RMORT	-0.8104	0.1831	-0.5566

Correlations Between the 'WITH' Variables and Their Canonical Variables

	W1	W2	W3
AL	0.2632	0.5024	-0.3175
B	0.0916	-0.1867	0.5579
CA	-0.0455	0.0832	0.5556
CU	-0.1972	-0.4149	0.2764
FE	0.5590	0.0520	-0.4349
K	0.2391	-0.1659	-0.5810
MG	0.5905	0.3413	0.1359
MN	0.4915	0.1043	-0.0240
MO	0.4635	-0.2913	0.2485
N	0.0479	-0.3942	0.5392
NA	0.0053	-0.0102	0.1522
P	0.0897	0.4123	0.0873
ZN	0.0259	-0.3093	0.0784

(7) Correlations Between the 'VAR' Variables and the Canonical Variables of the 'WITH' Variables

	W1	W2	W3
RCAL	-0.2946	0.1196	0.5209
RHEI	0.3586	0.5599	0.1370
RMORT	-0.6352	0.1197	-0.3192

Correlations Between the 'WITH' Variables and the Canonical Variables of the 'VAR' Variables

	V1	V2	V3
AL	0.2063	0.3284	-0.1821
B	0.0718	-0.1221	0.3199
CA	-0.0357	0.0544	0.3186
CU	-0.1546	-0.2712	0.1585
FE	0.4382	0.0340	-0.2494
K	0.1874	-0.1085	-0.3332
MG	0.4629	0.2231	0.0780
MN	0.3853	0.0682	-0.0137
MO	0.3633	-0.1904	0.1425
N	0.0375	-0.2577	0.3092
NA	0.0042	-0.0067	0.0873
P	0.0703	0.2695	0.0501
ZN	0.0203	-0.2022	0.0450

II. 1996 plantation

1. Foliage nutrient concentrations

Foliage nutrient concentrations are very useful in evaluating tree nutrition status and effects of fertilization on tree growth. The results of MANOVA indicate that there exist larger variations in foliage nutrient concentrations within the 1996 plantation during the last two years(Pr>F=0.0001). But the results of ANOVA show that at the end of the first growing season, differences in the concentrations of K, Mn, B and Ca were caused by fertilization. Variation in the concentrations of Al, Fe, Cu, P and Zn resulted from blocks. The concentration of Mg was influenced by both fertilization treatments and blocks. There is no difference in Mo, N and Na at the 0.05 significance level (Table 10). For the second growing season, however, only B, Al and K show differences between blocks. No differences in foliage nutrient concentrations were found between fertilization treatments.

Table 10. The p values for ANOVA of foliage nutrient concentrations for the 1996 ponderosa pine plantation.

Nutrient	Pr > F					
	1996			1997		
	Total SS	Treatment SS	Block SS	Total SS	Treatment SS	Block SS
Al	**0.0450**	0.3520	**0.0073**	**0.0202**	0.0765	**0.0158**
Mg	**0.0001**	**0.0003**	**0.0001**	0.3502	0.5799	0.1344
K	**0.0100**	**0.0025**	0.7238	**0.0001**	0.1658	**0.0001**
Mo	0.1117	0.3741	0.0335	0.2489	0.1979	0.4422
N	0.2306	0.3442	0.1602	0.5865	0.4845	0.6439
Mn	**0.0002**	**0.0001**	0.0822	0.6709	0.9372	0.1596
Fe	**0.0260**	0.1670	**0.0099**	0.7912	0.8637	0.4238
Cu	**0.0019**	0.2341	**0.0001**	0.8023	0.6432	0.8668
P	**0.0244**	0.1005	**0.0195**	0.1948	0.6264	**0.0319**
B	**0.0001**	**0.0001**	0.1514	**0.0521**	0.1107	**0.0534**
Ca	**0.0108**	**0.0049**	0.3742	0.3803	0.7115	0.0984
Na	0.2098	0.9070	0.0109	0.8487	0.9257	0.4197
Zn	**0.0078**	0.0535	**0.0070**	0.6127	0.6162	0.4645

In order to demonstrate the effects of fertilization and evaluate the characteristics of nutrient patterns within the 1996 plantation, the means and standard deviations of nutrient concentrations for each fertilization treatment are provided in Table 11. Nutrient concentrations significantly different from the controls due to fertilization are highlighted and underlined. Differences in boron concentration were caused by the "14-7-10 minor external" product. Foliage boron concentrations for all three application rates (5, 15 and 30 grams per tree, respectively) ranged from 157 to 284 ppm , 7 to 14 times of those for the control and the other three products. Such high concentrations resulted in serious "needle burn".

For calcium, trees fertilized with 15 and 30 grams of the fast release product 15-10-12, the 15 grams of the medium release product 16-8-12 and 30 grams of the slow release product 15-8-11 and minors external product 14-7-10 produced significantly higher foliage concentrations than unfertilized trees. Foliage potassium concentrations in trees fertilized with 15 and 30 grams of the fast and medium release products and 5, 15 and 30 grams of the slow release product were significant lower than those of the controls. All three application rates of the fast release product and the low application rate of the minors external product produced lower foliage magnesium concentrations than the controls. All three application rates of the minors external product resulted in low Mn concentrations compared with the controls.

Table 11. Characteristics of foliage nutrient concentrations for various fertilization treatments for the 1996 ponderosa pine plantation.

Treatment		N %	P %	K %	B	Cu	Zn	Fe
Control	1997	1.540 ± 0.140	0.157 ± 0.011	0.677 ± 0.128	25.350 ± 5.280	2.522 ± 0.501	52.550 ± 11.749	25.250 ± 3.154
	1996	1.915 ± 0.071	0.191 ± 0.011	0.656 ± 0.036	17.567 ± 2.862	3.125 ± 0.347	73.067 ± 22.825	26.283 ± 3.131
FR-5	1997	1.428 ± 0.049	0.151 ± 0.011	0.631 ± 0.021	27.375 ± 10.36	2.238 ± 0.116	84.000 ± 62.021	24.475 ± 2.640
	1996	1.918 ± 0.070	0.186 ± 0.005	0.629 ± 0.040	20.717 ± 3.197	3.153 ± 0.358	77.050 ± 33.077	26.267 ± 0.882
FR-15	1997	1.543 ± 0.057	0.170 ± 0.024	0.642 ± 0.056	21.967 ± 5.281	2.197 ± 0.059	69.367 ± 58.002	23.567 ± 3.213
	1996	1.893 ± 0.127	0.179 ± 0.007	0.606 ± 0.036	18.625 ± 2.203	2.995 ± 0.270	70.025 ± 36.459	22.650 ± 2.726
FR-30	1997	1.468 ± 0.070	0.159 ± 0.020	0.619 ± 0.047	33.575 ± 9.756	2.240 ± 0.377	45.025 ± 13.499	23.325 ± 1.382
	1996	2.035 ± 0.134	0.184 ± 0.007	0.620 ± 0.030	22.350 ± 4.546	3.112 ± 0.629	49.300 ± 10.691	24.383 ± 1.497
MR-5	1997	1.450 ± 0.075	0.154 ± 0.011	0.672 ± 0.127	26.475 ± 7.593	2.430 ± 0.120	49.575 ± 11.872	26.300 ± 3.189
	1996	2.006 ± 0.084	0.191 ± 0.006	0.605 ± 0.031	21.840 ± 2.665	3.252 ± 0.515	103.56 ± 50.718	25.660 ± 1.399
MR-15	1997	1.567 ± 0.221	0.165 ± 0.020	0.594 ± 0.000	22.833 ± 5.802	2.457 ± 0.153	110.30 ± 109.75	26.700 ± 2.722
	1996	1.988 ± 0.040	0.190 ± 0.004	0.609 ± 0.032	19.050 ± 2.319	3.070 ± 0.351	96.350 ± 59.493	24.000 ± 2.186
MR-30	1997	1.523 ± 0.096	0.168 ± 0.009	0.714 ± 0.192	18.667 ± 2.776	2.233 ± 0.200	37.733 ± 5.094	23.767 ± 3.408
	1996	1.988 ± 0.095	0.178 ± 0.004	0.592 ± 0.044	18.975 ± 4.186	2.665 ± 0.352	53.775 ± 35.568	21.550 ± 1.777
SR-5	1997	1.420 ± 0.101	0.161 ± 0.010	0.637 ± 0.048	25.820 ± 7.044	2.494 ± 0.274	59.300 ± 23.954	24.520 ± 1.648
	1996	1.985 ± 0.088	0.190 ± 0.018	0.642 ± 0.056	22.233 ± 2.613	3.293 ± 0.406	58.267 ± 12.353	25.033 ± 4.012
SR-15	1997	1.458 ± 0.108	0.154 ± 0.006	0.648 ± 0.099	24.617 ± 9.574	2.250 ± 0.202	67.000 ± 28.590	25.150 ± 2.856
	1996	1.985 ± 0.100	0.180 ± 0.009	0.600 ± 0.037	19.117 ± 2.994	3.405 ± 0.752	49.683 ± 10.403	24.617 ± 2.687
SR-30	1997	1.588 ± 0.198	0.160 ± 0.016	0.611 ± 0.028	23.160 ± 4.527	2.310 ± 0.238	56.760 ± 28.567	26.160 ± 2.603
	1996	1.986 ± 0.091	0.179 ± 0.009	0.585 ± 0.029	21.220 ± 4.364	3.122 ± 0.259	85.060 ± 35.453	24.980 ± 2.573
ME-5	1997	1.470 ± 0.067	0.155 ± 0.009	0.663 ± 0.094	25.033 ± 2.222	2.447 ± 0.183	46.583 ± 7.842	24.740 ± 2.415
	1996	1.963 ± 0.129	0.188 ± 0.008	0.658 ± 0.026	157.00 ± 22.06	3.013 ± 0.386	71.600 ± 36.491	24.167 ± 1.654
ME-15	1997	1.425 ± 0.064	0.151 ± 0.010	0.624 ± 0.001	29.600 ± 2.121	2.235 ± 0.191	60.900 ± 22.062	23.000 ± 0.989
	1996	1.890 ± 0.116	0.181 ± 0.010	0.663 ± 0.020	225.40 ± 82.51	2.736 ± 0.705	51.440 ± 24.004	23.880 ± 4.544
ME-30	1997	1.415 ± 0.021	0.161 ± 0.017	0.683 ± 0.045	37.550 ± 7.990	2.300 ± 0.071	64.550 ± 31.608	26.950 ± 0.636
	1996	1.988 ± 0.097	0.182 ± 0.009	0.657 ± 0.009	284.00 ± 54.55	2.922 ± 0.621	63.020 ± 24.991	23.400 ± 3.326

(continue from Table 11)

Treatment		Ca %	Mg %	Mn	Mo	Na	Al
Control	1997	0.199 ± 0.013	0.119 ± 0.009	107.03 ± 16.813	0.329 ± 0.097	45.275 ± 23.712	117.85 ± 22.706
	1996	0.201 ± 0.021	0.111 ± 0.007	108.67 ± 17.010	0.584 ± 0.153	37.583 ± 6.889	81.750 ± 36.552
FR-5	1997	0.191 ± 0.017	0.113 ± 0.006	118.68 ± 17.529	0.311 ± 0.057	27.775 ± 8.827	121.90 ± 23.356
	1996	0.212 ± 0.019	0.098 ± 0.007	107.05 ± 12.936	0.430 ± 0.075	45.683 ± 17.589	68.517 ± 19.794
FR-15	1997	0.232 ± 0.035	0.120 ± 0.017	129.67 ± 9.866	0.347 ± 0.096	32.533 ± 5.358	126.00 ± 15.100
	1996	0.252 ± 0.030	0.099 ± 0.009	103.90 ± 8.674	0.415 ± 0.044	41.700 ± 14.844	70.425 ± 40.725
FR-30	1997	0.199 ± 0.041	0.114 ± 0.021	119.25 ± 14.292	0.315 ± 0.085	26.950 ± 6.623	105.10 ± 39.642
	1996	0.255 ± 0.030	0.092 ± 0.014	108.92 ± 15.674	0.381 ± 0.099	45.950 ± 13.355	67.733 ± 21.250
MR-5	1997	0.205 ± 0.045	0.119 ± 0.017	122.50 ± 8.185	0.274 ± 0.022	38.175 ± 11.008	119.75 ± 4.992
	1996	0.224 ± 0.029	0.109 ± 0.009	116.80 ± 11.692	0.514 ± 0.130	43.300 ± 2.888	77.560 ± 12.016
MR-15	1997	0.227 ± 0.045	0.124 ± 0.009	116.00 ± 9.644	0.337 ± 0.097	33.100 ± 21.171	107.33 ± 13.577
	1996	0.239 ± 0.023	0.100 ± 0.008	111.80 ± 15.863	0.490 ± 0.094	37.200 ± 3.626	65.150 ± 28.995
MR-30	1997	0.176 ± 0.056	0.111 ± 0.019	113.13 ± 47.508	0.259 ± 0.018	29.300 ± 2.200	72.333 ± 37.873
	1996	0.217 ± 0.032	0.101 ± 0.008	108.13 ± 11.346	0.424 ± 0.143	41.275 ± 13.601	70.225 ± 35.874
SR-5	1997	0.196 ± 0.018	0.126 ± 0.007	120.40 ± 6.309	0.451 ± 0.109	42.060 ± 34.331	92.680 ± 33.580
	1996	0.213 ± 0.035	0.112 ± 0.013	112.75 ± 16.952	0.556 ± 0.180	38.850 ± 5.152	64.216 ± 31.339
SR-15	1997	0.200 ± 0.039	0.121 ± 0.014	121.33 ± 8.066	0.330 ± 0.061	34.233 ± 20.300	103.58 ± 23.194
	1996	0.216 ± 0.017	0.112 ± 0.006	108.95 ± 7.120	0.457 ± 0.161	37.983 ± 11.041	73.350 ± 22.441
SR-30	1997	0.195 ± 0.032	0.115 ± 0.011	115.64 ± 14.372	0.299 ± 0.086	27.820 ± 6.471	109.54 ± 21.927
	1996	0.252 ± 0.044	0.105 ± 0.014	104.80 ± 2.864	0.424 ± 0.069	40.360 ± 9.296	67.340 ± 25.527
ME-5	1997	0.196 ± 0.029	0.112 ± 0.007	118.00 ± 14.574	0.311 ± 0.096	31.000 ± 13.562	116.63 ± 24.649
	1996	0.210 ± 0.021	0.099 ± 0.009	126.00 ± 20.040	0.483 ± 0.174	45.617 ± 12.486	81.467 ± 27.035
ME-15	1997	0.215 ± 0.036	0.118 ± 0.006	126.00 ± 7.071	0.304 ± 0.019	27.900 ± 3.111	145.50 ± 14.849
	1996	0.214 ± 0.018	0.102 ± 0.010	157.00 ± 36.490	0.490 ± 0.159	44.760 ± 21.512	101.22 ± 30.919
ME-30	1997	0.181 ± 0.016	0.103 ± 0.008	119.00 ± 19.799	0.348 ± 0.082	31.850 ± 11.243	96.950 ± 25.527
	1996	0.254 ± 0.024	0.101 ± 0.008	130.40 ± 11.082	0.536 ± 0.246	40.300 ± 3.055	51.940 ± 19.160

A general trend in the foliage nutrient concentration between the first and second growing season is that for all treatment levels, the concentrations of N, P, Cu, Ca and Mo decreased after the second growing season, while the concentrations of Mg and Al increased. The concentrations of B and Mn decreased in trees fertilized with the minors external product, but tended to increase for all other treatments. There is no clear trend in the concentrations of Zn, Fe, K and Na. ANOVA on the differences in nutrient concentrations between the first and second growing season shows that there existed significant differences in P, K, B and Mg, among them, the variation in B was caused by treatments(pr>F=0.0001 vs. Pr>F=0.7082 for blocks). The variation in K and P resulted from both treatments and blocks, with larger partial influences from blocks(Pr>F = 0.0028 and 0.063 for treatments vs. Pr>F = 0.0001 and 0.0008, respectively). The variation in Mg was mostly caused by blocks (Pr>F=0.0003 vs. Pr>F=0.2382 for treatments).

2. Caliper growth

At the end of the first growing season, fertilization effects on tree caliper growth were detected. All fertilization treatments produced greater caliper growth than the controls (Figure 7 and Table 11). The mean caliper for the controls is 6.18 mm (The thick line for the controls was located below all fine lines for fertilization treatments in Figure 7). For ease of comparison, ranks for the mean caliper and its relative growth rates (actually they are the same for the first growing season because all treatments have the same starting mean caliper, namely, 3.4 mm at planting). The greatest relative growth rate, for example, 113.10% for the medium application rate (15 grams per tree) of the fast release product was given the largest ranking—4 and the least growth rate---85.68% for the controls was given a ranking--1. Although all fertilization treatments achieved larger mean caliper than the controls, the 5 grams per tree rate of the slow release product and the 15 and 30 grams per tree rates of the minors external product were not significantly different from the controls at 0.05 significance level. Based on the total rankings of three application rates for each product, the fast release product behaved best with a total ranking of 10, and second is the medium release and slow release products both with a ranking of 9. The minors external product behaved poorest both with a ranking of 7. The result is reasonable because the fast release product provided more nutrients than the medium release and slow release products. Although the medium release and the slow release products have the same ranking value, more variation existed between three application rates for the slow release. As to the relatively lower growth rate for the minors external product, the major reason is the boron toxicity, which are reflected by the burned needles and unusually high foliage boron concentration at the end of the first growing season.

For the second growing season, the ranking in relative growth rates among the four products changed. The minors external product behaved best with a ranking of 10, and second was the medium release product with a ranking of 8, and then the third is slow release product. The fast release product was lowest ranked. This result has shown the composite effects on tree growth due to the interaction between nutrient contents and ratios and release rates. From this result, it is obvious that micro nutrients contributed more to the growth rate.

Table 12. Caliper growth in the 1996 ponderosa pine plantation.

Fertilization treatments	First growing season			Second growing season			
	Mean Caliper (mm)	Relative Growth rate (%)	Rank	Mean Caliper (mm)	Rank	Relative Growth rate (%)	Rank
Control	6.18	85.68±12.49	1	15.00	2	129.62 ± 3.72	4
15-10-12 fast release 5g	7.07	104.95 ± 14.05	3	17.02	4	114.26 ± 11.26	3
15-10-12 fast release 15g	7.46	113.10 ± 9.18	4	15.90	3	99.31 ± 12.36	1
15-10-12 fast release 30g	7.64	106.30 ± 16.21	3	15.90	3	104.66 ± 18.16	2
16-08-12 medium. Release 5g	6.69	103.22 ± 15.48	3	14.69	1	117.54 ± 29.03	3
16-08-12 medium. Release 15g	7.16	107.38 ± 4.82	3	15.40	2	109.10 ± 7.97	2
16-08-12 medium. Release 30g	7.50	103.72 ± 10.68	3	16.34	3	123.29 ± 5.85	3
15-08-10 slow release 5g	6.57	94.48 ± 12.90	2	15.55	2	123.18 ± 12.14	3
15-08-10 slow release 15g	7.05	103.48 ± 24.37	3	15.53	2	116.05 ± 13.27	3
15-08-10 slow release 30g	6.99	113.35 ± 14.84	4	14.22	1	95.22 ± 17.82	1
14-07-10 minor external 5g	7.14	106.52 ± 15.10	3	16.61	4	124.30 ± 8.89	4
14-07-10 minor external 15g	6.92	101.71 ± 17.21	3	16.97	4	114.01 ± 4.34	3
14-07-10 minor external 30g	6.29	87.94 ± 16.37	1	14.40	1	115.04 ± 11.33	3

By comparing the rankings of the controls between the first and second growing season, it is apparent that the controls have the highest growth rate among all fertilization treatments for the second growing season. This means that fertilization produced other effects on tree growth during the second growing season. As a result, the mean caliper of the controls surpassed the mean calipers of many fertilization treatments such as the 30 grams per rate of the slow release and the minors external products, and the 5 grams per tree rate of the medium release product.

During the first growing season, higher growth rates due to fertilization caused the mean caliper of the three application rates of the fast release product, the low and medium rates of the medium release product, the medium and high application rates of the slow release product and the low application rate of the minors external product to be significantly higher than that of the controls (Table 8). However, during the second growing season, much lower growth rates for the fertilization treatments counteracted the positive growth response to fertilization during the preceding year, and resulting in no significant fertilization effects on mean caliper after the second growing season (pr.>0.05). ANOVA shows that all three application rates of the fast release product, the medium rate of the medium release product and the high rate of the slow release product produced lower growth rate than the controls.

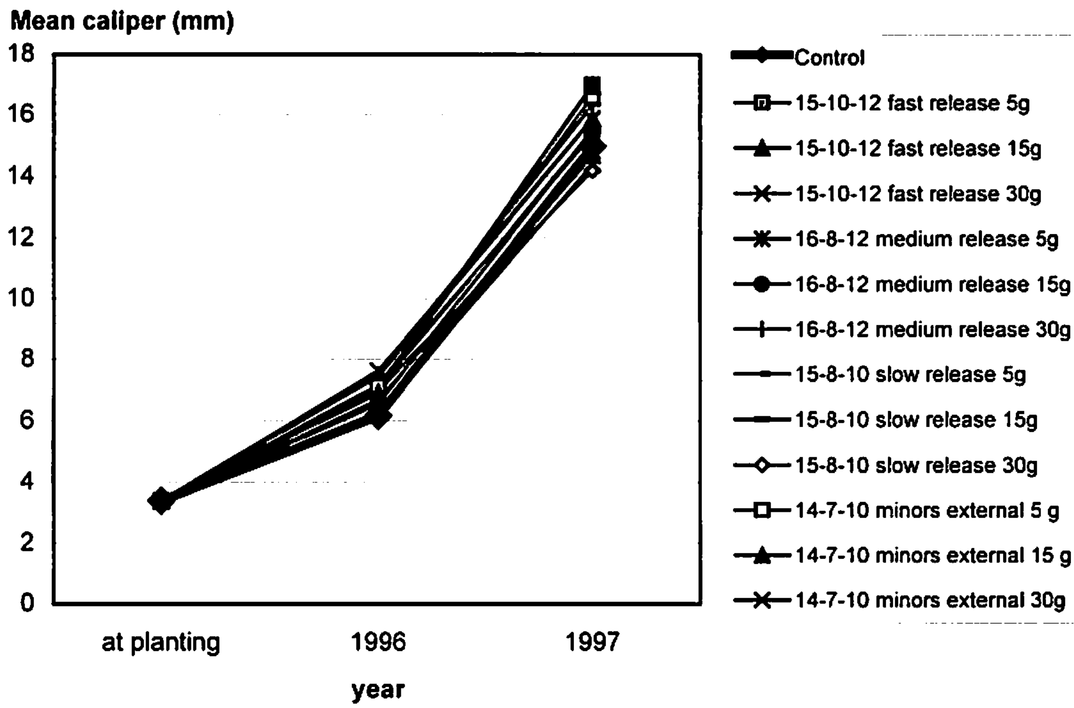

Figure 7. Caliper growth for various fertilization treatments in the 1996 ponderosa pine plantation.

It is more interesting to compare the growth rates between three application rates for each product (Figure 9).There existed an obvious interaction between products (including nutrient contents and release rates) and application rates. Relative caliper growth rates of trees treated with the slow release product increased with application rates in 1996, but decreased in 1997. Relative caliper growth rates of trees treated with the minors external product showed a decrease pattern with application rates for both 1996 and 1997, but the difference between the medium and high application rates was not obvious in 1997. Both the fast and the medium release products produced the largest growth rate for the medium application rates in 1996. However, the low application rate of the fast release product and the high application rate of the medium release product behaved best in 1997. Theoretically, the greatest production can be achieved only when supply balanced tree absorption. Two year field test results seem to support the conclusion that the release rates for all four products do not match tree's absorption (over release). The first two year's data (simply based on the total rankings of the relative growth rate and the mean caliper) indicated that for the fast , slow release and minors external products, low application rates are appropriate. For the slow release product, high application rates are best.

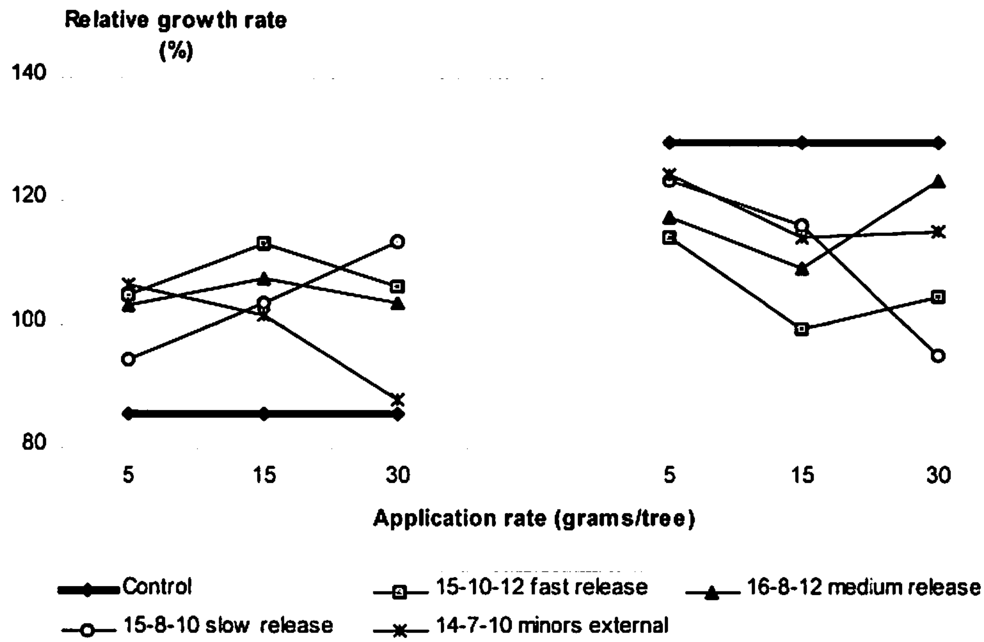

Figure 8. Relative caliper growth rates for various fertilization treatments in the 1996 ponderosa pine plantation

2.Height and mortality

Height is less responsive to fertilization than caliper. From Figure 9, it is obvious that at the end of 1996, mean eight differences between treatments is less than for caliper. By the end of 1997, although height differences creased, no significant fertilization effects were found because of large variation within treatments. The relative eight growth rates (Figure 10) also show stronger detrimental effects of fertilization on height growth during the econd growing season.

Unlike the 1997 plantation, no significant differences in mortality were found between treatments in the 1996 plantation. This may be related to the placement methods and the application rates of fertilizers. Fertilizers were applied at planting and placed in a hole 6 inches deep and 3 inches from the seedling location in the upward direction for the 1996 plantation. Appropriate doses may be another reason for the insignificant mortality pattern between treatments.

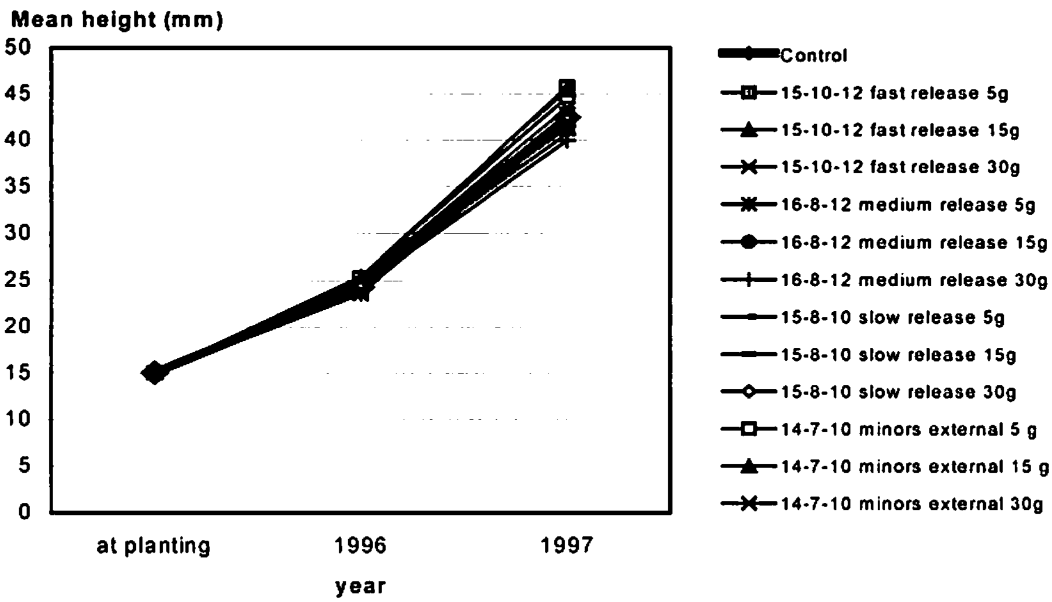

Figure 9. Height growth for various fertilization treatments in the 1996 ponderosa pine plantation.

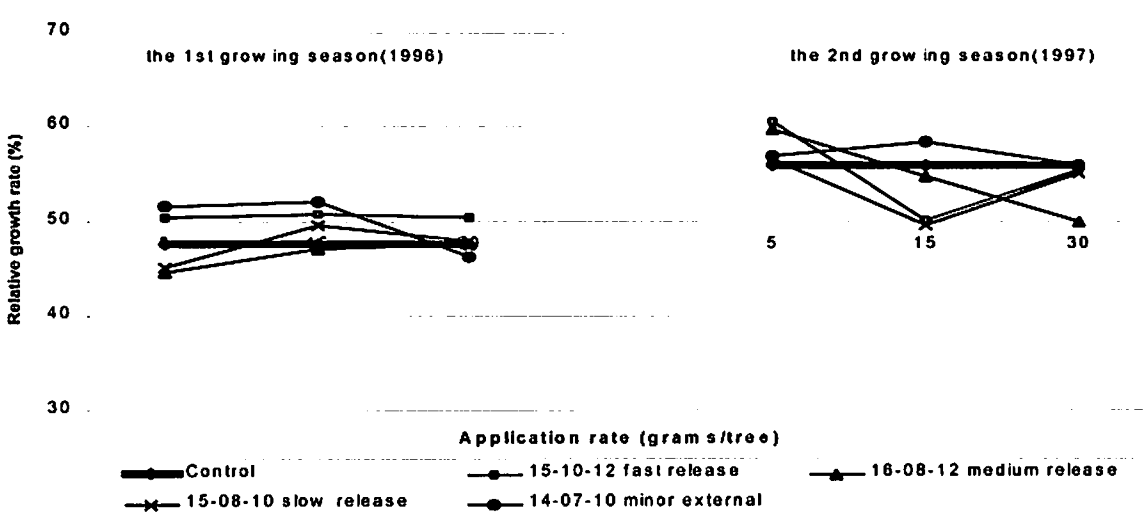

Figure 10. Relative height growth rates for various fertilization treatments in 1996 ponderosa pine plantation.

2. The relationship between foliage nutrient concentrations and ponderosa pine tree growth

ANOVA has shown large spatial variations for both foliage nutrient concentrations and tree growth (Tables 10 and 11). In order to evaluate the relationship between foliage nutrient concentrations and tree growth, covariance analysis using the thirteen nutrient concentrations as covariates and blocks as the categorical variable, relative caliper growth rates as the dependent variable was conducted under the general linear model (GLM) procedure of the SAS software. The results are summarized in Table 13.

Table 13. Partial coefficients and p values for foliage nutrient concentrations for the 1996 ponderosa pine plantation.

	The first growing season (1996)		The second growing season(1997)	
Source	Estimated Coefficients	Pr>|T| for Coefficients	Estimated Coefficients	Pr>|T| for Coefficients
N	0.0691	0.6561	-0.0377	0.8578
P	2.0690	0.3617	-6.6527	**0.0197**
K	-1.0067	**0.0648**	1.4742	**0.0018**
Ca	1.7977	**0.0011**	2.1616	0.1072
Mg	-0.3217	0.8628	-3.2206	0.1748
Al	0.0026	**0.0006**	-0.0008	0.4436
B	-0.00002	0.9203	-0.0054	0.1035
Mn	-0.0003	0.7541	0.0026	0.1784
Mo	-0.3590	**0.0146**	0.1831	0.5342
Fe	-0.0159	**0.0556**	-0.0012	0.4229
Zn	-0.0003	0.5310	-0.00002	0.9738
Na	-0.0002	0.6948	0.0019	0.1945
Cu	0.0890	**0.0467**	0.0779	0.4215

It is interesting that relative caliper growth rates were closely related to the foliage concentrations of K, Ca, Al, Mo Fe and Cu in 1996, but they were only related to P and K in 1997. It seems true that micro nutrients played an more important role in 1996 than in 1997. Although we are not very clear with how foliage nutrient concentrations affect tree growth, the sign of the partial coefficients of each nutrient can provide a clue. For example, the partial coefficient of K in 1996 was negative, but it turned to be positive in 1997. It is apparent that the negative sign in 1996 was caused by dilution (Figure 13). It is clear from Table 11 that higher growth rates resulted in lower K concentrations. In 1997, higher growth rates were associated with higher K concentrations. This, to some extent, indicates that K has different significances with growth periods and with the change of the status of other nutrients. Nitrogen does show any significance in the covariance analysis. However, its effects on tree growth should not be underestimated. Evidences in the dilution of nitrogen and phosphorus concentrations between 1996 and 1997 show that tree growth needs more nitrogen and phosphorus (Figures 11 and 12). Among the thirteen nutrients, none surpassed nitrogen and phosphorus in dilution. As to how nutrient concentrations affect tree growth, we will do more work in this coming growing season from ecophysiological aspects.

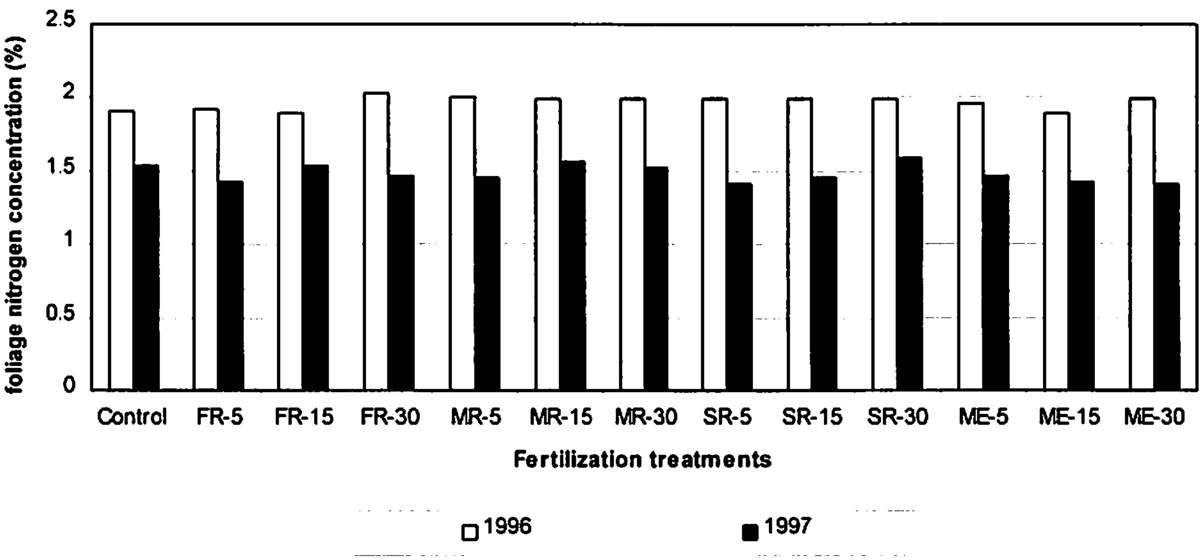

Figure 11. Foliage nitrogen concentrations for various fertilization treatments in the 1996 ponderosa pine plantation.

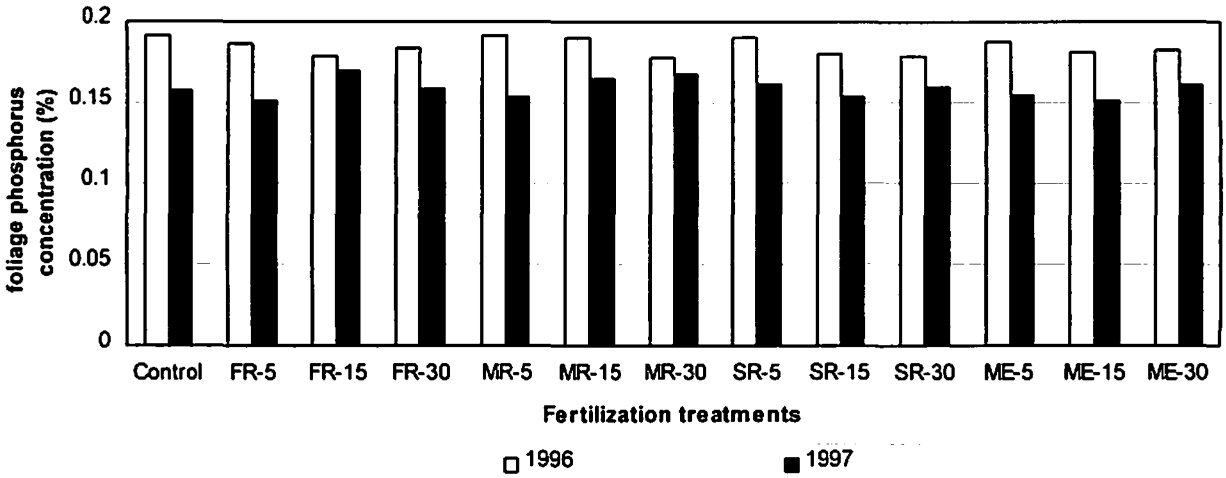

Figure 12. Foliage phosphorus concentration for various fertilization treatments in the 1996 ponderosa pine plantation.

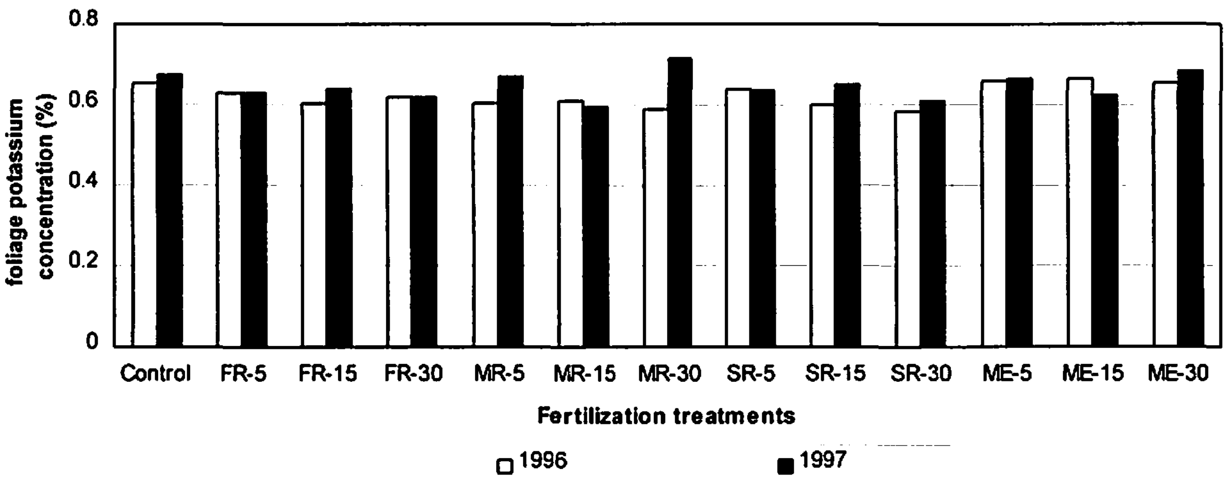

Figure 13 Foliage potassium concentration for various fertilization treatments in the 1996 ponderosa pine plantation.

Summary

1997 plantation

1. High application rates (3.2 grams per tree) of the fast (CB2-95) and medium (CB3-95) release products resulted in much lower root growth potential, which produced as high as 55.21 and36.46% mortality rates in the field.
2. Mortality is negatively related to all micro nutrients and N.
3. Low rates (0.8 grams per tree) of the fast release product, medium rates of the medium and slow (IOP) release products significantly increased height growth.
4. Height growth is positively related to P, Mg and Al, but negatively related to Cu.
5. Low and medium rates of the fast release product, medium rates of the medium release product, and medium and high rates of the slow release product significantly increased caliper growth.
6. Caliper growth is positively related to Ca, but negatively related to K and Fe.

1996 plantation

1. Fertilization had not significant effects on height growth in the past two years.
2. Fertilization significantly increased caliper growth in the first growing season (1996).Both mean calipers and relative caliper growth rates for fertilization treatments were higher than the controls. But in 1997, no fertilization treatments produced significantly higher mean caliper than the controls due to their lower relative growth rates than the controls.
3. Relative caliper growth rates in 1996 were closely related the foliage concentrations of K, Ca, Al, Mo, Fe and Cu, but they were only related to K and P in 1997. Much lower caliper growth rates in 1997 were closely related with the dilution of N and P.
4. In order to achieve larger growth rates, it seems to be reasonable that initial application rates needs to be higher or retreatment of seedlings prior to second growing season needs to be conducted.
5. Burned needles were caused by the extremely high boron concentrations in trees treated with the minors external product (14-07-10).

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