AN ABSTRACT OF THE THESIS OF

Patricio Javier Alzugaray Oswald for the degree of Master of Science in Forest Science presented on May 03, 2002.

Title: Effects of Fertilization at the Time of Planting on Field Performance of 1+1 Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] Seedlings.

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Abstract approved: ______________________________

Robert W. Rose, Jr.

To study the combined effects of seedling quality and fertilization at the time of planting, three experiments were established in western Oregon during the winter of 2000. The first experiment investigated the effect of preplanting root-volume and fertilization rate on the field performance of 1+1 Douglas-fir seedlings during two growing seasons. Results from this experiment showed that preplanting root volume is a good predictor of field performance. Seedlings with larger preplanting root volume survived and grew more than seedlings with smaller preplanting root volume. Fertilization at the time of planting slightly reduced survival, stimulated shoot and diameter growth during the first growing season, and reduced all parameters during the second growing season.

The second experiment examined the effects of fertilizer placement in combination with fertilization rate on the performance of 1+1 Douglas-fir seedlings during two growing seasons. Results of this experiment showed a significant interaction for seedling survival between fertilizer placement and fertilization rate. Seedlings fertilized on the roots at the highest rate had the lowest survival (50%), while survival of all other treatments was above 70%. Fertilizer placement and fertilization rate did not affect seedling growth during the first growing season. However, during the second growing season, seedlings fertilized on the surface and those dibbled fertilized grew the most in height and diameter. Fertilization rate reduced seedling height growth but did not affect stem diameter growth.

A third experiment monitored nutrient release patterns of similar controlled-release fertilizers with different fertilizer release rates applied on the field over a 14-month period. Fertilizers with shorter release periods released more fertilizer by weight than fertilizers with longer release periods. However, none of the fertilizers studied released their nutrients in the time specified by the manufacturer. It is suggested that low soil temperatures and low soil moisture may have delayed the release periods of the fertilizers.

Effects of Fertilization at the Time of Planting on Field Performance of 1+1 Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] Seedlings

by
Patricio Javier Alzugaray Oswald

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Patricio Javier Alzugaray Oswald, Author

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CONTRIBUTIONS OF AUTHORS

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This thesis is dedicated to my beloved wife

Claudia,

whose love, support and wisdom

during all these years have turned me in what I have become

EFFECTS OF FERTILIZATION AT THE TIME OF PLANTING ON FIELD PERFORMANCE OF 1+1 DOUGLAS FIR [*Pseudotsuga menziesii* (Mirb.) Franco] SEEDLINGS

CHAPTER I
GENERAL INTRODUCTION

INTRODUCTION

Reforestation success is closely linked to seedling quality, proper seedling handling and planting, and to silvicultural treatments applied during the initial stages of a plantation, such as site preparation, vegetation control, and fertilization. The objective of these treatments is to make the seedling environment more favorable for establishment and to promote rapid early growth of desirable species. Delaying the period between installation of a new plantation and complete occupation of the site by the desired species may result in a reduction of survival and growth rates due to competing vegetation for site resources and animal damage. Fertilizing at the time of planting in combination with the use of good quality stock may help to minimize these problems.

A series of three field experiments were established in western Oregon during the winter of 2000 to determine how do fertilization at the time of planting and seedling quality, determined by the size of the seedling root system influence the survival and growth of outplanted 1+1 Douglas-fir seedlings during the first two growing seasons in the field. The first experiment investigated the effect of preplanting root volume, used as an indicator of seedling quality, and fertilization rate on the performance of 1+1 Douglas-fir seedlings at the end of two growing seasons (Chapter II). The second experiment examined the effects of fertilizer placement in combination with fertilization rate on the performance of 1+1 Douglas-fir seedlings at the end of two growing seasons (Chapter III). A third experiment monitored nutrient release patterns of similar controlled-release fertilizers with different fertilizer release rates applied in the field over a 14-month period (Chapter IV). This thesis reports and discusses in the following two chapters results from the two outplanting studies and in the forth chapter results from the fertilizer release study.

ROOT VOLUME AS A PREDICTOR OF SEEDLING QUALITY

Seedling quality is determined by seedling performance in the field. High quality seedlings are those that "can survive prolonged environmental stresses and produce vigorous growth immediately following outplanting in a particular site" (Johnson and Cline 1991). Under optimal physiological conditions, seedling morphology is a good predictor of seedling quality (Ritchie 1984). Among seedling morphological parameters, seedling height and stem diameter have been the most used by nursery managers as grading criteria to assess seedling quality (Mexal and Landis 1990; Mexal and South 1990). However they are not always reliable (Boyer and South 1987).

Seedling root volume is an attractive criterion to assess seedling quality and predict subsequent seedling performance after outplanting because it can be measured both in containerized and bareroot nurseries using nondestructive methods (Burdett 1979; Racey 1985; Harrington et al. 1994). It is positively correlated with seedling survival and growth in the field (Rose et al. 1991a; Rose et al. 1991b; Rose et al. 1997). Seedlings with bigger root volume at the time of planting are better able to withstand transplant shock (Haase and Rose 1993) and have higher root growth potential (Carlson 1986, South et al. 1990) and increasing water (Carlson 1986) and mineral nutrient uptake (Haase and Rose 1994).

Among factors that influence seedling root development are length of the growing season (Boyer and South 1989), growing density (Carlson 1986, South et al. 1990, Simpson 1991), mineral nutrition (Pharis and Kramer 1964, Philipson and Coutts 1977, Friend et al. 1990), water availability (Pharis and Kramer 1964, Haase and Rose 1993, Rose et al. 1993, Kahn et al. 1996), and soil compaction (Page-Dumroese et al. 1998).

Generally, increasing nitrogen and phosphorus fertility results in larger seedlings with bigger root biomass (Pharis and Kramer 1964, Philipson and Coutts 1977, Friend et al. 1990). A two-fold increase in root biomass was measured when Douglas-fir seedlings were grown in a high nitrogen fertilization environment (Friend et al. 1990).

Similarly, increasing water availability during the growing season generally results in larger seedlings with a correspondingly larger root volume (Haase and Rose 1993, Rose et al. 1993, Kahn et al. 1996). A decrease in seedling growth may be observed however when they are grown under very high or very low soil moisture conditions. Douglas-fir seedlings exhibited optimum growth when grown between 29 and 53% soil water content (Kahn et al. 1996). Lopushinsky (1990) recommends that seedling predawn xylem water potentials should be maintained above –0.5 MPa during seedling growth and between –0.5 and –1MPa when reducing growth to induce dormancy.

Soil compaction increases soil bulk density by reducing porosity mainly in the large pores, where water flow and gas exchange occur. Soil compaction also increases soil strength and resistance to root penetration, resulting in a reduction of root growth (Warkentin 1984). An increase in 15 to 20% in soil bulk density can reduce the root volume of Douglas-fir seedlings by 64% (Page-Dumroese et al. 1998).

FERTILIZATION AT THE TIME OF PLANTING

Fertilization at the time of planting, or shortly after, is a worldwide silvicultural practice commonly used to increase plantation productivity by promoting early growth of seedlings during the period of seedling establishment. In the southeastern United States it has been used operationally in intensively managed plantations of loblolly (*Pinus taeda* L.) and slash (*Pinus elliottii* Engelm.) pine (Jokela et al. 1991). Since the early 1960's the use of controlled-release fertilizers in forest plantations has been promoted by some research foresters in the Pacific Northwest (Austin and Strand 1960; Rothacher and Franklin 1964; Smith et al. 1966). However, experiments undertaken in recent years show inconsistent responses of Douglas-fir and other planted conifer seedlings to fertilization (van den Driessche 1997).

Fertilization with 220 kg/ha of urea applied within one month after planting had no effect on survival and growth of Douglas-fir (plug+1) when used in combination with weed control and a negative effect on survival and growth when used without weed control at the end of the second growing season (Roth and

Newton 1996). For the same species, an increase in height of 31% compared with the unfertilized controls was measured after 6 years with Osmocote® (17-7-12) and Agriform® (20-10-5) at rates of 8.4 to 16.8g of nitrogen per tree (van den Driessche 1988). Applications of 21g of Osmocote® (17-5-11) per seedling, in a hole adjacent to Douglas-fir plugs grown in 25.8 cm^3 containers (15cm long) stimulated shoot growth by 42% compared to the unfertilized controls in the following two growing seasons after the application (Carlson and Preisig 1981). Similar results were obtained for western hemlock plugs grown in 65.6cm^3 containers after two growing seasons, when 21g of Osmocote (17-5-11) per seedling were applied in the planting hole (Carlson 1981). Fertilization with 50g of Nutricote® (16-10-10) stimulated both height and diameter relative growth rates of four different stocktypes (plugs grown in 36cm^3 containers, 1+1 plug transplants, seedlings grown in 1l containers planted as bareroot, and seedlings grown in 1l containers with copper coating planted as bareroot) of western hemlock during the first two growing seasons and reduced it in all stocktypes during the third growing season (Arnott and Burdett 1988).

The effectiveness of fertilization may be influenced by the placement of the fertilizer (van den Driessche 1990). For outplanted Douglas-fir seedlings, surface broadcast applications of Agriform® (20-10-5) resulted in greater survival and stem volume than adjacent placement, whereas adjacent placement of Osmocote® (17-7-

12) had greater stem volume (van den Driessche 1988). Height growth of Douglas-fir plugs grown in 25.8 cm^3 containers (15cm long) was more stimulated when 21g of Osmocote® (17-5-11) were placed in a hole adjacent to the seedling than in the planting hole (Carlson and Preisig 1981). Lateral root distribution and shoot-root dry weight were not affected by fertilizer placement (Carlson and Preisig 1981). Similarly, western hemlock plugs grown in 65.6cm^3 styrofoam containers had greatest height and diameter growth when 21g of Osmocote® (17-5-11) were applied in the planting hole rather than in an adjacent hole (Carlson 1981).

Fertilizer effectiveness may also be influenced by the release rate and environmental characteristics present at the application site during the growing season. Nutrient release rates of controlled-release fertilizers are highly dependent on both biotic and abiotic environmental factors, such as soil temperature, soil moisture, and soil microbial activity (Hauck 1985). Nominal nutrient release periods specified by manufacturers of controlled-release products are estimated under stable conditions of temperature, generally 21°C (Goertz 1993). However, these conditions seldom occur in the field. Analysis of Nutricote® prills (16-10-10) with a release rate of 12 months at 25°C, used in an outplanting study in British Columbia, revealed that only 54% of the nitrogen was released after 22 months since applied (Arnott and Burdett 1988).

On several outplanting studies in which controlled-release fertilizers of different formulations were compared, only small differences in nutrient response other than nitrogen have been observed (van den Driessche 1988). It has been suggested that the reason why a N-P-K formulation of controlled-release fertilizers has no effect other than nitrogen on growth may be due to the small amount of other nutrients relative to nitrogen present in the formulation (van den Driessche 1997).

The accuracy by which a rate and pattern of nutrient release can be predicted is determined by the composition of the fertilizer and the grower's ability to control and anticipate the effects of environmental factors of the soil-plant system in which the fertilizer is placed (Hauck 1985). Several studies have described nutrient release patterns of polymer-coated, controlled-release fertilizers under controlled temperature conditions (Lamont et al. 1987, Cabrera 1997, Huett and Gogel 2000). Such information is more useful to nursery growers, who are able to control and monitor growing media temperature and moisture. Reforestation foresters have to be at the mercy of natural rainfall and radiation to provide coated fertilizers adequate levels of soil moisture and soil temperature to trigger the mechanisms of nutrient release from the fertilizer.

CHAPTER II

EFFECTS OF PREPLANTING ROOT-VOLUME AND FERTILIZATION RATE ON FIELD PERFORMANCE OF 1+1 DOUGLAS-FIR [*Pseudotsuga menziesii* (Mirb.) Franco] SEEDLINGS

ABSTRACT

To determine the combined effects of preplanting root volume and fertilization rate on seedling field performance, Douglas-fir 1+1 seedlings, grown using standard practices at the Weyerhaeuser Aurora, OR Nursery, were sorted into four root-volume categories (8-13, 14-17, 18-22, and 23-35 cm^3), and planted in a recent clearcut in Oregon State University's McDonald-Dunn Research Forest on January 19, 2000 using a complete randomized block design with five replicates in a factorial treatment arrangement. A Polyon® Simplot fertilizer mixture, containing equal parts of three fertilizers with different release rates (3-4, 5-6, and 8-9 months) and similar NPK concentrations (19-6-12) was applied at the time of planting in the bottom of the planting hole to each root-volume category at five rates: 0 (unfertilized control), 15, 30, 45 and 60 g per seedling.

After two growing seasons in the field, there was no interaction between root volume and fertilization rate for seedling growth and survival. Seedlings with

larger preplanting root volume had greater survival and growth than seedlings with smaller preplanting root volume. There was a significant reduction in seedling survival and growth with increasing fertilization rate.

INTRODUCTION

During the initial stages of plantation establishment seedling growth is limited by competing vegetation for site resources and animal damage. The use of high quality seedlings that are able to survive and grow vigorously after outplanting, proper seedling handling and planting in combination with silvicultural practices such as site preparation, vegetation control and fertilization may reduce the time required by the desire species for complete occupation of the site.

Seedling morphology is a good indicator of seedling quality if seedling physiology is optimal (Ritchie 1984). Nursery managers have targeted seedling height and stem diameter as grading criteria to assess seedling quality (Mexal and Landis 1990; Mexal and South 1990). However they are not always reliable, especially when excessively tall seedlings are planted on dry sites (Boyer and South 1987).

Several authors have suggested including the size of seedling root system as grading criteria to assess seedling quality (Carlson 1986; Carlson 1990; Rose 1990;

Rose et al. 1991a; Rose et al. 1991b; Rose et al. 1997). If measured just before planting, it has been positively correlated with seedling survival and growth in the field (Rose et al. 1991a; Rose et al. 1991b; Rose et al. 1997). Probably because seedlings with bigger preplanting root volume tolerate better transplant shock (Haase and Rose 1993) and have higher root growth potential (Carlson 1986, South et al.1990) and increasing water (Carlson 1986) and mineral nutrient uptake from the soil (Haase and Rose 1994). Seedling preplanting root volume also is positively correlated with seedling height, stem diameter, and total biomass (Rose et al. 1991a; Rose et al. 1991b; Haase and Rose 1993), initial seedling size differences that were maintained over eight growing seasons in ponderosa pine and Douglas-fir seedlings (Rose et al. 1997).

Fertilization at the time of planting has become a common practice worldwide in hopes that seedling nutritional status and growth rates will be improved by the anthropogenic addition of mineral nutrients into the soil close to the outplanted seedling. Dry soluble fertilizers were traditionally applied in the past. Today with the development of the controlled-release technology, the use of controlled-release fertilizers at outplanting has gained increasing interest. Fertilization with controlled-release fertilizes allows the reforestation forester to extend the time in which sufficient dosages are delivered and to minimize the risk associated with overdosage (Hauck 1985; Goertz 1993). Thus, the use of controlled release fertilizers applied at the time of planting on seedlings with high preplanting root volume may increase seedling initial growth rates.

This study was design to determine how seedling survival and growth is stimulated by using larger seedlings in combination with increasing fertilization rates applied at the time of planting? Null hypotheses tested were:

1. Preplanting root volume does not significantly affect 1+1 Douglas-fir seedling survival and morphology at the end of two growing seasons in the field.
2. Fertilization rate does not significantly affect 1+1 Douglas-fir seedling survival and morphology at the end of two growing seasons in the field.
3. Preplanting root volume does not significantly interact with fertilization rate for seedling survival and morphology at the end of two growing seasons in the field.

MATERIALS AND METHODS

Plant material

Two year-old (1+1) bareroot Douglas-fir seedlings produced from seed collected from a seed orchard located in the Willamette Valley, OR, seed zone 262 (Oregon Department of Forestry 1996), were grown using standard practices at the Aurora, OR Weyerhaeuser Nursery. Following lifting, seedlings were graded to operational specifications. A sample of 2570 seedlings were randomly selected, transported to OSU, and placed in cold storage at 3°C in January 2000. At the laboratory, seedlings were washed free of soil and measured for root volume by water displacement (Harrington et al. 1994). Each seedling was numbered, tagged and returned to cold storage.

Treatments

Following measurement, according to the root-volume distribution of the 2570 seedlings (Figure II.1), four root-volume categories were established such that at least 500 seedlings could be assigned to each category: RV1 (root volume 8-13 cm^3), RV2 (root volume 14-17 cm^3), RV3 (root volume 18-22 cm^3), and RV4 (root volume 23-35 cm^3). Bundles of 20 randomly selected seedlings within each category were made and stored in a cooler at 3°C until outplanting.

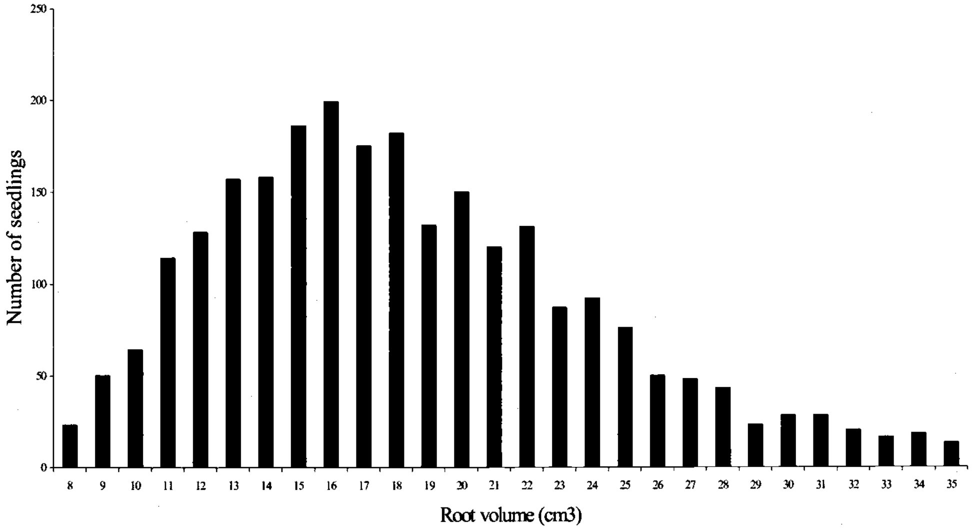

Figure II.1. Root-volume distribution for the 2000 seedlings used in the experiment.

Fertilizer treatments consisted of five rates of Simplot Polyon® fertilizer applied at the time of planting: 0 (unfertilized control), 15, 30, 45 and 60 g. Fertilizer was measured with plastic cups specially designed for this experiment, tossed in the bottom of the planting hole, and covered by a 1-2 cm layer of soil prior to planting the seedling on top of it. The fertilizer used in this experiment was a Simplot Polyon$^{\circledR}$ (19-6-12) mixture (Table II.1) containing equal parts of 3 fertilizers with different release rates (3-4, 5-6 and 8-9 months).

Table II.1. Nutrient composition (%) of the three Simplot Polyon$^{\circledR}$ fertilizers used to create the composite fertilizer applied in this experiment.

Fertilizer	Polyon 1 (3-4 months release rate)	Polyon 2 (5-6 months release rate)	Polyon 3 (8-9 months release rate)	Composite applied
Nutrient	Composition (%)			
Total nitrogen	19	19	18	18.67
NH_4	8.2	8.2	7.74	8.05
NO_3	10.8	10.8	10.26	10.62
P (P_2O_5)	5	6	6	5.67
K (K_2O)	12	12	12	12
Mg	1	0.9	0.9	0.93
S	1.8	1.7	1.7	1.73
Fe	0.45	0.45	0.45	0.45
Mn	0.2	0.19	0.19	0.193
Mo	0.009	0.009	0.009	0.009
Zn	0.056	0.055	0.05	0.054

Planting site

The planting site was in Oregon State University's McDonald-Dunn Research Forest, located 15 miles north of Corvallis, OR. The experiment was established in a recently (fall 1998) clearcut harvested of Douglas-fir. The site was sprayed with Accord®, Arsenal®, Oust®, and Escort® for brush, grass, and blackberry control. Landing piles were burned on the site in fall 1999 to reduce slash. After establishing the experiment an application of Transline® was made to control thistle. Early in the spring of 2001 the site was sprayed with Garlon® 4 and Atrazine® to control emerging competing vegetation composed mainly of big leaf maple, blackberries, poison oak, and oak sprouts. The site has a gently sloping east aspect. Soils belong to the Waldo series and are deep, well-drained, silty clay loams. Soil chemical characteristics are shown in Table II.2. Monthly rainfall in Corvallis during the study period is shown in Figure II.2. as an estimate for what might be at the experimental site. A soil temperature recorder was established at the site to record minimum, average and maximum soil temperatures 30 cm deep at three-days intervals throughout the growing season.

Table II.2. Soil chemical characteristics at the study site.

Organic matter (%)	NO_3 (ppm)	P (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	Na (ppm)	SO_4 (ppm)	Zn (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)	B (ppm)	CEC (meq/100g)	EC (dS/m)	pH
12.3	25.8	5.5	217.5	182.3	1034.5	11.3	3.3	0.2	5.5	16.5	2.5	0.2	9.4	0.4	5.7

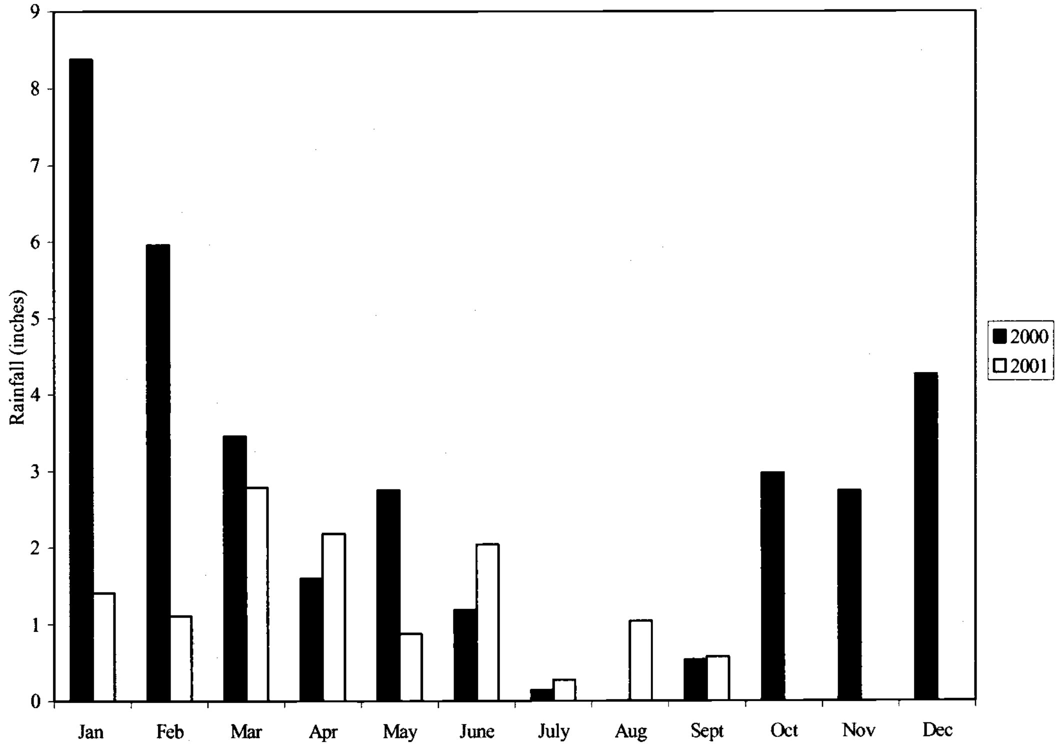

Figure II.2. Monthly rainfall in Corvallis, OR during the study period.

Planting

Seedlings were outplanted by a trained planting crew on January 19, 2000 at a 10’ x 10’ spacing. Prior to planting the site was laid out with color-coded pin flags; one per seedling at each planting hole. Each planter planted a variety of treatments to avoid confounding. Seedlings were protected from animal damage with rigid mesh tubes after planting.

Experimental design

Seedlings were outplanted in the field using a completely randomized block design with five blocks in a 4 x 5 factorial treatment arrangement (Four root-volume categories, 5 fertilization rates). Each treatment was randomly assigned to each row. Each block consisted of 20 rows of 20 seedlings each for a total of 2000 seedlings.

Data collection

In addition to the 2000 outplanted seedlings, 25 seedlings from each root-volume category were randomly selected and measured for height, stem diameter, shoot volume, and root volume. Seedlings from this subsample were then dried for 48 hours at 68°C. Total root, stem, foliar, and top dry weights were determined on each. The foliage was then ground and combined into three composite samples (Five seedlings each) for determination of initial foliar nutrient concentration and content. Foliar nutrient content was estimated by multiplying foliar nutrient concentration by the dry weight of 100 needles.

Survival, height and diameter were measured on the outplanted seedlings within one month after planting (February 2000), in July 2000, September 2000, and September 2001. Instances of browsing, chlorosis, frost damage, dead tops, and browning were also recorded.

After the first growing season in the field, three seedlings per treatment per block were randomly selected, excavated and taken to the laboratory for morphological assessment. Total height, seasonal height, stem diameter, diameter of the terminal bud, shoot volume and root volume were measured on each. The diameter of the terminal bud was measured on the widest cross section of the terminal bud.

Statistical analysis

The relationships among preplanting root volume to preplanting total height, stem diameter, shoot volume, shoot to root ratio, shoot dry weight, foliar dry weight, top dry weight, and root dry weight were examined using correlation analysis. Differences in preplanting total height, stem diameter, shoot volume, shoot to root ratio, shoot dry weight, foliar dry weight, top dry weight, and root dry weight among root-volume categories were analyzed using a one-way analysis of variance. A two-way factorial analysis of variance was used to analyze for differences in seedling survival, total height and stem diameter increments measured in the field, total height, seasonal height, stem diameter, diameter of the terminal bud, shoot volume, and root volume, measured at the laboratory, among root-volume categories and fertilization rates. An analysis of covariance (ANCOVA) was performed on final height and diameter to remove sources of variation due to initial height and stem diameter, respectively. Tukey's studentized range test was used to determine significant differences among treatment means at the $\alpha \leq 0.05$ level.

RESULTS

Preplanting morphology

Root volume was positively correlated with other morphological characteristics such as stem diameter ($r=0.81$; $p<0.0001$), shoot height ($r=0.54$; $p<0.0001$), shoot volume ($r=0.82$; $p<0.0001$), foliar dry weight ($r=0.81$; $p<0.0001$), stem dry weight ($r=0.78$; $p<0.0001$), top dry weight ($r=0.82$; $p<0.0001$), and root dry weight (r=0.93; p<0.0001). This means as seedling root volume increased, so did preplanting morphological parameters. Shoot-root ratio was not affected by preplanting root volume (p=0.65) (Table II.3).

Table II.3. Preplanting morphological characteristics by root-volume category.

Variable	Mean	Standard deviation	Coef. of variation (%)	Range
Root volume (cm^3)				
RV1	11.4 a	1.44	12.63	8.00-13.00
RV2	15.68 b	1.14	7.27	14.00-17.00
RV3	19.80 c	1.50	7.58	18.00-22.00
RV4	26.48 d	3.68	13.90	23.00-35.00
Total height (cm)				
RV1	26.96 a	4.32	16.02	18.00-41.50
RV2	31.12 b	5.29	17.00	22.50-41.00
RV3	32.04 b	5.07	15.82	21.50-44.00
RV4	35.68 c	5.52	15.47	26.00-44.00
Stem diameter (mm)				
RV1	4.95 a	0.42	8.48	4.23-5.76
RV2	5.59 b	0.52	9.30	4.61-6.69
RV3	6.17 c	0.67	10.86	4.74-7.90
RV4	7.12 d	1.05	14.75	5.96-10.50
Height-diameter ratio (cm/mm)				
RV1	5.47 a	0.92	16.82	3.91-7.86
RV2	5.58 a	0.91	16.31	4.24-7.71
RV3	5.21 a	0.80	15.36	3.99-6.90
RV4	5.05 a	0.78	15.45	3.60-6.71
Shoot volume (cm^3)				
RV1	14.24 a	2.99	21.00	9.00-22.00
RV2	20.16 b	5.01	24.85	13.00-34.00
RV3	23.56 b	5.28	22.41	13.00-35.00
RV4	32.80 c	9.21	28.08	20.00-58.00
Shoot-root ratio				
RV1	1.26 a	0.24	19.05	0.77-1.83
RV2	1.28 a	0.26	20.31	0.81-2.00
RV3	1.19 a	0.26	21.85	0.65-1.61
RV4	1.23 a	0.27	21.95	0.80-1.71
Shoot dry weight (g)				
RV1	2.27 a	0.48	21.15	1.47-3.74
RV2	3.29 b	0.78	23.71	2.10-4.71
RV3	3.88 b	1.01	26.03	1.87-6.50
RV4	5.38 c	1.75	32.53	2.92-9.82
Foliar dry weight (g)				
RV1	2.26 a	0.49	21.68	1.54-3.42
RV2	2.94 b	0.79	26.87	2.01-5.34
RV3	3.48 b	0.65	18.68	2.49-5.25
RV4	4.74 c	1.12	23.63	3.13-7.65
Top dry weight (g)				
RV1	4.52 a	0.92	20.35	3.05-7.16
RV2	6.22 b	1.49	23.95	4.22-10.05
RV3	7.36 b	1.46	19.84	4.36-10.93
RV4	10.11 c	2.76	27.30	6.14-17.47
Root dry weight (g)				
RV1	2.76 a	0.51	18.48	1.95-4.11
RV2	3.70 b	0.39	10.54	2.96-4.43
RV3	4.67 c	0.61	13.06	3.71-6.22
RV4	6.41 d	1.78	27.77	4.90-9.78

[*] Root volume categories for this and subsequent tables: RV1 8-13 cm^3; RV2 14-17 cm^3; RV3 18-22 cm^3; RV4 23-35 cm^3.

Initial nutrient concentration and nutrient content did not differ significantly among root-volume categories (Table II.4 and II.5). So, regardless of initial size, seedlings started with similar nutrition.

Field performance

The interaction between root-volume category and fertilization rate was not significant for seedling survival, total height, stem diameter, and height and stem diameter growth at each measuring period (Table II.6 and Table II.7). Therefore, the effects of root volume were averaged over fertilization rate and vice versa. Initial height added a significant amount of variation among root-volume categories and fertilization rates for total height measured in July 2000 ($p<0.0001$), September 2000 ($p<0.0001$), and September 2001($p=0.0104$) (Table II.8). Initial stem diameter added a significant amount of variation among root volume categories and fertilization rates for stem diameter measured in July ($p<0.0001$) and September 2000 ($p<0.0001$), but did not for stem diameter measured in September 2001 ($p=0.0953$) or any stem diameter growth between measuring dates ($p>0.05$) (Table II.8).

Table II.4. Preplanting nutrient concentration by root-volume category.

Mineral element	Mean	Standard deviation	Coef. of variation (%)	Range
N (%)				
RV1	2.37	0.26	10.97	2.17-2.67
RV2	2.50	0.12	4.80	2.37-2.60
RV3	2.46	0.03	1.22	2.43-2.48
RV4	2.29	0.17	7.42	2.17-2.49
P (%)				
RV1	0.19	0.01	5.26	0.19-0.20
RV2	0.20	0.03	15.00	0.17-0.22
RV3	0.21	0.02	9.52	0.20-0.23
RV4	0.22	0.01	4.55	0.22-0.23
K (%)				
RV1	0.63	0.06	9.52	0.60-0.70
RV2	0.70	0.20	28.57	0.50-0.90
RV3	0.73	0.06	8.22	0.70-0.80
RV4	0.77	0.06	7.79	0.70-0.80
S (%)				
RV1	0.22	0.07	31.82	0.14-0.27
RV2	0.24	0.06	25.00	0.18-0.28
RV3	0.25	0.02	8.00	0.23-0.26
RV4	0.25	0.04	16.00	0.20-0.28
Ca (%)				
RV1	0.69	0.03	4.35	0.66-0.72
RV2	0.72	0.12	16.67	0.61-0.84
RV3	0.71	0.06	8.45	0.65-0.75
RV4	0.73	0.05	6.85	0.67-0.77
Mg (%)				
RV1	0.19	0.02	10.53	0.17-0.20
RV2	0.19	0.04	21.05	0.15-0.22
RV3	0.17	0.02	11.76	0.16-0.19
RV4	0.18	0.01	5.56	0.17-0.19
Na (%)				
RV1	0.08	0.03	37.50	0.06-0.11
RV2	0.11	0.02	18.18	0.09-0.12
RV3	0.08	0.02	25.00	0.06-0.10
RV4	0.08	0.04	50.00	0.05-0.12
B (ppm)				
RV1	43.30	4.42	10.21	38.20-46.10
RV2	44.80	2.23	4.98	43.00-47.30
RV3	44.00	6.84	15.55	37.60-51.20
RV4	44.93	7.57	16.85	39.60-53.60
Zn (ppm)				
RV1	101.33	9.29	9.17	91.00-109.00
RV2	98.33	5.51	5.60	92.00-102.00
RV3	86.00	2.65	3.08	84.00-89.00
RV4	85.67	10.07	11.75	75.00-95.00
Mn (ppm)				
RV1	325.33	58.16	17.88	275.00-389.00
RV2	342.33	63.09	18.43	270.00-386.00
RV3	378.00	43.72	11.57	347.00-428.00
RV4	388.33	18.48	4.76	367.00-399.00
Fe (ppm)				
RV1	1866.67	140.12	7.51	1710.00-1980.00
RV2	1603.33	86.22	5.38	1510.00-1680.00
RV3	1470.00	270.74	18.42	1160.00-1660.00
RV4	1613.33	315.65	19.57	1250.00-1820.00
Cu (ppm)				
RV1	19.00	5.29	27.84	15.00-25.00
RV2	14.33	2.08	14.52	12.00-16.00
RV3	13.67	2.08	15.22	12.00-16.00
RV4	35.00	33.15	94.71	12.00-73.00

Table II.5. Preplanting nutrient content by root-volume category.

Mineral element	Mean	Standard deviation	Coef. of variation (%)	Range
N (mg/100 needles)				
RV1	6.97	0,26	3.73	6.68-7.16
RV2	7.40	0.58	7.84	7.02-8.06
RV3	7.70	0.66	8.57	7.13-8.43
RV4	7.55	0.54	7.15	6.94-7.97
P (mg/100 needles)				
RV1	0.57	0.09	15.79	0.48-0.66
RV2	0.58	0.07	12.07	0.54-0.66
RV3	0.67	0.10	14.93	0.61-0.78
RV4	0.74	0.03	4.05	0.70-0.77
K (mg/100 needles)				
RV1	1.89	0.41	21.69	1.50-2.31
RV2	2.06	0.57	27.67	1.60-2.70
RV3	2.31	0.36	15.58	2.03-2.72
RV4	2.53	0.28	11.07	2.24-2.80
S (mg/100 needles)				
RV1	0.64	0.23	35.94	0.43-0.89
RV2	0.72	0.13	18.06	0.58-0.84
RV3	0.78	0.03	3.85	0.75-0.81
RV4	0.82	0.15	18.29	0.64-0.91
Ca (mg/100 needles)				
RV1	2.06	0.31	15.05	1.75-2.38
RV2	2.11	0.16	7.58	1.95-2.27
RV3	2.24	0.34	15.18	1.89-2.55
RV4	2.40	0.06	2.50	2.35-2.46
Mg (mg/100 needles)				
RV1	0.55	0.07	12.73	0.50-0.63
RV2	0.55	0.06	10.91	0.48-0.59
RV3	0.54	0.07	12.96	0.46-0.59
RV4	0.59	0.02	3.39	0.58-0.61
Na (mg/100 needles)				
RV1	0.23	0.04	17.39	0.20-0.28
RV2	0.32	0.04	12.50	0.27-0.35
RV3	0.26	0.07	26.92	0.19-0.31
RV4	0.26	0.16	61.54	0.38-0.11
B (mg/100 needles)				
RV1	0.01	0.003	30.00	0.010-0.015
RV2	0.01	0.001	10.00	0.012-0.014
RV3	0.01	0.003	30.00	0.012-0.017
RV4	0.01	0.002	20.00	0.013-0.017
Zn (mg/100 needles)				
RV1	0.03	0.004	13.33	0.026-0.034
RV2	0.03	0.002	6.67	0.027-0.030
RV3	0.03	0.002	6.67	0.025-0.029
RV4	0.03	0.004	13.33	0.024-0.030
Mn (mg/100 needles)				
RV1	0.10	0.03	30.00	0.08-0.13
RV2	0.10	0.01	10.00	0.09-0.12
RV3	0.12	0.02	16.67	0.10-0.15
RV4	0.13	0.01	7.69	0.12-0.14
Fe (mg/100 needles)				
RV1	0.55	0.09	16.36	0.48-0.65
RV2	0.47	0.03	6.38	0.44-0.50
RV3	0.46	0.05	10.87	0.39-0.49
RV4	0.53	0.12	22.64	0.40-0.62
Cu (mg/100 needles)				
RV1	0.005	0.0007	14.00	0.005-0.006
RV2	0.004	0.0003	7.50	0.004-0.005
RV3	0.004	0.0006	15.00	0.004-0.005
RV4	0.012	0.0119	99.17	0.004-0.026

Table II.6. ANOVA tables for seedling survival, total height, stem diameter, total height and stem diameter growth over two growing seasons after outplanting.

Source of variation	D.F.	Mean square	F	p	Mean square	F	p	Mean square	F	p
		Initial height			Height growth between Feb '00 and July '01			Height growth between July '00 and Sept '01		
Block	4	6.06	2.04	0.097	11.98	12.85	<.0001	2.37	4.26	0.0036
Root volume category (RV)	3	276.61	93.23	<.0001	21.09	22.62	<.0001	0.05	0.09	0.9670
Fertilizer rate (FR)	4	1.72	0.58	0.6784	4.54	4.88	0.0015	0.32	0.58	0.6759
RV x FR	12	3.33	1.12	0.3565	1.57	1.68	0.0880	0.20	0.36	0.9733
Error	76	2.97			0.93			0.56		
		Height growth between Feb '00 and Sept '01			Height growth between Sept '00 and Sept '01			Height growth between Feb '00 and Sept '01		
Block	4	20.94	13.89	<.0001	500.13	10.62	<.0001	670.73	12.58	<.0001
Root volume category (RV)	3	22.15	14.70	<.0001	104.58	2.22	0.0926	180.73	3.39	0.0223
Fertilization rate (FR)	4	5.98	3.97	0.0056	354.04	7.52	<.0001	297.93	5.59	0.0005
RV x FR	12	2.08	1.38	0.1945	67.44	1.43	0.1703	78.29	1.47	0.1552
Error	76	1.51			47.1			53.34		
		Initial Stem diameter			Stem diameter in Sept '01			Stem diameter growth between Feb '00 and July '00		
Block	4	0.12	2.56	0.0449	31.21	10.82	<.0001	1.20	22.48	<.0001
Root volume category (RV)	3	15.57	328.90	<.0001	46.81	16.23	<.0001	0.16	2.96	0.0376
Fertilizaton rate (FR)	4	0.05	1.02	0.4049	23.55	8.17	<.0001	0.13	2.47	0.0517
RV x FR	12	0.05	0.97	0.4840	3.58	1.24	0.2725	0.06	1.16	0.3252
Error	76	0.05			2.88			0.05		
		Stem diameter growth between July '00 and Sept '00			Stem diameter growth between Feb '00 and Sept '00			Stem diameter growth between Sept '00 and Sept '01		
Block	4	0.51	6.34	0.0002	2.12	15.33	<.0001	19.18	9.00	<.0001
Root volume category (RV)	3	0.04	0.50	0.6833	0.30	2.15	0.1010	6.74	3.16	0.0293
Fertilizaton rate (FR)	4	0.24	3.04	0.0222	0.56	4.03	0.0051	19.09	8.96	<.0001
RV x FR	12	0.03	0.37	0.9709	0.08	0.60	0.8396	2.95	1.38	0.1929
Error	76	0.08			0.14			2.13		
		Stem diameter growth between Feb '00 and Sept '01			Survival '00			Survival '01		
Block	4	32.27	11.57	<.0001	378.62	4.41	0.0029	909.69	3.86	0.0066
Root volume category (RV)	3	9.27	3.32	0.0241	179.65	2.09	0.1079	968.04	4.11	0.0094
Fertilization rate (FR)	4	23.48	8.42	<.0001	321.99	3.75	0.0077	1624.06	6.89	<.0001
RV x FR	12	3.59	1.29	0.2428	136.00	1.59	0.1138	264.85	1.12	0.3545
Error	76	2.79			85.76			235.77		

Table II.7. ANOVA tables for seedling morphological parameters measured from a sample taken from the field 14 months after outplanting.

Source of variation	D.F.	Mean square	F	p	Mean square	F	p	Mean square	F	p
		Total height			Seasonal height			Stem diameter		
Block	4	31.10	2.07	0.0930	5.16	1.22	0.3085	2.62	3.12	0.0198
Root volume category (RV)	3	375.00	24.97	<.0001	21.18	5.02	0.0032	23.47	27.99	<.0001
Fertilization rate (FR)	4	7.50	0.50	0.7361	10.44	2.47	0.0514	0.70	0.83	0.5087
RV x FR	12	14.70	0.98	0.4770	3.63	0.86	0.5891	1.06	1.26	0.2609
Error	75	15.02			4.22			0.84		
		Diameter terminal bud			Shoot volume			Root volume		
Block	4	0.40	2.34	0.0627	216.67	1.32	0.2710	342.72	5.15	0.0010
Root volume category (RV)	3	0.89	5.25	0.0024	4128.07	25.11	<.0001	1046.08	15.73	<.0001
Fertilization rate (FR)	4	1.05	6.18	0.0002	319.11	1.94	0.1123	215.72	3.24	0.0164
RV x FR	12	0.31	1.83	0.0579	176.33	1.07	0.3950	80.14	1.21	0.2955
Error	75	0.17			164.38			66.49		
		Shoot-root ratio								
Block	4	1.12	8.94	<0.0001						
Root volume category (RV)	3	0.13	1.05	0.3759						
Fertilization rate (FR)	4	0.77	6.16	0.0002						
RV x FR	12	0.13	1.08	0.3885						
Error	75	0.12								

Table II.8. ANCOVA tables for seedling total height, stem diameter, total height and stem diameter growth over two growing seasons after outplanting.

Source of variation	D.F.	Mean square	F	p	Mean square	F	p	Mean square	F	p
		Total height in July '00			Total height in Sept '00			Total height in Sept '01		
Block	4	10.95	11.61	<.0001	20.66	13.58	<.0001	660.14	12.27	<.0001
Initial height	1	215.71	228.75	<.0001	245.27	161.21	<.0001	371.96	6.91	0.0104
Root volume category (RV)	3	5.86	6.22	0.0008	3.85	2.53	0.0635	55.41	1.03	0.3844
Fertilization rate (FR)	4	4.40	4.67	0.0020	6.08	4.00	0.0054	280.83	5.22	0.0009
RV x FR	12	1.54	1.64	0.0997	2.11	1.39	0.1903	77.43	1.44	0.1675
Error	75	0.94			1.52			53.80		
		Height growth between Feb '00 and July '00			Height growth between July '00 and Sept '00			Height growth between Feb '00 and Sept '00		
Block	4	10.95	11.61	<.0001	2.44	4.43	0.0029	20.66	13.58	<.0001
Initial height	1	0.11	0.11	0.7358	0.95	1.72	0.1933	0.42	0.27	0.6025
Root volume category (RV)	3	5.86	6.22	0.0008	0.21	0.39	0.7606	3.85	2.53	0.0635
Fertilization rate (FR)	4	4.40	4.67	0.0020	0.41	0.75	0.5637	6.08	4.00	0.0054
RV x FR	12	1.54	1.64	0.0997	0.24	0.44	0.9430	2.11	1.39	0.1903
Error	75	0.94			0.55			1.52		
		Height growth between Sept '00 and Sept '01			Height growth between Feb '00 and Sept '01			Stem diameter in July '00		
Block	4	492.71	10.36	<.0001	660.14	12.27	<.0001	1.04	20.24	<.0001
Initial height	1	13.14	0.28	0.6007	18.24	0.34	0.5622	2.20	42.66	<.0001
Root volume category (RV)	3	57.56	1.21	0.3119	55.41	1.03	0.3844	0.13	2.45	0.0699
Fertilization rate (FR)	4	335.42	7.05	<.0001	280.83	5.22	0.0009	0.10	1.93	0.1148
RV x FR	12	66.20	1.39	0.1887	77.43	1.44	0.1675	0.06	1.15	0.3345
Error	75	47.56			53.80			0.05		
		Stem diameter in Sept '00			Stem diameter in Sept '01			Stem diameter growth between Feb '00 and July '00		
Block	4	1.95	14.11	<.0001	32.47	11.54	<.0001	1.04	20.24	<.0001
Initial stem diameter	1	2.38	17.24	<.0001	8.03	2.85	0.0953	0.17	3.31	0.0730
Root volume category (RV)	3	0.12	0.88	0.4537	1.58	0.56	0.6428	0.13	2.45	0.0699
Fertilization rate (FR)	4	0.51	3.72	0.0081	23.48	8.34	<.0001	0.10	1.93	0.1148
RV x FR	12	0.08	0.55	0.8777	3.63	1.29	0.2428	0.06	1.15	0.3345
Error	75	0.14			2.81			0.05		
		Stem diameter growth between July '00 and Sept '00			Stem diameter growth between Feb '00 and Sept '00			Stem diameter growth between Sept '00 and Sept '01		
Block	4	0.51	6.28	0.0002	1.95	14.11	<.0001	19.51	9.13	<.0001
Initial stem diameter	1	0.00	0.04	0.8333	0.12	0.90	0.3456	1.67	0.78	0.3803
Root volume category (RV)	3	0.01	0.16	0.9248	0.12	0.88	0.4537	1.72	0.80	0.4954
Fertilization rate (FR)	4	0.24	3.01	0.0232	0.51	3.72	0.0081	18.96	8.87	<.0001
RV x FR	12	0.03	0.37	0.9712	0.08	0.55	0.8777	2.98	1.39	0.1881
Error	75	0.08			0.14			2.14		
		Stem diameter growth between Feb '00 and Sept '01								
Block	4	32.47	11.54	<.0001						
Initial stem diameter	1	0.88	0.31	0.5779						
Root volume category (RV)	3	1.58	0.56	0.6428						
Fertilization rate (FR)	4	23.48	8.34	<.0001						
RV x FR	12	3.63	1.29	0.2428						
Error	75	2.81								

Root-volume effects

Preplanting root volume significantly affected seedling survival at the end of the second growing season (p=0.0094) and did not affect it after the first growing season in the field (Table II.6). At the end of the second growing, seedlings in RV4 had the highest survival and those in RV3, RV2 and RV1 the lowest (Table II.9).

Similar to the results for seedling pretreatment morphology, initial field height and field stem diameter differed significantly ($p<0.0001$) among root-volume categories (Table II.6). Initial height and stem diameter of seedlings in RV4 were significantly greater than that of seedlings in RV3, RV2, and RV1, which also differed significantly from one another for both variables (Table II.9). By the end of the first and second growing seasons, seedlings in RV4 had the highest shoot height and stem diameter, although means were only statistically different for stem diameter (Table II.9). Similarly, seedlings in RV4 had the greatest height and stem diameter growth in all measuring dates, resulting in the greatest growth overall (Table II.9).

Results from the sample taken from the field in March 2001 were consistent with the data obtained by measuring the whole experiment in the field. Seedlings in RV4 had the greatest values for most of morphological attributes measured (Table II.10).

Table II.9. Means of seedling survival, total height, stem diameter, total height and stem diameter growth over two growing seasons after outplanting averaged over fertilization rate and root volume. Means in a column followed by the same letter do not significantly differ at the $\alpha \leq 0.05$ level.

Variable	Total height (cm)				Total height growth (cm)					Survival (%)
Root volume category	Initial	July '00*	Sept '00*	Sept '01*	Feb '00-July '00	July '00-Sept '00	Feb '00-Sept '00	Sept '00-Sept '01	Feb '00-Sept '01	Sept '00
RV1	27.11 a	35.87 a	37.58 a	57.84 a	5.22 a	1.48 a	6.70 a	19.38 a	26.08 a	86.32 a
RV2	29.17 b	36.82 b	38.37 a	55.91 a	6.12 b	1.45 a	7.57 b	17.16 a	24.73 a	88.80 a
RV3	31.89 c	37.58 c	38.96 a	57.63 a	6.82 c	1.45 a	8.28 c	18.94 a	27.22 ab	86.76 a
RV4	34.77 d	38.16 c	39.44 a	60.58 a	7.34 c	1.55 a	8.88 c	22.11 a	30.99 b	92.20 a
Fertilization rate (g)										
0	31.24 a	36.40 a	37.66 a	63.34 a	5.66 a	1.30 a	6.95 a	25.80 a	32.75 a	92.20 a
15	30.60 a	37.40 b	38.98 b	59.93 ab	6.67 b	1.57 a	8.24 b	20.92 b	29.16 ab	91.75 ab
30	30.75 a	37.60 b	39.01 b	57.63 bc	6.87 b	1.40 a	8.27 b	18.62 bc	26.90 bc	89.75 ab
45	30.56 a	36.90 ab	38.50 b	55.21 c	6.17 ac	1.59 a	7.75 b	16.67 bc	24.43 c	82.75 c
60	30.52 a	37.24 b	38.82 b	53.84 c	6.51 bc	1.56 a	8.07 b	14.98 c	23.05 c	86.15 bc

Variable	Stem diameter (mm)				Stem diameter growth (mm)					Survival (%)
Root volume category	Initial	July '00*	Sept '00*	Sept '01	Feb '00-July '00	July '00-Sept '00	Feb '00-Sept '00	Sept '00-Sept '01	Feb '00-Sept '01	Sept '01
RV1	4.66 a	6.20 a	6.86 a	11.24 a	0.84 a	0.63 a	1.47 a	5.11 a	6.58 a	72.96 a
RV2	5.24 b	6.42 a	7.08 a	11.70 a	0.94 ab	0.65 a	1.59 a	4.87 a	6.46 a	73.04 a
RV3	5.77 c	6.60 a	7.22 a	12.76 b	1.00 b	0.63 a	1.63 a	5.36 ab	6.99 ab	77.44 a
RV4	6.52 d	6.78 a	7.46 a	14.32 c	1.02 b	0.72 a	1.73 a	6.07 b	7.80 b	86.20 b
Fertilization rate (g)										
0	5.59 a	6.44 a	7.19 ab	14.09 a	0.88 a	0.76 ab	1.64 ab	6.86 a	8.50 a	88.45 a
15	5.51 a	6.61 a	7.40 a	13.09 ab	1.07 a	0.79 a	1.86 a	5.72 b	7.59 ab	82.75 a
30	5.49 a	6.53 a	7.15 b	12.20 bc	0.99 a	0.62 ab	1.61 b	5.09 bc	6.70 bc	79.45 a
45	5.55 a	6.47 a	7.05 b	11.66 c	0.92 a	0.58 bc	1.50 b	4.61 c	6.11 c	68.75 b
60	5.60 a	6.44 a	6.98 b	11.48 c	0.88 a	0.54 c	1.42 b	4.46 c	5.88 c	67.75 b

* Means were adjusted for initial height

Table II.10. Means of seedling morphological parameters measured from a sample taken from the field 14 months after outplanting averaged over root-volume category and fertilization rate. Means in a column followed by the same letter do not significantly differ at the $\alpha \leq 0.05$ level.

Variable	Total height (cm)	Seasonal height (cm)	Stem diameter (mm)	Diameter terminal bud (mm)	Shoot volume (cm^3)	Initial Root-volume (cm^3)	Root volume (cm^3)	Shoot-root ratio
Root volume category								
RV1	33.49 a	6.57 a	7.54 a	3.24 a	26.89 a	11.47 a	14.72 a	1.93 a
RV2	37.46 b	7.88 b	8.27 b	3.45 ab	36.76 b	15.64 b	19.01 a	2.06 a
RV3	40.44 c	8.80 b	9.22 c	3.63 b	46.06 c	20.03 c	23.84 b	1.98 a
RV4	42.56 c	8.05 b	9.73 c	3.67 b	57.34 d	26.87 d	29.97 c	2.09 a
Fertilization rate								
0	38.09 a	6.95 a	8.63 a	3.15 a	40.20 a	18.82 a	25.80 a	1.69 a
15	38.45 a	7.95 a	8.93 a	3.67 c	48.17 a	18.28 a	25.07 ab	2.05 b
30	39.43 a	8.80 a	8.80 a	3.72 c	42.21 a	18.51 a	20.33 bc	2.15 b
45	38.62 a	8.12 a	8.66 a	3.54 bc	40.90 a	18.61 a	19.27 c	2.18 b
60	37.84 a	7.30 a	8.44 a	3.40 ab	37.34 a	18.30 a	18.97 c	2.00 ab

Fertilization effects

Seedling survival differed significantly among fertilization rate treatments at the end of the first ($p=0.0077$) and second ($p<0.0001$) growing seasons (Table II.6). At the end of both growing seasons, unfertilized control seedlings survived the most but did not differ significantly from seedlings fertilized at a rate equal or less than 30g (Table II.9).

Height growth was stimulated by fertilization during the first growing season (Table II.9). Unfertilized control seedlings grew significantly less than all other fertilized treatments (Table II.9). During the second growing season, increasing fertilization rate significantly decreased seedling height growth (Table II.6), resulting in a significant height growth reduction over the two growing seasons (Table II.9).

During the first growing season, stem diameter growth was stimulated the most by fertilizing at a rate of 15g per seedling (Table II.9). As for height, increasing fertilization rate significantly reduced stem diameter growth during the second growing season, resulting in a significant stem diameter growth reduction overall (Table II.9).

Results from the sample taken during March of 2001 showed at that point no effect of fertilization on shoot height ($p=0.7361$), seasonal height ($p=0.0514$), stem diameter ($p=0.5087$) and shoot volume ($p=0.1123$) (Table II.7). Increasing fertilization rate significantly reduced seedling root volume ($p=0.0164$), affecting seedling shoot-root ratio ($p=0.0002$) (Table II.7). Shoot-root ratio was highest on seedlings fertilized with 45g and lowest on the unfertilized controls. The diameter of the terminal bud was also affected by fertilization ($p=0.0002$) (Table II.7). It was highest on seedlings fertilized with 30g and lowest on the unfertilized controls (Table II.10).

DISCUSSION

Root-volume effects

Results of this experiment were consistent with findings of other researchers (Rose et al. 1991a; Rose et al. 1991b; Haase and Rose 1993), regarding the positive correlation between preplanting root volume and other seedling morphological attributes such as stem diameter, shoot volume and seedling biomass (Table II.3). However, as Rose et al. (1997) pointed out, despite a high coefficient of determination for root volume and stem diameter (r=0.81), stem diameter by itself is insufficient criteria to assess seedling quality. Seedlings may have large diameters with small root volume and vice-versa due to root loss during lifting, handling and storing. If regeneration foresters rely only on stem diameter to separate planting stock from cull stock, seedlings with large diameters and small root volumes can be sent to outplanting.

Careful seedling handling and proper planting at the time of establishing the experiment contributed to the good survival at the end of the first growing season. Rainfall during 2001 was considerably lower than that in 2000 (Figure II.2), which may have resulted in a significant reduction in seedling survival at the end of the second growing season (Table II.9).

Consistent with results from previous studies (Rose et al. 1991a; Rose et al. 1991b; Rose et al. 1997), this experiment showed that seedling preplanting root volume is a good criterion for predicting subsequent seedling field performance. Seedlings with larger preplanting root volume had greater survival, height and stem diameter growth than seedlings with smaller preplanting root volume at the end of the first and second growing seasons (Tables II.9 and II.10). This may be explained by the fact that immediately after planting, seedlings depend on their preplanting root system for water and nutrient uptake. Seedlings with larger root systems may have be able to better tolerate transplant shock (Haase and Rose 1993) due to higher root hydraulic conductivity (Carlson 1986). As the growing season progressed and soil temperatures increased, well-planted seedlings with larger root volume may have established more quickly and started water uptake earlier in the growing season than seedlings with smaller root volume. This could result from Carlson (1986). Under a more abundant water supply, seedlings with larger root volume may have absorbed and allocated more nutrients into growth than that with smaller root volume (Haase and Rose 1994).

Fertilization effects

Although fertilized seedlings grew significantly more in height than the unfertilized controls during the first growing season (Table II.9), differences between them may not be considered biologically meaningful. The lack of a greater seedling growth response to fertilization during the first growing season could be attributed to low soil temperature and low soil moisture at the study site during the first growing season, which prevented the optimal functioning of the applied fertilizer.

The release mechanism of polymer-coated, controlled-release fertilizers is mainly temperature dependent. Nominal release periods specified by the manufacturer of the fertilizer are generally estimated at 21°C (70 °F) (Goertz 1993). Aside from the unusually high soil temperature value recorded for April 2000, likely because the sensor stayed on the soil surface for several days, maximum soil temperatures at the study site only reached an average of 21°C during August 2000 (Table II.11). At this point in time, it was estimated from a fertilizer release study established on the same site, (using the same fertilizer), that only about 30% of the initial amount of fertilizer was released (Figure II.3). Approximately 20% had been released by June when soil moisture is not yet limiting for height growth of Douglas-fir seedlings in the PNW (Lavender 1984). However, even the small amount of nutrients delivered early in the growing season was enough to establish a significant difference in total height in the fertilized seedlings relative to the unfertilized controls (Table II.9).

Table II.11. Monthly average soil temperatures at the study site and monthly rainfall at Corvallis, OR.

Date	Average soil temperature °C	Maximum soil temperature °C	Monthly rainfall (mm)
Feb-00	-	-	151
Mar-00	7.6	10.9	88
April-00	11.4	24.4	41
May-00	13.7	18.5	70
June-00	17.6	18.9	30
July-00	19.5	20.6	4
Aug-00	20.1	21.1	0
Sept-00	17.2	18.2	14
Oct-00	13.1	13.7	75
Nov-00	7.8	9	70
Dec-00	6	9.2	108
Jan-01	5.5	6.2	36
Feb-01	5.7	6.2	28
Mar-01	7.9	8.5	71
April-01	9.4	10.3	55

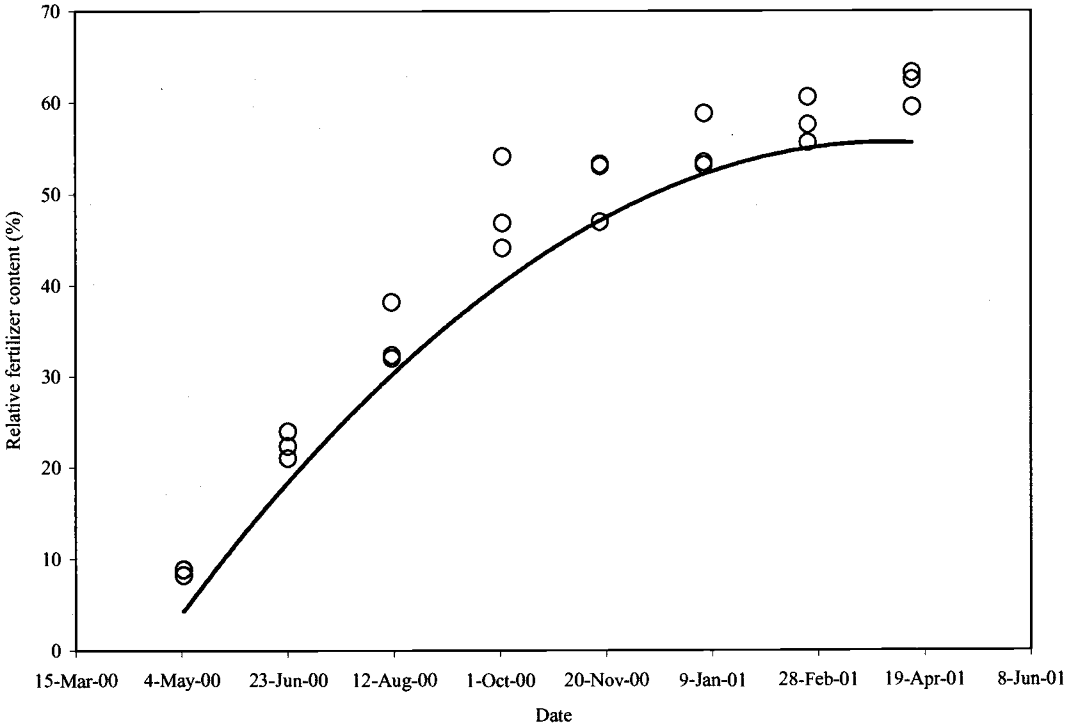

Figure II.3. Relative fertilizer release content by weight across time for the fertilizer used at the study.

Another possible explanation for the lack of biologically meaningful seedling growth response to fertilization during the first growing season in the field may be attributed to transplant shock resulting from low soil moisture. At the end of the first growing season most of the seedlings exhibited "bottle brushing" symptoms (reduced terminal growth with shortened and greater number of needles per unit leader), which are characteristics of seedlings in shock (Haase and Rose

1993). Measurements of seedling seasonal height (Table II.10) are similar to those documented by Haase and Rose (1993) when Douglas-fir seedlings were grown in 6 to 18% soil water content. Under such conditions, soil mineral nutrient uptake by the seedlings may have been considerably reduced (Haase and Rose 1994). van den Driessche (1988), when comparing the effects of different controlled-release fertilizers applied at the time of planting, reported a decrease in nutrient content of two-year-old bareroot Douglas-fir seedlings six months after planting. At the end of the first growing season his fertilization treatments had slightly higher concentrations than the unfertilized controls and little differences in growth. Similarly, Walker (1999 a, b) reported poor growth responses to fertilization at the end of the first growing season for both bareroot and containerized Jeffrey pine seedlings when using several controlled-release fertilizers applied at the time of planting in a harsh dry site in the Eastern Sierra Nevada.

At the beginning of the second growing season, increasing fertilization rate at the time of planting significantly reduced seedling root volume (Figure II.4), resulting in a significant increase in seedling shoot-root ratio by volume (Figure II.5). Due to the temperature-dependent nature of polymer-coated, controlled-release fertilizers, fertilizer prills applied in the planting hole continued releasing nutrients into the soil during the summer, fall, and winter of 2001, increasing fertilizer salt concentration at the rooting zone (Figure II.3). The low rainfall during the winter of 2001 compared to the winter of 2000 and the scarce rainfall during the summer of 2000 (Figure II.2) may also have contributed to the increase in salt concentration at the rhizosphere.

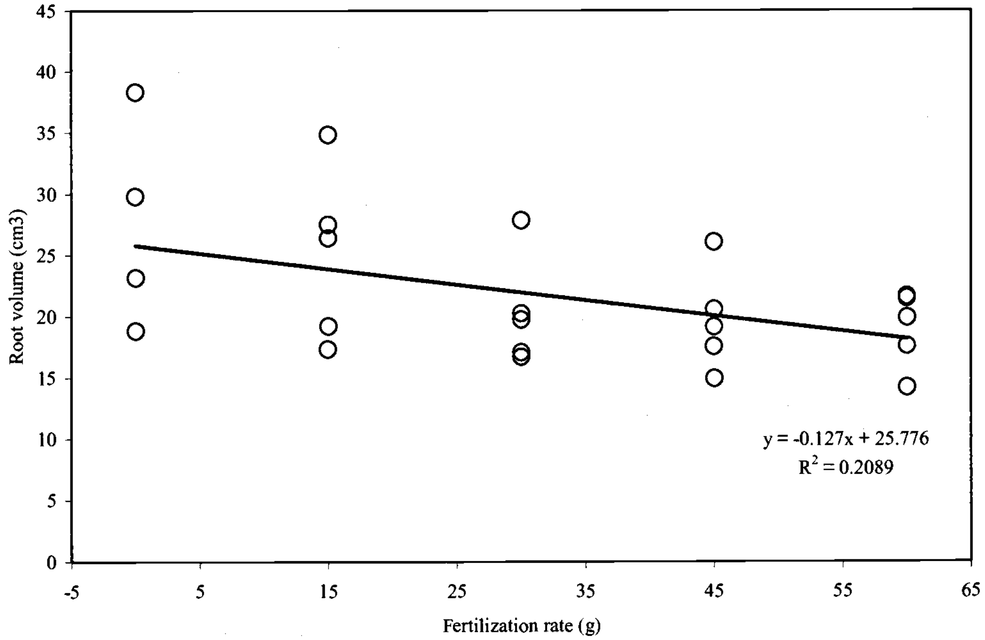

Figure II.4. Effect of fertilization rate on seedling root volume after one growing season in the field.

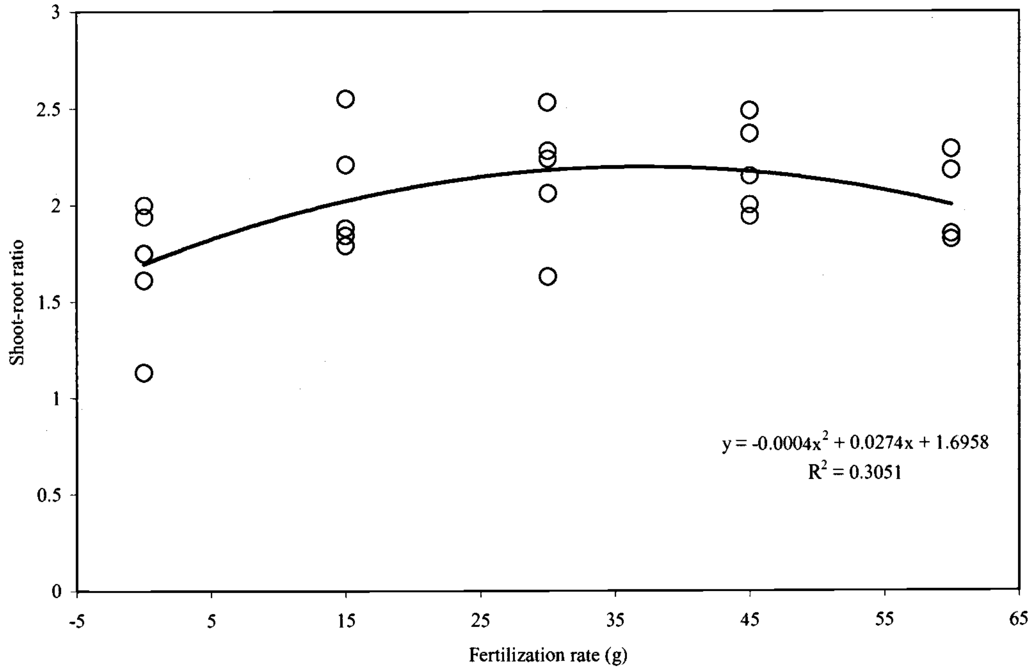

Figure II.5. Effect of fertilization rate on seedling shoot-root ratio after one growing season in the field.

Early in the second growing season (April 2001), more than 50% (by weight) of the applied fertilizer had released (Figure II.3). Nitrogen (80% of initial content), potassium (60% of initial content) and sulfur (30% of initial content) were the main macronutrients delivered to the rhizosphere. Phosphorus and magnesium were delivered at less than 20% of their initial content (Figure II.6). Applications of increasing rates of nitrogen-based, polymer-coated, controlled-release fertilizers beneath the roots of outplanted Douglas-fir seedlings may have restricted root proliferation into the lower soil zones, reducing total root-volume and increasing the shoot-root ratio. Olsthoorn et al. (1991) reported that ammonium sulfate applied to Douglas-fir seedlings at 340 kg/ha, decreased seedling root length and specific root length (ratio of root length to root dry weight) especially in soil layers with high accumulation of ammonium. They further add that, shoot dry weight was stimulated in such magnitude, that shoot-root ratio of seedlings fertilized at the highest rate was almost twice that of the unfertilized controls. Similarly, de Visser and Keltjens (1993) working with the same species reported a significant decrease in root biomass and specific root length with increasing rates of ammonium sulfate fertilizers.

All authors mention that the cause of root development modification by ammonium based fertilizers is due to an increase of aluminum and hydrogen ions concentrations in the soil solution resulting from the acidification of soils produced both by nitrification of ammonium and excretions of hydrogen ions by the plant during ammonium uptake. Unfortunately, only initial soil chemical characteristics were determined for this experiment, which prevented estimating the changes in soil characteristics after seedling fertilization. Therefore, in order to measure these changes in soil characteristics after fertilizer applications, it would be recommendable in future fertilization experiments to analyze the soils prior to and after fertilization, with emphasis on the effects of fertilization on the rhizosphere.

Jacobs (2002) also found for Douglas-fir seedlings, that lateral root dry weight and the number of active root tips beneath a layer of Osmocote Plus® fertilizer (15-9-12) with a nominal release period of 5-6 months, was significantly reduced with increasing fertilization rates, reducing seedling root dry weight and root volume overall. He attributed his results to "a localized increase in fertilizer salt concentrations" that may have increased toxic ion concentrations and damaged root apical meristems as a result of a reduction in soil osmotic potential.

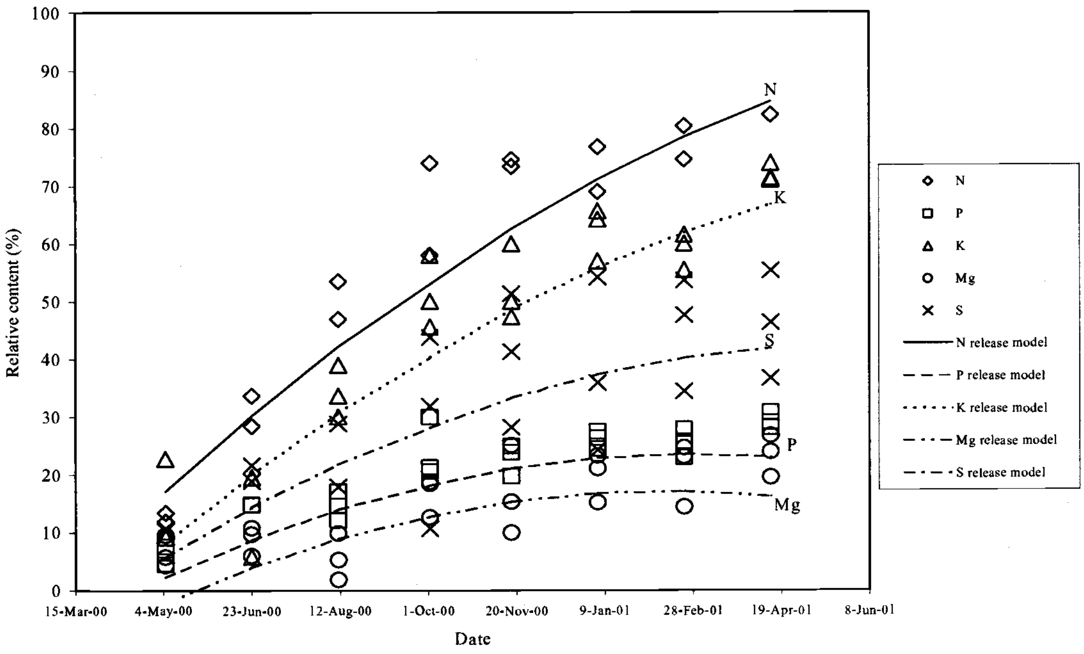

Figure II.6. Relative macronutrient release across time for the fertilizer used at the study.

Regardless of the cause for reduction in seedling root volume with increasing fertilization rate, seedlings fertilized at the highest rates had high shoot-root ratios. As the growing season progressed and soil moisture became limited, seedlings with higher shoot-root ratios were no longer be able to satisfy their transpirational water losses than those with lower shoot-root ratios. This may explain their lower survival and growth rates. Jacobs (2002), when assessing seedling physiology on a subset of seedlings in this study, found significantly higher predawn xylem water potentials and lower stomatal conductance during the summer of 2000 in seedlings fertilized at the highest rate (60g) as compared to the unfertilized controls. Similarly, de Visser and Keltjens (1996) measured higher xylem water potentials on three-year-old Douglas-fir seedlings during exposure to a two-week drought period in a pot experiment when they were fertilized with higher rates of ammonium sulfate than those fertilized at lower rates. They attributed their responses to a significant increase in shoot-root ratio with increasing applications of ammonium sulfate due to "both a stimulated shoot growth and a simultaneous hampering of root growth" as a result of soil acidification and soil osmotic potential reduction.

In my experiment since both height growth and shoot volume were not significantly affected by increasing fertilization rate at the beginning of the second growing season (Table II.10), increasing amounts of fertilizers applied to the rooting zone of 1+1 Douglas-fir seedlings may have damaged their root systems and reduced their ability to uptake water and nutrients from the soil.

CONCLUSIONS

The null hypothesis of no preplanting root volume effect on survival and morphology of 1+1 Douglas-fir seedlings at the end of two growing seasons in the field was rejected. The null hypothesis of no fertilization rate effect on survival, and morphology of 1+1 Douglas-fir seedlings at the end of two growing seasons was also rejected. The null hypothesis of no interaction effect between preplanting root volume and fertilization rate for seedling survival and morphology was not rejected.

The results from this study confirmed that preplanting root volume is a good criterion to predict initial seedling field performance after outplanting. Seedlings with the biggest preplanting root volume (RV4) had the highest survival, diameter and height growth at the end of two growing seasons in the field. Nursery growers should put emphasis in the adequate implementation of nursery management practices tending to maximize seedling root volume and minimize roots lost during seedling lifting, handling and storage. Similarly, reforestation foresters should pay special attention to using seedlings with the largest root systems and should encourage planters to take good care of seedling root systems during planting, because every unit of root biomass that is lost can retard seedling establishment by reducing their absorption surface. It is important also to keep seedling shoot-root ratio balanced. In this study, during the second growing season seedlings with excessively high shoot-root ratios, resulting probably from unbalanced nutrition, did not grow as well as those seedlings with lower shoot-root ratios.

Perhaps as a result of low soil temperatures that limited nutrient release from the fertilizers applied in this study, fertilization at the time of planting with polymer-coated, controlled-release fertilizers slightly stimulated seedling growth and reduced seedling survival at the end of the first growing season. During the second growing season, increasing fertilization rate resulted in a significant reduction of seedling survival and growth, likely due to a reduction in seedling drought resistance and root development restriction as a result of unfavorable soil chemistry.

Thus, based on results of two growing seasons, it would be recommendable to avoid the application of this type of fertilizer to the rooting zone of 1+1 Douglas-fir seedlings at the time of planting in sites with moderate to severe soil moisture limitations.

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CHAPTER III

EFFECTS OF FERTILIZER PLACEMENT AND FERTILIZATION RATE ON FIELD PERFORMANCE OF 1+1 DOUGLAS-FIR [*Pseudotsuga menziesii* (Mirb.) Franco] SEEDLINGS

ABSTRACT

To determine the combined effects of fertilizer placement and fertilization rate, Douglas-fir seedlings (1+1) grown under operational conditions at the Lava Nursery (Parkdale, OR) were planted in a recently (winter 1999) clearcut harvested Douglas-fir stand located in the west slope of the Cascades Range on February 11, 2000 using a complete randomized block design with five replicates in a factorial treatment arrangement. At the time of planting, Scott's Osmocote Plus® (15-9-11), with a release rate of 12-14 months was applied at three rates (17, 35, and 50g per seedling) using four different placements: in the hole (below the roots), dibbled to the side, in the hole (on the roots), and surface broadcast.

At the end of two growing seasons in the field, there was a significant interaction for seedling survival between fertilizer placement and fertilization rate. Survival of seedlings fertilized at the highest rate applied on the roots was the lowest (50%), while all other treatments survived between 70% and 96%. There was no effect of fertilizer placement and fertilization rate on seedling growth during

the first growing season. However, during the second growing season, seedlings fertilized on the surface and those dibbled fertilized grew the most in height and diameter. Fertilization rate reduced seedling height growth but did not affect stem diameter growth.

INTRODUCTION

Worldwide, fertilization at the time of planting has become a common silviculture practice used to increase plantation productivity by stimulating seedling growth during the initial stages of seedling establishment through the anthropogenic addition of mineral nutrients into the soil. During the 1970'and 1980's dry solids fertilizers broadcasted on the soil surface around the seedling predominated in outplanting operations (Jokela et al. 1991). Due to the rapid solubility of dry solids fertilizers, nutrients delivered by these materials were available to the seedlings only for a short period of time and could cause plant injury (Benson 1997). The development of controlled-release fertilizers, offered reforestation foresters the opportunity to supply adequate rates of nutrients through a longer period of time and to place the fertilizer closer to the seedling (Hauck 1985; Goertz 1993).

Results from several outplanting studies have suggested that the effectiveness of fertilization with controlled-release fertilizers may be influenced by the placement of the fertilizer (van den Driessche 1990). Survival and stem volume of outplanted two-year-old bareroot Douglas-fir seedlings was greater when Agriform® (20-10-5) was applied on the soil surface than buried adjacent to the seedling, whereas, Osmocote® (17-7-12) applied in an adjacent hole had greater stem volume than surface applications (van den Driessche 1988). Shoot growth of Douglas-fir seedlings grown in 25.8 cm^3 containers (15cm long) was increased when 21g of Osmocote® (17-5-11) were placed in an adjacent hole than in the planting hole (Carlson and Preisig 1981). On the other hand, when used on western hemlock seedlings grown in 65.6 cm^3 containers, 21g of Osmocote® applied in the planting hole stimulated more height and diameter growth than an adjacent placement (Carlson 1981).

Thus, this study was design to determine the fertilizer placement and fertilization rate that maximizes seedling survival and growth during the initial stages of seedling establishment. Null hypotheses tested were:

1. Fertilizer placement does not significantly affect survival, morphology, foliar nutrient concentration and content of 1+1 Douglas-fir seedlings at the end of two growing seasons in the field.

2. Fertilization rate does not significantly affect survival, morphology, foliar nutrient concentration, and foliar nutrient content of 1+1 Douglas-fir seedlings at the end of two growing seasons in the field.
3. Fertilizer placement and fertilization rate do not significantly interact for survival, morphology, foliar nutrient concentration, and foliar nutrient content of 1+1 Douglas-fir seedlings at the end of two growing seasons in the field.

MATERIALS AND METHODS

Plant material

Two-year-old (1+1) bareroot Douglas-fir seedlings from a low elevation seed source (Molalla, OR) were grown under standard practices at the Lava Nursery, Parkdale, OR, and outplanted in a complete randomized block design with five replicates. Seedling morphology and nutritional status at the time of planting are shown in Table III.1.

Treatments

Scott's Osmocote Plus® fertilizer (15-9-11) with a release rate of 12-14 months (21°C) (Table III.2) was applied to seedlings at three different rates: 17, 35 and 50g per seedling. Each of the three rates was applied to seedlings using plastic cups cut to specific size to deliver the specified amount of fertilizer. Fertilizer was applied using four placements:

1. In the hole (below the roots): Fertilizer was measured, tossed in the bottom of the planting hole, and covered by 1-2cm layer of soil. Then, the seedling was planted on top avoiding root contact with the fertilizer.
2. Dibbled to the side: The seedling was planted; the fertilizer was measured and put in a hole approximately 15 to 20cm deep adjacent to the roots of the seedling (approx. 5cm from the main stem). The fertilizer was not in contact with the root system.
3. In the hole (on the roots): The planting hole was excavated, the seedling was put in the hole and the roots were partially covered with soil leaving approximately 50% of the root system exposed. The fertilizer was applied around the roots in intimate contact with them. The planting hole was then filled with soil.
4. Surface broadcast: The seedling was planted; the fertilizer was measured and

broadcasted in a 40-50cm diameter circle around the stem of the seedling.

Table III.1. Mean, standard deviation, coefficient of variation and range for seedling pretreatment morphology and nutritional status.

Variable	Mean	Standard deviation	Coef. of variation (%)	Range
Morphology				
Total height (cm)	36.92	7.91	21.42	18.00-53.00
Stem diameter (mm)	6.46	1.24	19.20	3.73-9.07
Height-diameter ratio (cm/mm)	5.77	1.00	17.33	3.32-7.99
Shoot volume (cm^3)	32.29	12.55	38.87	8.00-61.00
Shoot-root ratio	1.86	0.46	24.73	0.94-2.92
Root volume (cm^3)	17.97	7.49	41.68	3.00-41.00
Root dry weight (g)	4.13	1.69	40.92	1.11-9.40
Stem dry weight (g)	4.35	1.99	45.75	0.99-9.58
Foliar dry weight (g)	4.28	1.48	34.58	1.27-6.68
Shoot dry weight (g)	8.55	3.24	37.89	2.32-15.60
Nutritional status				
N (%)	1.61	0.14	8.70	1.46-1.74
P (%)	0.17	0.02	11.76	0.15-0.18
K (%)	0.70	0.20	28.57	0.50-0.90
S (%)	0.17	0.03	17.65	0.14-0.19
Ca (%)	0.75	0.04	5.33	0.71-0.78
Mg (%)	0.14	0.02	14.29	0.13-0.16
Na (%)	0.05	0.02	40.00	0.04-0.07
B (ppm)	36.10	6.43	17.81	31.90-43.50
Zn (ppm)	45.67	4.51	9.88	41.00-50.00
Mn (ppm)	90.67	3.51	3.87	87.00-94.00
Fe (ppm)	693.00	447.94	64.64	421.00-1210.00
Cu (ppm)	9.33	0.58	6.22	9.00-10.00

Table III.2. Nutrient composition (%) of Osmocote® Plus (15-9-12).

Nutrient	%
Total nitrogen	15.0
NH_4	7.0
NO_3	8.0
Phosphorus (P_2O_5)	9.0
Potassium (K_2O)	12.0
Mg	1.0
S	2.3
B	0.02
Cu	0.05
Fe	0.45
Mn	0.06
Mo	0.02
Zn	0.05

Planting site

The experiment was established in a recently (winter 1999) clearcut, harvested of Douglas-fir (site index 119) owned by Willamette Industries, located approximately 35 miles northeast of Corvallis, OR on the west slope of the Cascades Range. The site has a slope of 13% and an elevation of 690'. The soils belong to the Hazelair series and are deep, well-drained, silty clay loams. Prior to planting, the site was broadcast burned to remove slash and vegetation. Applications of Transline® and Oust® were made during the summer of 2000. Figure III.1 shows monthly rainfall in Corvallis, OR during the study period.

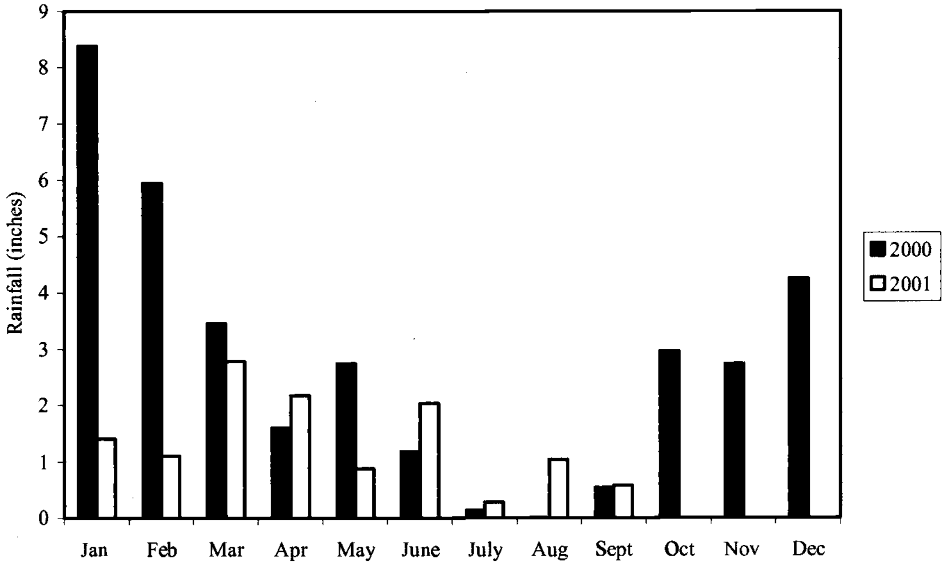

Figure III.1. Monthly rainfall in Corvallis, OR during the study period.

Planting

Seedlings were planted on February 11, 2000. Before planting, the site was laid out with color-coded pin flags; one per seedling at each planting hole. Planting was done by a trained crew at a 10' x 10' spacing. Each planter planted a variety of treatments to avoid confounding. A tagged wire pin was placed next to each seedling identifying its block and treatment.

Data collection

At the time of planting, 59 seedlings were randomly selected and brought to OSU for measurements of height, stem diameter, shoot and root volume. Seedlings were dried for 48 hours at 68°C. Root, stem, foliar, and total dry weight were determined on each. The foliage was then ground and combined into three composite samples (5 seedlings each) for determination of initial foliar nutrient concentration and content. Foliar nutrient content was determined by multiplying foliar nutrient concentration by the dry weight of 100 needles.

Three weeks after planting, initial height and stem diameter were measured in the field. Additional field measurements of height and stem diameter were taken in June, August, December 2000, and September 2001. Since patterns of mortality were evident early in the growing season, seedling survival was assessed in May 2000 in addition to each of the measuring dates. Instances of browsing, chlorosis, frost damage, dead tops, and browning were also recorded during the growing season.

At the beginning of the second growing season, before seedlings broke bud (March 2001), three randomly selected seedlings per treatment per block were excavated and taken to the laboratory to perform a morphological assessment on them. Measurements of total height, seasonal height, stem diameter, crown length, field needle length, field needle density, lateral length, current lateral length, root volume, and shoot volume were made on each. Crown length represents the length from the lowest whorl with live branches, at least in two quadrants, to the tip of the terminal bud. Field needle length was estimated averaging the length of the five longest needles on the current leader. Counting the number of needles in a 2.54 cm current leader stem segment and then dividing that number by 2.54 calculated field needle density. Lateral length was estimated by averaging the length of the six longest laterals. Current lateral length was determined by averaging the length of the current laterals on the six longest laterals.

After characterizing seedling morphology, each seedling was dissected into five components and dried at 65 °C for 48 h and weighted. The components were field-grown needles, nursery-grown needles, field-grown stems, nursery-grown stems, and roots.

Field grown needles were then ground and combined into a composite sample (3 seedlings each) for determination of foliar nutrient concentration and content. Foliar nutrient content was determined by multiplying foliar nutrient concentration by the dry weight of 33 needles.

Statistical analysis

A two-way factorial analysis of variance (ANOVA) was used to determine significant differences among fertilizer placements and fertilization rates. When a significant interaction effect was detected, individual treatment means were compared otherwise means of the main effects fertilizer placement and fertilization rate were compared. Residuals were examined to check the equal variance assumption among treatments. Normal probability plots were examined to check the normality assumption. Tukey's studentized range test was used to determine significant differences among treatment means at the $\alpha \leq 0.05$ level.

RESULTS

Survival

There was a significant interaction effect ($p<0.05$) between fertilizer placement and fertilization rate for seedling survival on all measuring dates (Table III.3). Seedlings fertilized at the highest rate (50 g) applied on the roots had significantly lower survival than all other treatments on all measuring dates (Table III.4).

The analysis of variance F-test showed no interaction effect between fertilization rate and fertilizer placement for all other variables except for nursery needle dry weight; therefore the effects of fertilizer placement averaged over fertilization rate were compared, and vice versa.

Table III.3. ANOVA tables for seedling survival, total height, stem diameter, total height and stem diameter growth over two growing seasons after outplanting.

Source of variation	D.F.	Mean square	F	p	Mean square	F	p	Mean square	F	p
		Survival in May '00			Survival in June '00			Survival in July '00		
Block	4	4.77	0.27	0.8937	18.06	0.56	0.6916	67.48	1.09	0.3712
Fertilizer placement (FP)	3	91.79	5.26	0.0034	115.16	3.58	0.0211	399.60	6.48	0.0010
Fertilization rate (FR)	2	74.02	4.24	0.0207	125.02	3.89	0.0279	348.35	5.65	0.0065
FP x FR	6	85.79	4.92	0.0006	147.57	4.59	0.0011	367.02	5.95	0.0001
Error	44	17.45			32.15			61.66		
		Survival in Aug '00			Survival in Dec '00			Survival in Sept '01		
Block	4	251.06	2.33	0.0703	394.21	3.05	0.0265	473.98	3.39	0.0168
Fertilizer placement (FP)	3	785.44	7.30	0.0004	1098.24	8.50	0.0001	1225.71	8.76	0.0001
Fertilization rate (FR)	2	550.12	5.11	0.0101	823.32	6.37	0.0037	1054.47	7.54	0.0015
FP x FR	6	417.61	3.88	0.0034	598.29	4.63	0.0010	561.44	4.01	0.0027
Error	44	107.56			129.19			139.91		
		Initial height			Total heigth in June '00			Total height in Aug '00		
Block	4	59.83	3.37	0.0173	44.74	2.11	0.0950	31.25	1.36	0.2619
Fertilizer placement (FP)	3	31.53	1.77	0.1659	25.26	1.19	0.3231	40.75	1.78	0.1651
Fertilization rate (FR)	2	10.97	0.62	0.5439	9.10	0.43	0.6532	15.35	0.67	0.5168
FP x FR	6	14.62	0.82	0.5584	18.64	0.88	0.5169	20.64	0.90	0.5028
Error	44	17.76			21.16			22.91		
		Total height in Dec '00			Total height in Sept '01			Total height growth 2000		
Block	4	33.58	1.44	0.2358	60.09	1.15	0.3444	12.19	1.75	0.1555
Fertilizer placement (FP)	3	51.62	2.22	0.0993	158.23	3.04	0.0389	2.58	0.37	0.7742
Fertilization rate (FR)	2	18.17	0.78	0.4642	141.98	2.72	0.0766	14.13	2.03	0.1433
FP x FR	6	20.89	0.90	0.5049	107.11	2.06	0.0782	5.72	0.82	0.5591
Error	44	23.26			52.11			6.96		
		Total height growth 2001			Cumulative height growth			Initial diameter		
Block	4									
Fertilizer placement (FP)	3	50.09	1.06	0.3897	106.59	1.64	0.1812	0.93	3.47	0.0150
Fertilization rate (FR)	2	323.37	6.82	0.0007	283.25	4.36	0.009	0.33	1.23	0.3097
FP x FR	6	228.80	4.82	0.0128	132.03	2.03	0.1432	0.02	0.09	0.9121
Error	44	48.10	1.01	0.4287	83.76	1.29	0.2821	0.21	0.80	0.5781
		47.44			64.99			0.27		
		Stem diameter in June '00			Stem diameter in Aug '00			Stem diameter in Dec '00		
Block	4	0.66	1.72	0.1632	0.84	1.59	0.1943	0.83	1.10	0.3691
Fertilizer placement (FP)	3	0.41	1.07	0.3735	0.66	1.25	0.3023	0.88	1.16	0.3342
Fertilization rate (FR)	2	0.26	0.68	0.5097	0.44	0.83	0.4435	0.54	0.72	0.4945
FP x FR	6	0.52	1.37	0.2492	0.50	0.94	0.4733	0.53	0.69	0.6564
Error	44	0.38			0.53			0.76		
		Stem diameter in Sept '01			Stem diameter growth 2000			Stem diameter growth 2001		
Block	4	8.32	5.62	0.0010	1.66	3.84	0.0092	8.45	8.78	<.0001
Fertilizer placement (FP)	3	2.15	1.45	0.2412	0.57	1.31	0.2831	4.64	4.81	0.0055
Fertilization rate (FR)	2	2.11	1.42	0.2519	0.35	0.82	0.4475	4.79	4.97	0.0113
FP x FR	6	2.01	1.36	0.2532	0.46	1.06	0.4010	1.20	1.25	0.3010
Error	44	1.48			0.43			0.96		
		Cumulative stem diameter growth								
Block	4	7.87	5.69	0.0009						
Fertilizer placement (FP)	3	3.47	2.5	0.0715						
Fertilization rate (FR)	2	2.56	1.85	0.1699						
FP x FR	6	1.96	1.42	0.2290						
Error	44	1.39								

Table III.4. Means of seedling survival over two growing seasons after outplanting. Means in a column follwed by the same letter do not significantly differ at the $\alpha \leq 0.05$ level.

Variable		Survival (%)					
		May '00	June '00	July '00	Aug '00	Dec '00	Sept '01
Fertilizer							
Placement	Rate (g)						
Roots	17	99.0 a	99.0 a	96.0 ab	93.0 ab	91.0 ab	91.0 a
	35	96.0 a	96.0 ab	93.0 ab	83.8 ab	79.8 bc	73.8 bc
	50	85.0 b	82.0 c	67.0 c	59.0 c	51.4 d	50.4 d
Hole	17	97.8 a	97.8 a	95.8 ab	92.8 ab	87.8 ab	86.8 ab
	35	96.0 a	90.0 b	87.0 b	81.6 b	73.4 c	70.4 c
	50	99.0 a	99.0 a	93.0 ab	90.0 ab	88.0 ab	87.0 ab
Surface	17	100.0 a	100.0 a	97.0 ab	95.0 a	94.0 a	93.8 a
	35	96.0 a	96.0 ab	92.0 ab	88.0 ab	84.6 abc	84.6 ac
	50	100.0 a	99.0 a	97.0 ab	93.0 ab	92.0 ab	90.0 a
Dibbled	17	100.0 a	99.0 a	99.0 a	97.0 a	97.0 a	96.0 a
	35	96.0 a	96.0 ab	94.0 ab	93.0 ab	93.0 a	92.0 a
	50	99.0 a	99.0 a	98.0 a	96.0 a	90.0 ab	87.0 ab

Fertilizer placement effects on seedling morphology

Shoot height, stem diameter, height and stem diameter growth were not affected by fertilizer placement during the first growing season ($p>0.05$) (Table III.3). However, seedlings fertilized on the roots tended to have slightly higher values for these parameters (Table III.5).

Table III.5. Means of seedling total height, stem diameter, total height and stem diameter growth over two growing seasons after outplanting averaged over fertilizer placement and fertilization rate. Means in a column followed by the same letter do not significantly differ at the $\alpha \leq 0.05$ level.

Date	Mar '00	June '00	Aug '00	Dec '00	Sept '01	2000	2001	Cumulative
Variable			Total height (cm)				Height growth (cm)	
Fertilizer placement								
Dibbled	32.03 a	38.50 a	40.38 a	41.02 a	65.43 a	8.99 a	24.41 a	33.40 a
Surface	32.37 a	38.81 a	40.88 a	41.32 a	65.44 a	8.95 a	24.12 a	33.08 a
Hole	32.83 a	39.32 a	41.28 a	41.80 a	59.46 b	8.97 a	17.66 b	26.62 b
Roots	35.24 a	41.38 a	44.06 a	45.03 a	60.22 ab	9.80 a	15.18 b	24.98 b
Fertilization rate (g)								
17	33.72 a	39.72 a	41.66 a	42.04 a	65.32 a	8.32 a	23.28 a	31.60 a
35	32.29 a	38.75 a	40.77 a	41.49 a	62.60 ab	9.20 a	21.11 a	30.31 a
50	33.34 a	40.04 a	42.52 a	43.35 a	59.99 b	10.00 a	16.65 b	26.65 a
Variable			Stem diameter (mm)				Stem diameter growth (mm)	
Fertilizer placement								
Dibbled	5.94 a	7.36 a	8.19 a	8.79 a	13.08 a	2.84 a	4.29 a	7.14 a
Surface	5.88 a	7.30 a	8.21 a	8.84 a	12.43 a	2.95 a	3.59 ab	6.55 a
Hole	6.11 a	7.49 a	8.13 a	8.71 a	12.45 a	2.60 a	3.74 a	6.34 a
Roots	6.20 a	7.68 a	8.59 a	9.25 a	12.19 a	3.05 a	2.94 b	5.99 a
Fertilization rate (g)								
17	6.01 a	7.41 a	8.14 a	8.72 a	12.89 a	2.71 a	4.17 a	6.88 a
35	6.03 a	7.38 a	8.26 a	8.93 a	12.48 a	2.90 a	3.56 ab	6.46 a
50	6.07 a	7.59 a	8.44 a	9.05 a	12.25 a	2.97 a	3.20 b	6.17 a

Results obtained from the field were consistent with results obtained from a sample of seedlings at the beginning of the second growing season prior bud break. Although significant only for lateral length (p=0.0271), current lateral length (p=0.0202), field stem dry weight (p=0.0165), nursery stem dry weight (p=0.0122) and shoot dry weight (p=0.0250) (Table III.6), seedlings fertilized on the roots tended to have the highest values for all seedling morphological attributes and those dibble fertilized the lowest (Table III.7 and III.8).

Table III.6. ANOVA tables for seedling morphological parameters measured 13 months after outplanting.

Source of variation	D.F.	Mean square	F	p	Mean square	F	p	Mean square	F	p
		Total height			Seasonal height			Stem diameter		
Block	3	25.81	0.98	0.4141	6.78	0.70	0.5609	1.39	1.04	0.3862
Fertilizer placement (FP)	3	65.73	2.50	0.0770	5.99	0.62	0.6100	3.06	2.29	0.0961
Fertilization rate (FR)	2	52.52	1.99	0.1523	2.97	0.31	0.7386	1.01	0.76	0.4754
FP x FR	6	23.66	0.90	0.5080	1.08	0.11	0.9946	0.73	0.55	0.7682
Error	33	26.34			9.73			1.33		
		Shoot volume			Root volume			Shoot-root ratio		
Block	3	440.64	1.29	0.2947	209.15	1.45	0.2465	0.49	5.31	0.0043
Fertilizer placement (FP)	3	913.03	2.67	0.0636	87.94	0.61	0.6139	0.19	2.06	0.1247
Fertilization rate (FR)	2	157.42	0.46	0.6351	22.46	0.16	0.8566	0.21	2.29	0.1171
FP x FR	6	85.33	0.25	0.9561	84.16	0.58	0.7414	0.12	1.27	0.2995
Error	33	342.03			144.41			0.09		
		Crown length			Lateral length			Current lateral length		
Block	4	67.96	2.43	0.0620	12.45	3.36	0.0175	4.12	2.34	0.0694
Fertilizer placement (FP)	3	72.55	2.59	0.0647	12.44	3.36	0.0271	6.37	3.62	0.0202
Fertilization rate (FR)	2	102.62	3.66	0.0337	8.35	2.25	0.1170	0.02	0.01	0.9912
FP x FR	6	37.53	1.34	0.2601	0.93	0.25	0.9569	1.55	0.88	0.5171
Error	44	28.01			3.71			1.76		
		Field needle dry weight			Nursery needle dry weight			Field stem dry weight		
Block	4	6.18	2.02	0.1082	0.86	3.67	0.0115	3.16	2.39	0.0651
Fertilizer placement (FP)	3	5.07	1.66	0.1901	0.85	3.62	0.0203	5.02	3.80	0.0165
Fertilization rate (FR)	2	0.59	0.19	0.8241	1.26	5.40	0.0080	0.20	0.15	0.8608
FP x FR	6	0.69	0.23	0.9660	0.71	3.03	0.0145	0.52	0.39	0.8788
Error	44	3.06			0.23			1.32		
		Nursery stem dry weight			Shoot dry weight			Root dry weight		
Block	4	20.43	2.54	0.0532	83.49	2.91	0.0322	46.63	2.34	0.0703
Fertilizer placement (FP)	3	32.81	4.08	0.0122	98.55	3.43	0.0250	17.88	0.90	0.4512
Fertilization rate (FR)	2	7.55	0.94	0.3992	22.88	0.80	0.4572	5.38	0.27	0.7649
FP x FR	6	2.81	0.35	0.9068	7.91	0.28	0.9456	8.89	0.45	0.8443
Error	44	8.05			28.72			19.97		

During the second growing season, fertilizer placement significantly affected shoot height (p=0.0389), height (p=0.0007) and stem diameter growth (p=0.0113) and cumulative height growth (p=0.009) (Table III.3). Seedling dibble fertilized had the highest values for all morphological parameters measured in the field and in general those fertilized on the roots the lowest (Table III.5).

Table III.7. Means of seedling morphological parameters measured from a sample taken from the field 13 months after outplanting averaged over fertilizer placement and fertilization rate. Means in a column followed by the same letter do not significantly differ at the $\alpha \leq 0.05$ level.

Variable	Total height (cm)	Height growth (cm)	Stem diameter (mm)	Shoot volume (cm3)	Root volume (cm3)	Shoot-root ratio	Crown length (cm)	Lateral length (cm)	Current lat.length (cm)
Fertilizer placement									
Dibbled	41.14 a	8.51 a	9.86 a	50.83 a	32.89 a	1.61 a	38.16 a	13.11 b	5.07 b
Surface	45.11 a	9.18 a	10.84 a	63.28 a	35.64 a	1.80 a	41.71 a	13.97 ab	6.22 a
Hole	44.06 a	9.69 a	10.50 a	60.56 a	34.36 a	1.81 a	39.36 a	14.30 ab	6.12 a
Roots	46.69 a	10.16 a	11.00 a	72.01 a	39.22 a	1.92 a	43.00 a	15.31 a	6.59 a
Fertilization rate (g)									
17	45.04 a	9.27 a	10.54 a	62.67 a	36.83 a	1.76 a	41.22 ab	14.51 a	6.03 a
35	42.18 a	9.03 a	10.30 a	58.16 a	35.23 a	1.69 a	38.03 b	13.43 a	5.98 a
50	45.53 a	9.86 a	10.81 a	64.19 a	34.52 a	1.91 a	42.42 a	14.58 a	5.99 a

Table III.8. Means of seedling dry weights of seedling morphological components averaged over fertilizer placement and fertilization rate. Means in a column followed by the same letter do not significantly differ at the $\alpha \leq 0.05$ level.

Variable	Field needle dry weight (g)	Field stem dry weight (g)	Nursery stem dry weight (g)	Shoot dry weight (g)	Root dry weight (g)
Fertilizer placement					
Dibbled	4.57 a	2.24 b	8.61 b	16.63 b	11.98 a
Surface	5.49 a	2.87 ab	10.34 ab	20.14 ab	12.65 a
Hole	5.34 a	3.01 ab	10.09 b	19.33 ab	12.59 a
Roots	5.97 a	3.65 a	12.22 a	22.86 a	14.50 a
Fertilization rate (g)					
17	5.40 a	2.95 a	10.73 a	20.50 a	13.52 a
35	5.15 a	2.84 a	9.61 a	18.52 a	12.72 a
50	5.48 a	3.04 a	10.60 a	20.20 a	12.55 a

Fertilizer placement effects on seedling nutrition

Fertilizer placement significantly affected nitrogen (p<0.0001), phosphorus (p=0.0498), potassium (p<0.0001), magnesium (p=0.0178), calcium (p=0.0194), copper (p=0.0023), boron (p<0.0001), zinc (p<0.0001) foliar concentration (Table III.9), and nitrogen (p<0.0001), calcium (p=0.0052), manganese (p=0.0335), and zinc (p=0.0056) foliar content (Table III.10).

Table III.9. ANOVA tables for seedling foliar nutrient concentration.

Source of variation	D.F.	Mean square	F	p	Mean square	F	p	Mean square	F	p
		N concentration			P concentration			K concentration		
Block	4	0.2	1.17	0.3352	0.0019	1.84	0.1371	0.012	4.17	0.0055
Fertilizer placement (FP)	3	5.75	33.96	<0.0001	0.003	2.8	0.0498	0.03	11.12	<0.0001
Fertilization rate (FR)	2	1.25	7.35	0.0016	0.0033	3.14	0.0523	0.009	2.96	0.0613
FP x FR	6	0.32	1.90	0.0995	0.0009	0.8	0.5765	0.005	1.66	0.1498
Error	44	0.17			0.0011			0.003		
		Ca concentration			Mg concentration			S concentration		
Block	4	0.008	2.15	0.0884	0.0004	0.53	0.7138	0.0009	0.57	0.6822
Fertilizer placement (FP)	3	0.014	3.62	0.0194	0.0024	3.7	0.0178	0.0029	1.98	0.1298
Fertilization rate (FR)	2	0.003	0.68	0.509	0.0003	0.4	0.6724	0.0019	1.28	0.287
FP x FR	6	0.005	1.19	0.3263	0.0004	0.59	0.738	0.0003	0.22	0.9695
Error	44	0.004			0.0007			0.0015		
		Mn concentration			Fe concentration			Cu concentration		
Block	4	16863	1.36	0.2604	329343	33.12	<0.0001	5.63	5.4	0.0011
Fertilizer placement (FP)	3	24971	2.02	0.1235	17280	1.74	0.1715	5.79	5.56	0.0023
Fertilization rate (FR)	2	20318	1.64	0.204	15604.00	1.57	0.2185	0.62	0.6	0.555
FP x FR	6	7980	0.65	0.6937	10505	1.06	0.4013	1.59	1.52	0.1908
Error	44	12371			9943			1.04		
		B concentration			Zn concentration					
Block	4	35.5	0.66	0.6195	166.00	2.37	0.0653			
Fertilizer placement (FP)	3	694.32	13	<0.0001	618.00	8.83	<0.0001			
Fertilization rate (FR)	2	71.81	1.34	0.2701	233.00	3.33	0.0439			
FP x FR	6	104.19	1.95	0.0912	27.00	0.39	0.8813			
Error	44	53.41			70.00					

Table III.10. ANOVA tables for seedling foliar nutrient content.

Source of variation	D.F.	Mean square	F	p	Mean square	F	p	Mean square	F	p
		N content			P content			K content		
Block	4	0.0067	1.52	0.21	0.00005	4.95	0.002	0.00031	4.46	0.0038
Fertilizer placement (FP)	3	0.0739	16.75	<0.0001	0.00001	0.56	0.6455	0.00	1.39	0.2577
Fertilization rate (FR)	2	0.0036	0.83	0.4403	0.00003	3.63	0.0338	0.00014	2.03	0.1418
FP x FR	6	0.0032	0.73	0.6246	0.00002	1.96	0.089	0.00008	1.19	0.3282
Error	44	0.0044			0.00001			0.00007		
		Ca content			Mg content			S content		
Block	4	0.00018	3.54	0.0128	0.000007	1.57	0.1959	0.00004	1.93	0.1208
Fertilizer placement (FP)	3	0.00024	4.80	0.0052	0.000011	2.39	0.0801	0.00006	2.73	0.0541
Fertilization rate (FR)	2	0.00013	2.43	0.099	0.000008	1.67	0.1984	0.00003	1.26	0.2926
FP x FR	6	0.00006	1.2	0.3241	0.000005	1.15	0.3471	0.00003	1.17	0.336
Error	44	0.00005			0.000005			0.00002		
		Mn content			Fe content			Cu content		
Block	4	208	2.07	0.0991	1865	22.84	<0.0001	0.038	4.43	0.0039
Fertilizer placement (FP)	3	315	3.14	0.0335	145	1.77	0.1652	0.019	2.15	0.1056
Fertilization rate (FR)	2	159	1.58	0.2159	23.00	0.28	0.7603	0.006	0.71	0.4943
FP x FR	6	132	1.31	0.2695	56	0.68	0.6646	0.006	0.69	0.6612
Error	44	100			82			0.009		
		B content			Zn content					
Block	4	0.7	1.07	0.3828	2.16	3.34	0.0170			
Fertilizer placement (FP)	3	8.16	12.49	<0.0001	3.05	4.73	0.0056			
Fertilization rate (FR)	2	1.03	1.58	0.2164	2.00	3.09	0.0544			
FP x FR	6	1.52	2.32	0.0470	0.32	0.49	0.8116			
Error	44	0.65			0.65					

Seedlings fertilized on the roots had on average 25%, 46% and 77% more nitrogen content in their foliage than those fertilized in the bottom of the planting hole, on the surface and dibble fertilized, respectively (Table III.11).

Table III.11. Means of seedling nutrient concentration and content averaged over fertilizer placement and fertilization rate. Means in a column followed by the same letter do not significantly differ at the $\alpha \leq 0.05$ level.

Nutrient	N	P	K	Mg	S	Ca	Mn	Fe	Cu	B*	Zn
						Nutrient concentration					
	(%)	(%)	(%)	(%)	(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Fertilizer placement											
Dibbled	2.926 c	0.163 b	0.503 b	0.120 b	0.194 a	0.394 a	242 a	358 a	4.764 b	30 bc	29 b
Surface	3.093 c	0.156 ab	0.499 b	0.129 b	0.221 a	0.456 b	215 a	342 a	4.818 b	26 c	32 b
Hole	3.555 b	0.137 a	0.420 a	0.115 ab	0.190 a	0.431 ab	302 a	378 a	4.262 ab	32 b	22 a
Roots	4.232 a	0.134 a	0.422 a	0.101 a	0.203 a	0.401 a	278 a	302 a	3.578 a	40 a	19 a
Fertilization rate (g)											
17	3.193 a	0.162 a	0.486 a	0.114 a	0.210 a	0.423 a	292 a	326 a	4.510 a	34 a	29 a
35	3.522 b	0.142 a	0.446 a	0.115 a	0.203 a	0.409 a	252 a	375 a	4.409 a	32 a	24 b
50	3.640 b	0.139 a	0.450 a	0.120 a	0.192 a	0.429 a	234 a	334 a	4.148 a	30 a	23 b
						Nutrient content (g / 33 needles)					
Fertilizer placement											
Dibbled	0.204 c	0.011 a	0.035 a	0.008 a	0.014 a	0.027 b	17.10 b	24.53 a	0.327 ab	2.047	2.056 ab
Surface	0.247 bc	0.013 a	0.040 a	0.010 a	0.018 a	0.036 a	17.21 b	26.66 a	0.380 b	2.047	2.612 b
Hole	0.288 b	0.011 a	0.034 a	0.009 a	0.015 a	0.035 a	24.93 a	31.42 a	0.351 ab	2.617	1.807 a
Roots	0.361 a	0.012 a	0.036 a	0.009 a	0.018 a	0.035 a	24.44 a	25.37 a	0.303 a	3.495	1.624 a
Fertilization rate (g)											
17	0.266 a	0.013 a	0.039 a	0.009 a	0.017 a	0.035 a	23.97 a	25.86 a	0.360 a	2.797	2.375 a
35	0.268 a	0.011 b	0.034 a	0.008 a	0.016 a	0.030 a	19.36 a	27.36 a	0.324 a	2.459	1.828 a
50	0.291 a	0.011 b	0.036 a	0.010 a	0.015 a	0.035 a	19.43 a	27.76 a	0.336 a	2.398	1.872 a

* The interaction between fertilizer placement and fertilization rate was significant for Boron content

Fertilization rate effects on seedling morphology

Although fertilization rate was nonsignificant during the first growing season, increasing fertilization rate tended to increase height and diameter growth (Table III.5). As for fertilizer placement, results obtained from the sample taken at the beginning of the second growing season prior bud break, were consistent with the results obtained from the field. Fertilization rate significantly affected only seedling crown length (p=0.0337) (Table III.6). Crown was longest on seedlings fertilized at the highest rate (50g) and lowest on those seedlings fertilized at the medium rate (35g) (Table III.7). Although nonsignificant, increasing fertilization rate tended to decrease root volume and root dry weight (Table III.7). There was a significant interaction effect (p=0.0145) between fertilizer placement and fertilization rate for nursery needle dry weight (Table III.6). Nursery needles of seedlings fertilized with 17g broadcasted at the surface were the heaviest and those fertilized with 35g applied on the roots the lightest (Figure III.2).

During the second growing season, increasing fertilization rate resulted in a significant decrease in height (p=0.0128) and stem diameter growth (p=0.0113) (Table III.3).

Fertilization rate effects on seedling nutrition

Increasing fertilization rate significantly increased nitrogen foliar concentration (p=0.0016) and significantly reduced zinc foliar concentration (p=0.0439) (Table III.9), and phosphorus foliar content (p=0.0338) (Table III.10). Both nutrient concentration and nutrient content of all other elements analyzed in this experiment were not significantly affected by fertilization rate (Table III.9 and III.10).

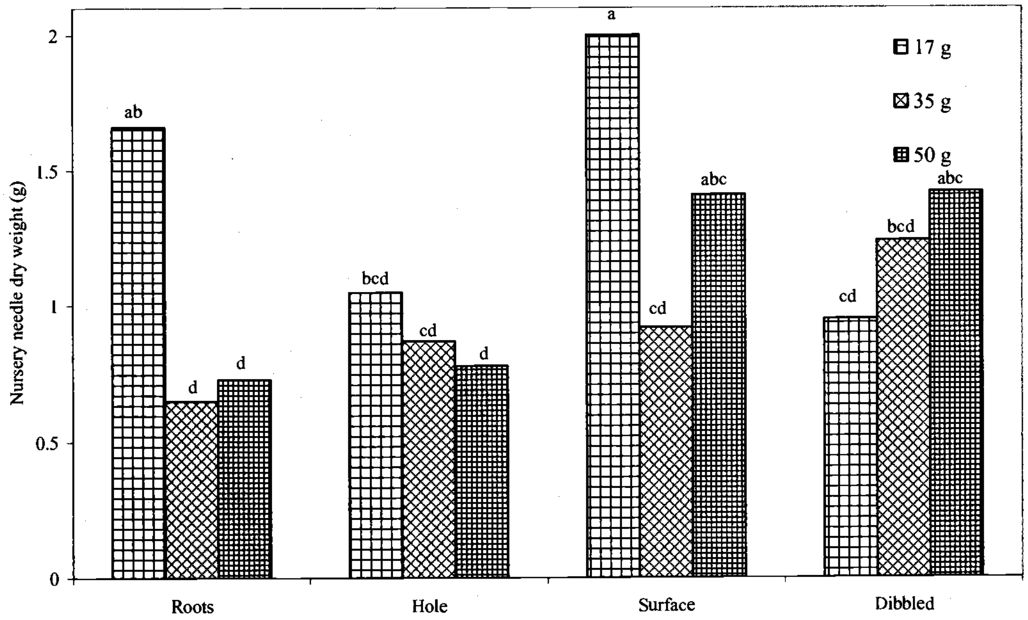

Figure III.2. Effect of fertilizer placement and fertilization rate on nursery needle dry weight, measured 13 months after outplanting. Means followed by the same letter do not significantly differ at the $\alpha \leq 0.05$ level.

DISCUSSION

Since good care was taken at the time of planting and implementing the treatments at the study site, seedling performance may be attributed mainly to treatment effects and site conditions during the study period.

Low survival of seedlings fertilized at 35g and 50g on the roots may have been the result of high salt concentration in the rhizosphere increased by low soil moisture and high soil temperatures. Walker (1999a, 1999b) reported significant reductions in seedling survival both for bareroot and containerized Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.) seedlings after fertilization with 30g of different temperature-dependent, controlled-release fertilizers in a xeric site in the Eastern Sierra Nevada. High salt concentrations in the rhizosphere may result in low soil water potentials that may lead to water stress (Brockley 1988).

Fertilizer placement effects

Although nonsignificant, initially, shoot height was greatest in seedlings fertilized on the roots. This may be explained by the planting technique used to implement this treatment. To apply the fertilizer, seedlings were half planted leaving the roots partially exposed, and then the fertilizer was placed on the roots and covered with soil. It is reasonable to believe that seedlings in this treatment were planted less deep than all other fertilizer placement treatments. This illustrates a crucial control that must be exercised on future fertilization studies in order to avoid confounding.

Despite having been planted shallower, fertilization on the roots tended to stimulate seedling growth more than all other fertilizer placement treatments during the first growing season (Table III.5, III.7 and III.8). Carlson and Preisig (1981) reported that significantly more biomass accumulated in the stem and lateral branches of Douglas-fir plug seedlings when Osmocote® (17-5-11) and Agriform® (22-8-2) were applied in the planting hole compared to an adjacent hole. Similarly, shoot height growth of western hemlock was stimulated more when 21g of Osmocote® (17-5-11) were applied in the planting hole than in an adjacent hole (Carlson 1981).

Nitrogen uptake by the seedlings was significantly stimulated by positioning the fertilizer in contact with the root system (Table III.11). Several authors have reported that nitrogen release from polymer-coated, controlled-release fertilizers occur more rapidly than all other nutrients present in the fertilizer prills (Huett 1997a, Huett 1997b, Huett and Morris 1999, Huett and Gogel 2000). Huett and Gogel (2000) determined that at a steady temperature of 30°C, 90% of nitrogen, phosphorus, and potassium in Osmocote® (15-3.5-9.1), with a nominal release period of 12-14 months, was released after 25.7, 37.7, and 28.3 weeks since the application, respectively, and that the maximum release rate on nitrogen release occurred over the 7-13 week period. Increasing the growing-media temperature in 10°C, reduced even more the release period (Huett and Gogel 2000). Results from a fertilizer release study established on the coast range where a Polyon®-coated, controlled-release fertilizer was applied during the winter, showed that only 30% of the fertilizer was released at the end of the summer, nitrogen being the main nutrient released from the fertilizer prills at that point (Alzugaray 2002 unpublished).

Presumably, higher amounts of nitrogen taken up by seedlings fertilized on the roots may explain their slightly better growth during the first growing season (Table III.5, III.7 and III.8). This may be attributed to the linear relationship between plant leaf nitrogen concentration and maximum photosynthesis (Lambers et al.1998). It has been documented that maximum photosynthesis increases linearly with increasing nitrogen concentration, regardless of the species (Field and Mooney 1986). The excessively high leaf nitrogen concentration of seedlings fertilized on the roots and in the planting hole (Table III.11), resulted in a significant reduction of seedling height growth during the second growing season relative to the seedlings dibble fertilized and those fertilized on the surface (Table III.5). The amount of rainfall during the winter of 2001 was considerably lower than that in 2000 (Figure III.1), which may have reduced water availability to the seedlings during the second growing season. It has been demonstrated for several conifer species that increasing nitrogen levels reduces drought resistance of seedlings by shifting carbon allocation from roots to shoots (Pharis and Kramer 1964, Etter 1969, Ingestad 1979, Hunt 1989, Friend et al. 1990), resulting in seedlings with higher shoot-root ratios incapable of satisfying water demand by the shoots.

Although nonsignificant at 0.05, values for shoot-root ratios for the seedlings in this study tended to increase when positioning the fertilizer closer to root system of the seedlings at the beginning of the second growing season (Table III.7), coinciding with the increase in foliar nitrogen concentration (Figure III.3). Thus, when seedlings grown under an abundant supply of nitrogen were exposed to the summer drought of 2001 (Figure III.1), survival and growth rates may have been reduced, due to the inability of the smaller root system to supply enough water to satisfy the transpirational losses by the larger shoots.

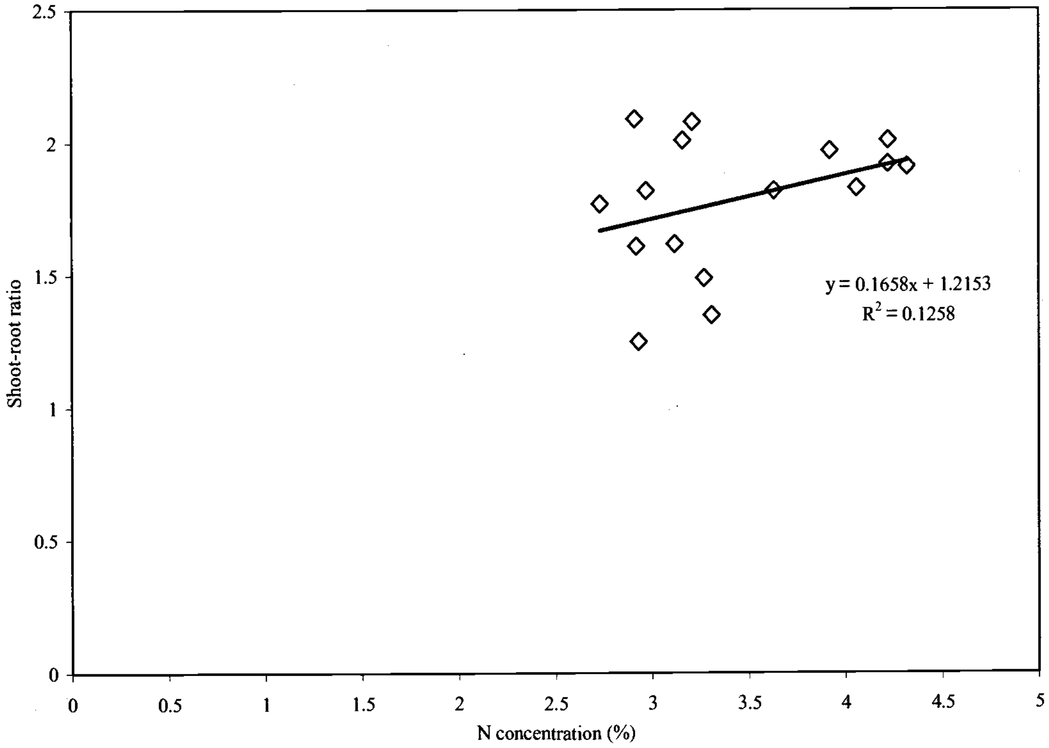

Figure III.3. Relationship between foliar nitrogen concentration and shoot-root ratio (by volume).

Survival of lodgepole pine seedlings grown under different nitrogen regimes was reduced after exposure to drought when increasing the amount of nitrogen supplied (Etter 1969). van Den Driessche (1992), examined the performance of different stocktypes for Douglas-fir and found that unbalanced bareroot stock with a shoot-root ratio ≥ 2 had significantly lower survival and growth than more balanced seedlings. Similar results were reported by Boyer and South (1987) when planting excessive tall loblolly pine seedlings in a sandy droughty site. It would have been recommendable to support this theory to perform an additional seedling morphological assessment at the end of the second growing season.

On the other hand, phosphorus foliar concentration decreased significantly with increasing nitrogen foliar concentration (Table III.11). This may be attributed to poor mycorrhizal infection in the rhizosphere as a result of high soil nitrogen concentrations (Bjorman 1970). Phosphorus uptake by the plants is enhanced by mycorrhizal fungi (Lambers et al. 1998). Hunt (1989), comparing the effects of different controlled-release fertilizers in mycorrhizal infection, reported that Osmocote® in particular, applied to containerized engelmann spruce seedlings was the most detrimental to mycorrhizal colonization both in species diversity and intensity.

Fertilization rate effects

In this study, fertilization rate had only a slight effect of foliar nutrient concentration and content (Table III.11). Douglas-fir nutrient requirements at this stage may have been satisfied with fertilization at the lowest rate (17g). Donald and

Visser (1989) attributed the low response of increasing fertilization rates of urea formaldehyde applied to one-year-old *Pinus elliotti* seedlings to the low nutrient requirements of the species during its early growing stages. Pharis and Kramer (1964) noted only slight increases in nitrogen foliar concentrations of loblolly pine seedlings after supplying them with NH_4NO_3 above 50 ppm. Similar results were reported by Ingestad (1979) for *Pinus silvestris* and *Picea abies* when applying increasing levels of nitrogen above 80 mg/l.

CONCLUSIONS

The null hypothesis of no fertilizer placement effect on morphology, foliar nutrient concentration, and foliar nutrient content of 1+1 Douglas-fir seedlings at the end of two growing seasons was rejected. The null hypothesis of no fertilization rate effect on morphology, foliar nutrient concentration, and foliar nutrient content of 1+1 Douglas-fir seedlings at the end of two growing seasons was also rejected. The null hypothesis of no interaction effect between fertilizer placement and fertilization rate for survival, morphology, foliar nutrient concentration, and foliar nutrient content of 1+1 Douglas-fir seedlings at the end of two growing seasons was not rejected for survival and was rejected for seedling morphology, foliar nutrient concentration and foliar nutrient content.

During the first growing season seedlings fertilized on the roots tended to grow more in height and diameter than all other fertilizer placement treatments, however differences between means were not statistically significant at the $\alpha \leq 0.05$ level. During the second growing season, seedlings fertilized on the surface and those dibbled fertilized grew the most in height and stem diameter resulting in the largest seedlings at the end of this study.

Application of the highest level (50g) of fertilizer on the roots resulted in the lowest survival at the end of two growing seasons.

Seedlings fertilized on the roots and in the planting hole increased significantly their nitrogen foliar concentration and content at the end of the first growing season. Increasing fertilization rate resulted in a slightly increase in nitrogen foliar concentration and content. As nitrogen foliar concentration and content increased phosphorous foliar concentration and content decreased.

Results from this study suggest that Osmocote® Plus (15-9-12) should be applied to 1+1 Douglas-fir seedlings in an adjacent hole or on the soil surface at rates lower than 17g on sites where soil moisture is expected to be limited during a long period during the growing season. Although further research is required, it seems to be possible to stimulate seedling growth, perhaps as a consequence of facilitating nitrogen uptake by the plant, by placing 17g of Osmocote® Plus (15-9-12) on the roots of 1+1 Douglas-fir seedlings on more mesic sites.

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CHAPTER IV
NUTRIENT RELEASE PATTERNS OF FOUR CONTROLLED-RELEASE FERTILIZERS

ABSTRACT

To assess nutrient release patterns of four Simplot Polyon® controlled-release fertilizers with different nominal release periods and similar nutrient compositions, samples of 30g of each fertilizer were buried in the ground 30cm deep in February 2000. The fertilizer was placed in PVC rings five inches in diameter and half inch wide, sealed with nylon socks to allow exposure to soil moisture and temperature. Every seven weeks, from May 2000 to April 2001, one PVC ring per fertilizer replicate was randomly selected, excavated, and analyzed to determine the amount of residual nutrients.

After the completion of this experiment, the fertilizer with the shortest release period (3-4 months) released approximately 64% of the fertilizer (by weight), and that with the longest release period (8-9 months) released 47%. It is suggested that low soil temperatures and low soil moisture may have delayed the release period of the fertilizers. Depending on fertilizer release period, it was estimated that 63 to 85% of initial nitrogen content, 48 to 79% initial potassium

content, 19 to 38% initial P content, 6 to 37% initial Mg content, 28 to 50% initial S content, and 5 to 10% initial Zn content was released by the end of the experiment. Regardless of fertilizer release period, 9% of initial Mo content, and 4% of initial Fe and Mn content, were released to the soil.

INTRODUCTION

Nutrient release rates of coated-controlled-release fertilizers are a function of the coating characteristics, surrounding temperature, moisture and microbial activity (Hauck 1985). Thin coatings, high temperatures, adequate moisture and elevated microbial activity will accelerate the nutrient release of coated-controlled-release fertilizers. Release periods specified by the manufacturer of these products are calculated based on the amount of fertilizer released (by weight) under stable conditions of temperature, generally 21°C or 25°C (Goertz 1993). However, when applied in the field ideal conditions of soil temperature and moisture seldom occur throughout a growing season. Analysis of Nutricote (16-10-10), with a release period of 12 months estimated at 25°C, used in an outplanting study in British Columbia, showed that only 54% of nitrogen present within the coating was released 22 months after the application (Arnott and Burdett 1988).

On several outplanting studies in which coated-controlled-release fertilizers have been compared, only small differences in seedling nutrient response other than nitrogen has been observed for Douglas-fir seedlings (van den Driessche 1988). It has been suggested that the reason why a N-P-K formulation of coated-controlled-release fertilizers has no effect other than nitrogen on seedling growth may be attributed to the small amount of the other nutrients present in the fertilizer relative to nitrogen (van den Driessche 1997).

Nutrient release patterns of coated-controlled-release fertilizers have been described on several studies under controlled temperature conditions (Lamont et al. 1987; Cabrera 1997; Huett et al. 2000). However, such information is more useful to nursery growers, who can control and monitor growing media temperature and moisture. For the reasons exposed above, this information may have restricted applicability for fertilizer use in the field. Since there is an increasing interest in using controlled-release fertilizers in outplanting operations, this study was design to describe nutrient release patterns of four coated-controlled-release fertilizers with different release rates under field conditions.

MATERIALS AND METHODS

Samples of four Simplot® controlled-release fertilizers (Table IV.1) with different nominal release periods (3-4, 5-6, 8-9, and a mixture of all three) and similar nutrient compositions were buried 30cm deep on February 7, 2000. The experimental site is located at OSU's McDonald-Dunn Research Forest 15 km north of Corvallis, OR. The site has a gently sloping east aspect. Soils belong to the Waldo series and are deep, well-drained, silty clay loams. Table IV.2 details chemical characteristics of the soils at the study site. A temperature recorder was established at the site to monitor soil temperature at 3 days intervals at a depth of 30cm during the study period.

Table IV.1. Nutrient composition (%) of the three Simplot Polyon® fertilizers used in this experiment.

Fertilizer	Polyon 1 (3-4 months release rate)	Polyon 2 (5-6 months release rate)	Polyon 3 (8-9 months release rate)	Composite applied
Nutrient	Composition (%)			
Total nitrogen	19	19	18	18.67
NH_4	8.2	8.2	7.74	8.05
NO_3	10.8	10.8	10.26	10.62
P (P_2O_5)	5	6	6	5.67
K (K_2O)	12	12	12	12
Mg	1	0.9	0.9	0.93
S	1.8	1.7	1.7	1.73
Fe	0.45	0.45	0.45	0.45
Mn	0.2	0.19	0.19	0.193
Mo	0.009	0.009	0.009	0.009
Zn	0.056	0.055	0.05	0.054

Table IV.2. Soil chemical characteristics at the study site.

Organic matter (%)	NO_3 (ppm)	P (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	Na (ppm)	SO_4 (ppm)	Zn (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)	B (ppm)	CEC (meq/100g)	EC (dS/m)	pH
12.3	25.8	5.5	217.5	182.3	1034.5	11.3	3.3	0.2	5.5	16.5	2.5	0.2	9.4	0.4	5.7

Fertilizer samples were 30g each and were placed in a PVC ring (0.5" x 5" diameter). Each ring was sealed with a nylon sock to avoid fertilizer prill loss and permit exposure to soil moisture and temperature. The experiment was established using a completely randomized block design with three blocks. There were 8 rings of each treatment in each block. Every seven weeks, one sample per treatment per block was randomly selected, excavated and taken to the laboratory. The first samples were excavated on May 5, 2000 (13 weeks after initiation) and the last on April 13, 2001 (62 weeks after initiation of the study).

Fertilizer samples were dried for 48 hours at 68°C. Dry weight was determined and recorded on each. After collecting all the samples, fertilizer prills were ground using a porcelain mortar and pestle and were sent to a Simplot® laboratory for nutrient analyses. Table IV.3 lists the methods used for determination of nutrient concentrations. Residual nutrient content (i.e. grams of nutrients remaining in the fertilizer collected from the field) of each sample at each sampling date was calculated by multiplying nutrient concentration obtained from laboratory analyses by the dry weight of the sample. Residual nutrient content was expressed as a percentage of the initial amount present in the fertilizer prills. Nutrient content release as a percentage of the initial amount present in the fertilizer prills at each sampling date was calculated by subtracting residual nutrient content at each sampling date from 100%.

Table IV.3. Laboratory procedures used by the Simplot laboratory to determine fertilizer prills nutrient concentrations.

Nutrient	Procedure	Source
NH_3	Kjeldahl distillation method	Association of Florida Phosphate Chemists, 1991
NO_3	Devarda method	Official Methods of Analysis of AOAC International, 2000
P_2O_5	Automated method+Bran Lubbe Industrial method No.803-86T	Official Methods of Analysis of AOAC International, 2000
K_2O	Atomic absorption spectrometry	Flame Atomic Absorption Spectrometry Analytical Methods, 1989
S	Gravimetric method	Official Methods of Analysis of AOAC International, 2000
Mg, Fe, Mn, Mo, and Zn	Samples were digested in four parts of HNO3 1:1, one part HCl, and analyzed on a Perkin Elmer 3000 DV ICP using radial viewing (Scott Sabel 2002, personal communication).	

Initial nutrient concentrations were compared against nutrient concentrations specified by the manufacturer using the one-sample t-test at the $\alpha \leq 0.05$ level. To model nutrient release and residual content across time, mathematical equations for individual nutrients were developed through the fit of the following model using the mixed procedure (SAS Institute Inc. 1999): μ{nutrient residual or release content | *weeks, RELEASE PERIOD*} = *weeks* + *weeks*^{2} + RELEASE PERIOD + (*weeks* x RELEASE PERIOD). The square term of the numerical explanatory variable "weeks" was added to model the curvilinear relationship between time and the response variable. Terms in the model with p-values greater than 0.05 were considered nonsignificant and were removed from the model. The model was refitted until all terms in the model were significant or no more terms could be removed, whichever happened first. Model coefficients and contrasts between coefficients were tested at the $\alpha \leq 0.05$ level. Residuals were examined to check the normality and equal variance assumptions among treatments.

RESULTS

Initial nutrient concentrations

Ammonia (NH_3) initial concentration coincided with manufacturer specifications only for the intermediate release rate ($p=0.0572$), while mean nitrate, sulfur, and iron initial concentrations coincided for all release rates ($p>0.05$) (Table IV.4). Phosphorus, potassium, magnesium, molybdenum and zinc initial concentrations were significantly higher than those specified by the manufacturer of the fertilizer among all fertilizer release rates ($p<0.05$). Manganese initial concentration coincided with specifications of the manufacturer for the 3-4 and 8-9 months release rate ($p>0.05$) but did not for 5-6 months release rate ($p=0.0218$).

Table IV.4. Manufactured and mean initial nutrient concentration by fertilizer release period.

Fertilizer release period (months)	Nutrient	Nutrient concentration specified by manufacturer (%	Mean nutrient concentration (%)	Standard error	Sample size n	t-ratio	p-value
3-4	NH3-N	8.200	8.920	0.0200	3	36.00	0.0008
	NO3-N	10.800	10.450	0.4100	2	0.85	0.5502
	P	2.100	3.050	0.0400	3	21.75	0.0021
	K	9.900	11.160	0.0060	3	200.00	0.0000
	Mg	1.000	1.500	0.0200	3	25.00	0.0016
	S	1.800	1.660	0.3200	3	0.44	0.7045
	Fe	0.450	0.480	0.0100	3	3.00	0.0955
	Mn	0.200	0.200	0.0030	3	0.00	1.0000
	Mo	0.009	0.005	0.0003	3	13.33	0.0056
	Zn	0.056	0.070	0.0000	3	-	-
5-6	NH3-N	8.200	8.680	0.1200	3	4.00	0.0572
	NO3-N	10.800	10.440	0.2300	2	1.57	0.3619
	P	2.500	3.030	0.0300	3	14.33	0.0048
	K	9.900	10.900	0.0400	3	23.50	0.0018
	Mg	0.900	1.440	0.0200	3	27.00	0.0014
	S	1.700	1.990	0.2000	3	1.45	0.2841
	Fe	0.450	0.480	0.0090	3	3.33	0.0794
	Mn	0.190	0.210	0.0030	3	6.67	0.0218
	Mo	0.009	0.005	0.0003	3	13.33	0.0056
	Zn	0.055	0.007	0.0000	3	-	-
8-9	NH3-N	7.740	8.580	0.0200	3	42.00	0.0006
	NO3-N	10.260	10.780	0.3300	3	1.58	0.2558
	P	2.500	2.940	0.0500	3	6.80	0.0209
	K	9.900	10.760	0.0700	3	11.43	0.0076
	Mg	0.900	1.440	0.0100	3	54.00	0.0003
	S	1.700	1.750	0.0500	3	1.00	0.4226
	Fe	0.450	0.480	0.0100	3	3.00	0.0955
	Mn	0.190	0.200	0.0060	3	1.67	0.2375
	Mo	0.009	0.005	0.0000	3	-	-
	Zn	0.050	0.007	0.0000	3	-	-

Nutrient release patterns

Mathematical equations developed to model nutrient release across time of individual nutrients for each fertilizer are shown in Table IV.5. Relative fertilizer release (by weight) of ammonia, phosphorus, potassium, and zinc had a curvilinear relationship with time. Nitrate, sulfur, magnesium, iron, manganese, and molybdenum had a linear release across time. There was a significant interaction between fertilizer release period and time for relative fertilizer dry weight ($p=0.0179$), potassium ($p=0.0102$), phosphorus ($p<0.0001$) and magnesium ($p<0.0001$) relative content.

Fertilizers with shorter release periods delivered more nutrients than those with longer release period up to the 13th week, after which fertilizers delivered nutrients at a similar rate, with the exception of fertilizer dry weight, potassium, magnesium and phosphorus. None of the fertilizers studied in this experiment released 80% or more of its initial content at the time specified by the manufacturer.

Table IV.5. Nutrient release models

Release period	Mean nutrient relative release content at week (t)
3-4 months	$N_{(t)} = -2.7407+2.8286t-0.02288t^2$
	$NH_{3(t)} = -23.1501+3.8285t-0.03368t^2$
	$NO_{3(t)} = 29.0604+0.9604t$
	$P_{(t)} = -6.9463+1.167t-0.00726t^2$
	$K_{(t)} = -20.6153+2.819t-0.01947t^2$
	$Mg_{(t)} = -2.9629+0.6371t$
	$S_{(t)} = 8.1326+0.6725t$
	$Fe_{(t)} = 0.7528+0.05416t$
	$Mn_{(t)} = 1.9091+0.02102t$
	$Mo_{(t)} = 5.7445+0.04991t$
	$Zn_{(t)} = 8.6891-0.2428t+0.004297t^2$
5-6 months	$N_{(t)} = -16.0722+2.8286t-0.02288t^2$
	$NH_{3(t)} = -41.7623+3.8285t-0.03368t^2$
	$NO_{3(t)} = 17.7358+0.9604t$
	$P_{(t)} = -9.6639+0.96222t-0.00726t^2$
	$K_{(t)} = -30.2685+2.5112t-0.01947t^2$
	$Mg_{(t)} = -5.3774+.2241t$
	$S_{(t)} = -0.5498+0.6725t$
	$Fe_{(t)} = 0.7528+0.05416t$
	$Mn_{(t)} = 1.9091+0.02102t$
	$Mo_{(t)} = 5.7445+0.04991t$
	$Zn_{(t)} = 3.3643-0.2428t+0.004297t^2$
8-9 months	$N_{(t)} = -24.4254+2.8286t-0.02288t^2$
	$NH_{3(t)} = -46.2878+3.8285t-0.03368t2$
	$NO_{3(t)} = 8.5641+29.0604+0.9604t$
	$P_{(t)} = -10.434+0.91139t-0.00726t^2$
	$K_{(t)} = -31.4517+2.486t-0.01947t^2$
	$Mg_{(t)} = -4.95631+0.1792t$
	$S_{(t)} = -14.0878+0.6725t$
	$Fe_{(t)} = 0.7528+0.05416t$
	$Mn_{(t)} = 1.9091+0.02102t$
	$Mo_{(t)} = 5.7445+0.04991t$
	$Zn_{(t)} = 6.8661-0.2428t+0.004297t^2$
Mixture	$N_{(t)} = -16.9164+2.8286t-0.02288t^2$
	$NH_{3(t)} = -34.4393+3.8285t-0.03368t^2$
	$NO_{3(t)} = 12.828+0.9604t$
	$P_{(t)} = -4.6885+0.9741t-0.00726t^2$
	$K_{(t)} = -28.0414+2.6672t-0.01947t^2$
	$Mg_{(t)} = -4.8998+0.3755t$
	$S_{(t)} = -2.7064+0.6725t$
	$Fe_{(t)} = 0.7528+0.05416t$
	$Mn_{(t)} = 1.9091+0.02102t$
	$Mo_{(t)} = 5.7445+0.04991t$
	$Zn_{(t)} = 7.7663-0.2428t+0.004297t^2$

Within the same nominal release period, there was a significant interaction ($p<0.0001$) between the type of macronutrient and time for relative macronutrient release (Figure IV.1). Among macronutrients, nitrogen compounds, both ammonia and nitrate released the most while phosphorus and magnesium the least. Potassium and sulfur released at intermediate rates (Figure IV.1).

Regardless of the nitrogen source, ammonia and nitrate release was the same in all but the 5-6 month release period (Figure IV.2). Micronutrient release was marginal (Figure IV.3).

Residual and release fertilizer by weight

The interaction between time and fertilizer release period for fertilizer weight was significant ($p=0.0179$). Fertilizer with the shortest release period released the most fertilizer (on a dry weight basis), and that with the longest release period the least. At the end of this experiment, only between 47 (3-4 months) and 64% (8-9 months) of the initial amount of fertilizer was released from the rings (Figure IV.4).

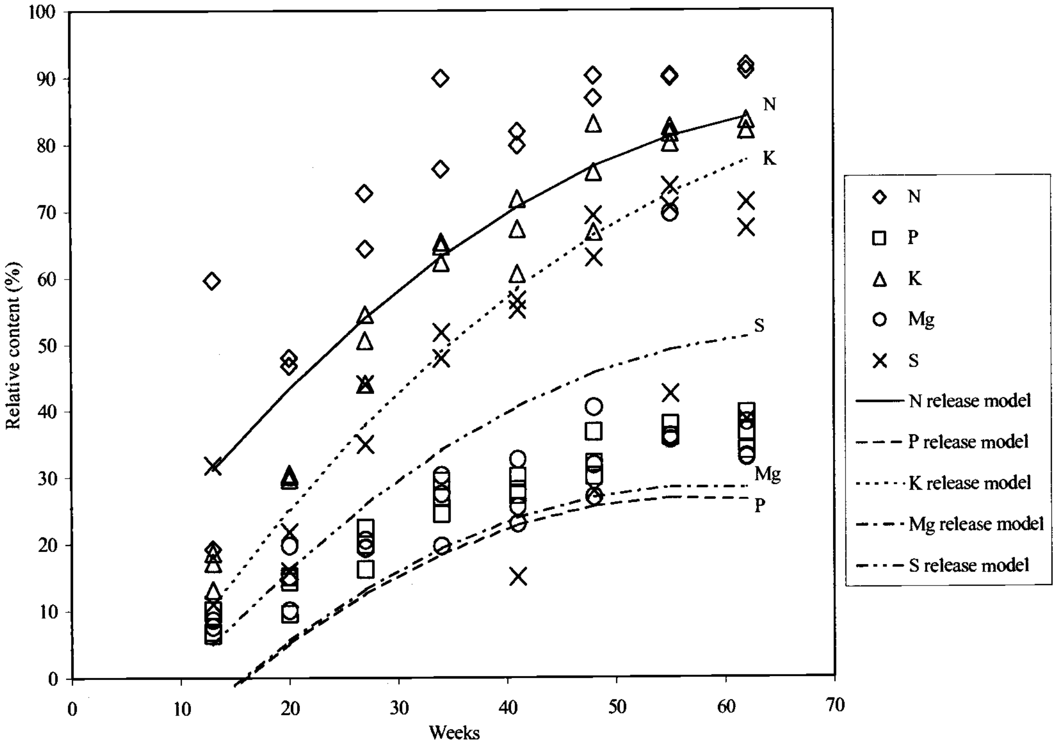

Figure IV.1a. Relative macronutrient release across time for fertilizer with a 3-4 months release period.

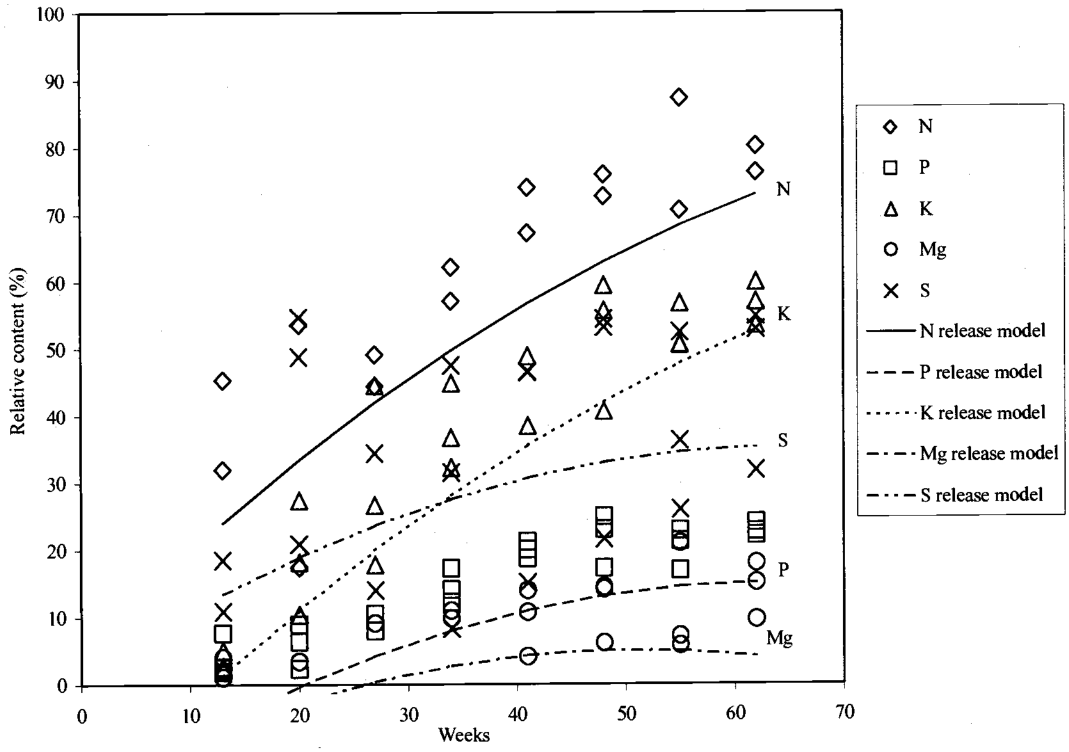

Figure IV.1b. Relative macronutrient release across time for fertilizer with a 5-6 months release period.

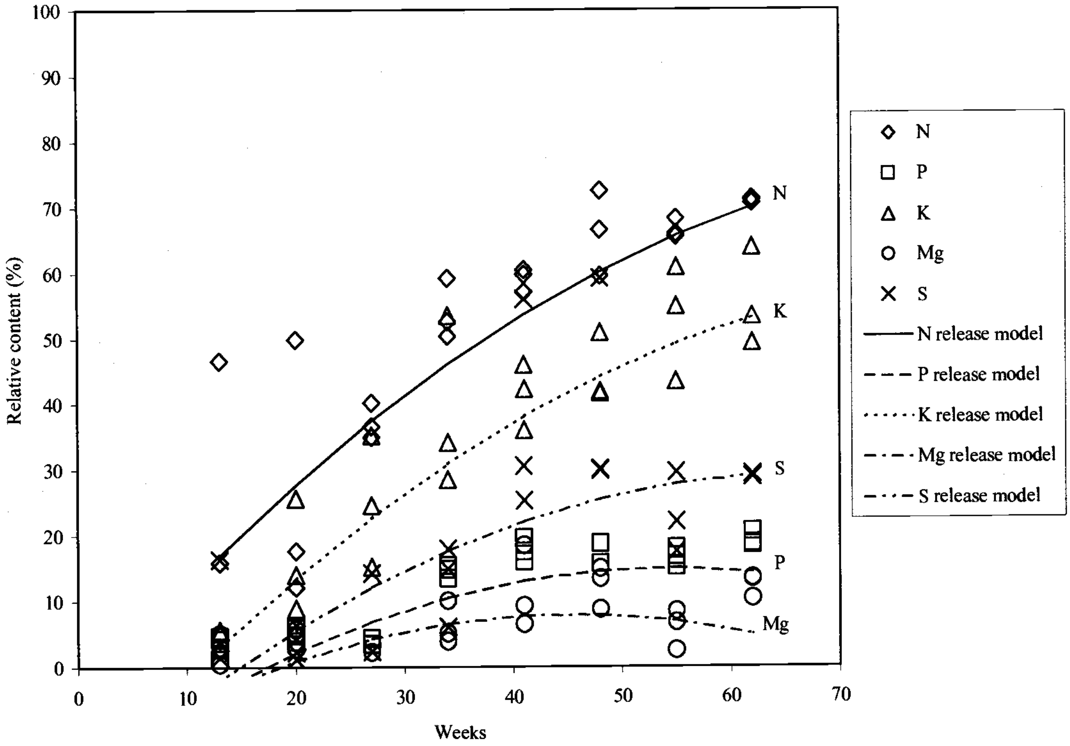

Figure IV.1c. Relative macronutrient release across time for fertilizer with a 8-9 months release period.

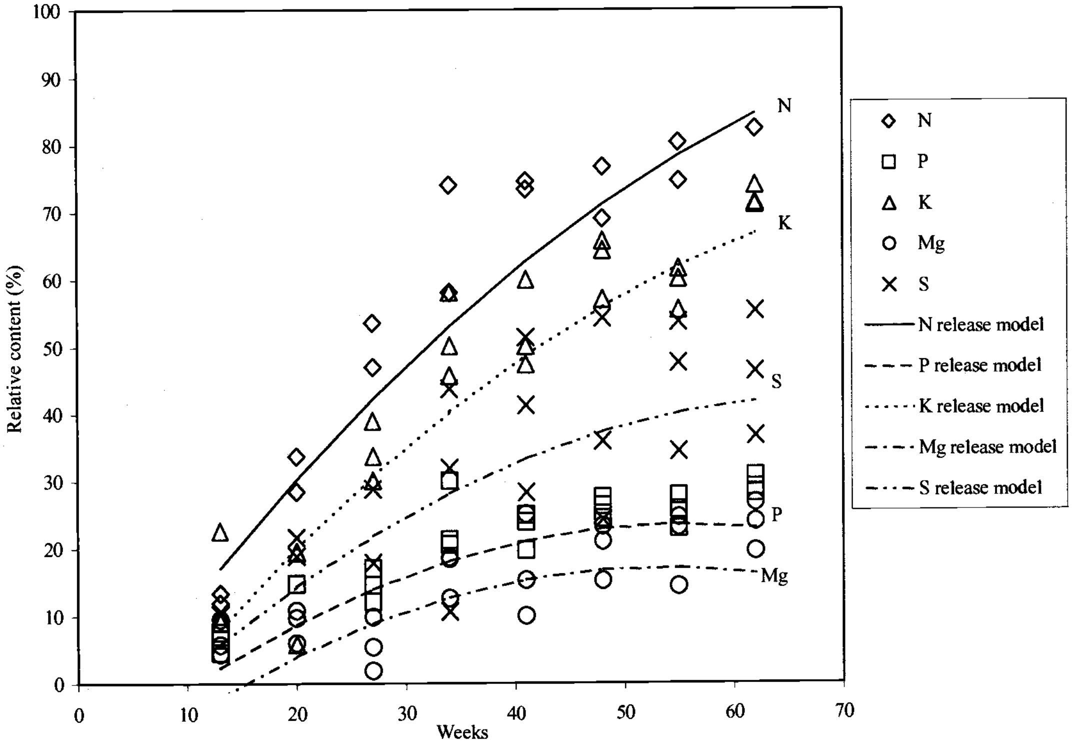

Figure IV.1d. Relative macronutrient release across time for fertilizer with a mix release period.

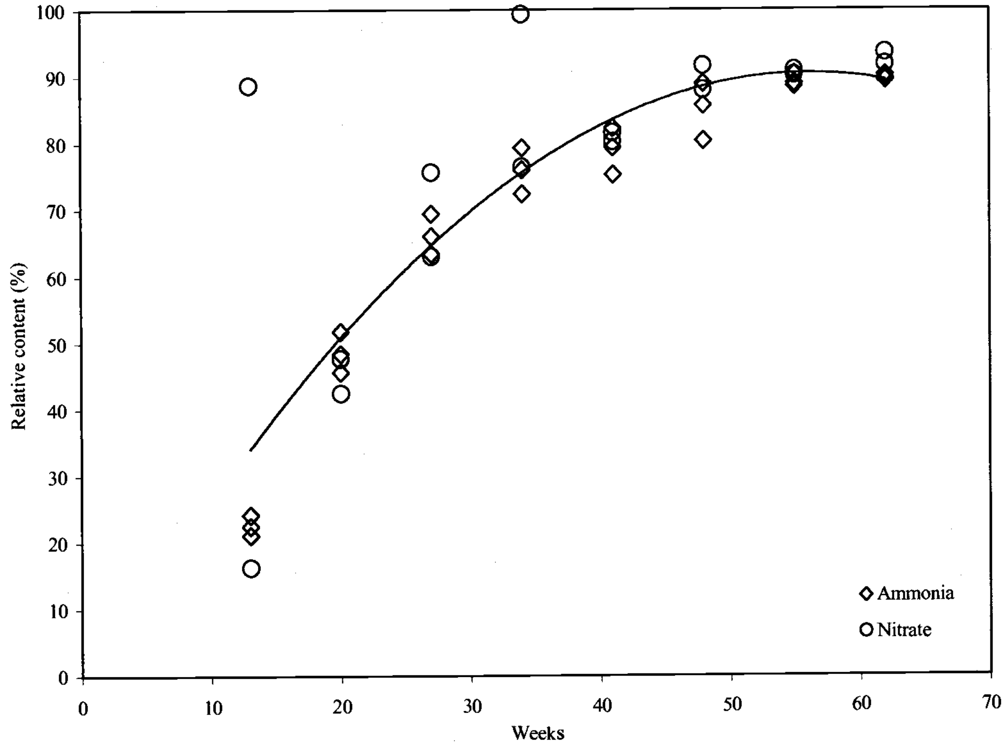

Figure IV.2a. Ammonia and nitrate relative release across time for fertilizer with a 3-4 months release period.

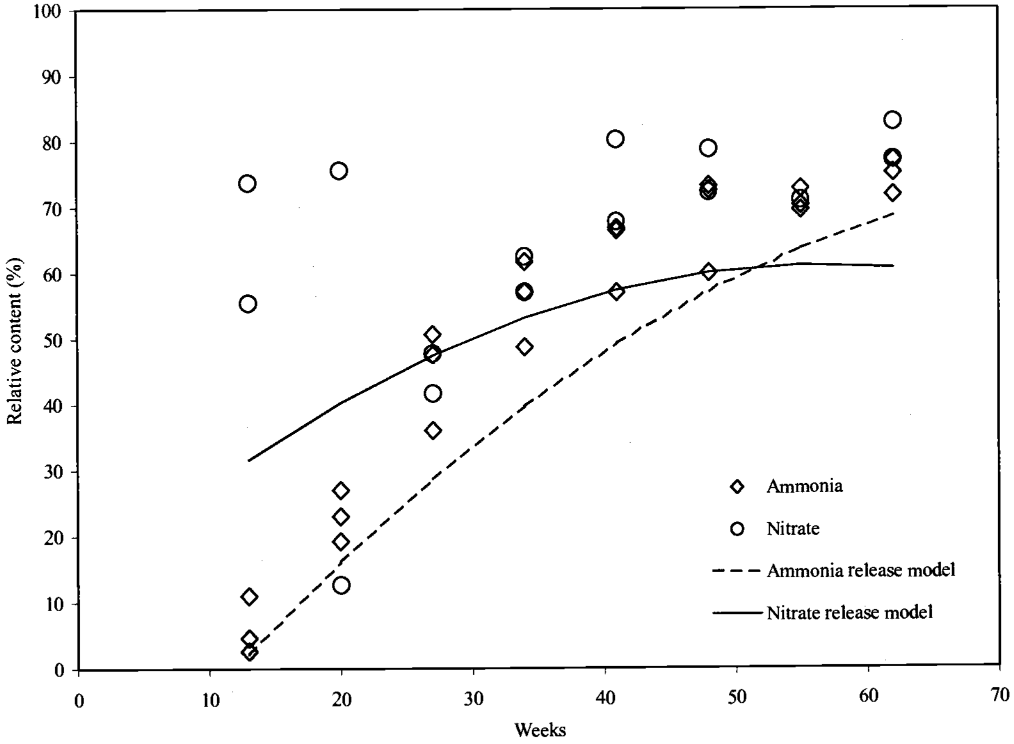

Figure IV.2b. Ammonia and nitrate relative release across time for fertilizer with a 5-6 months release period.

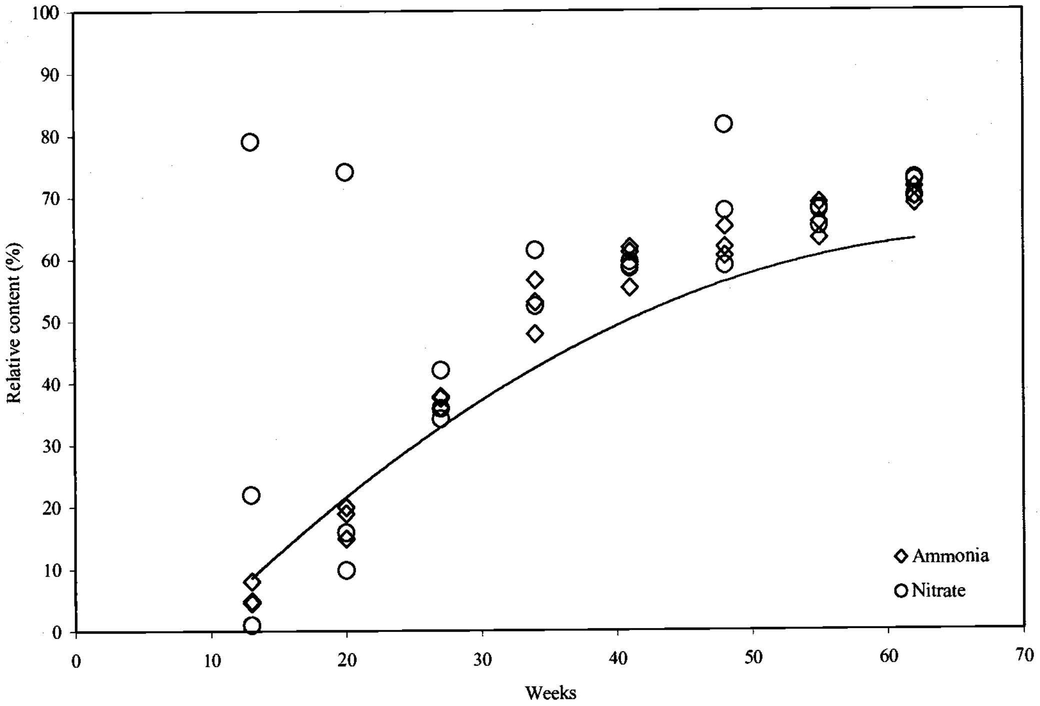

Figure IV.2c. Ammonia and nitrate relative release across time for fertilizer with a 8-9 months release period.

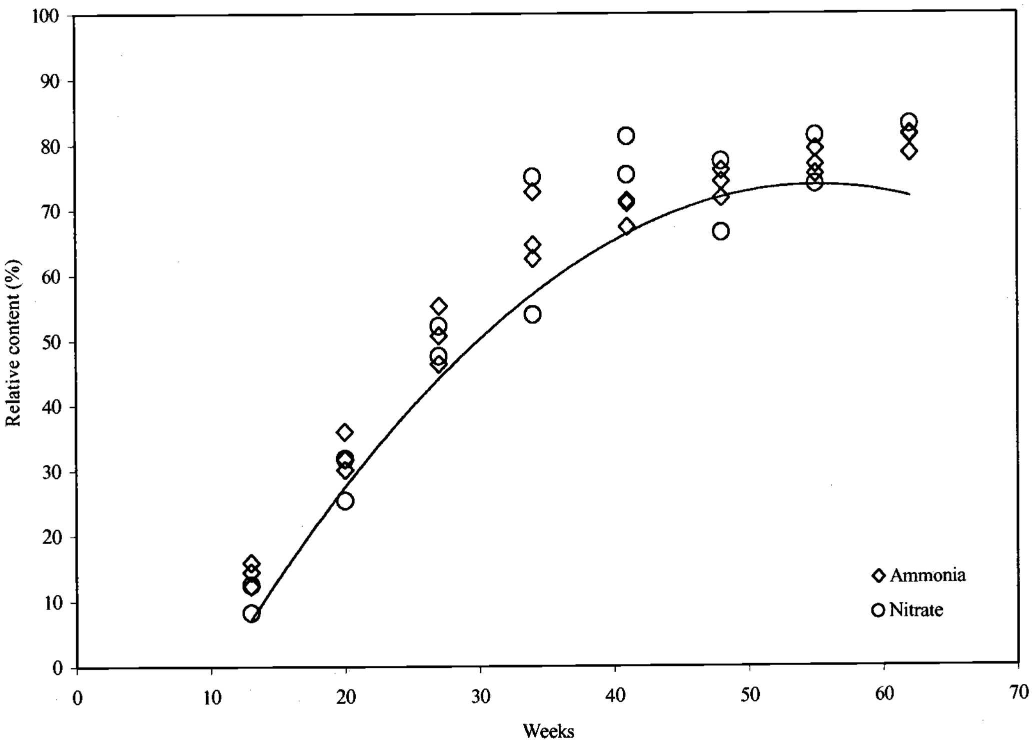

Figure IV.2d. Ammonia and nitrate relative release across time for fertilizer with a mix release period.

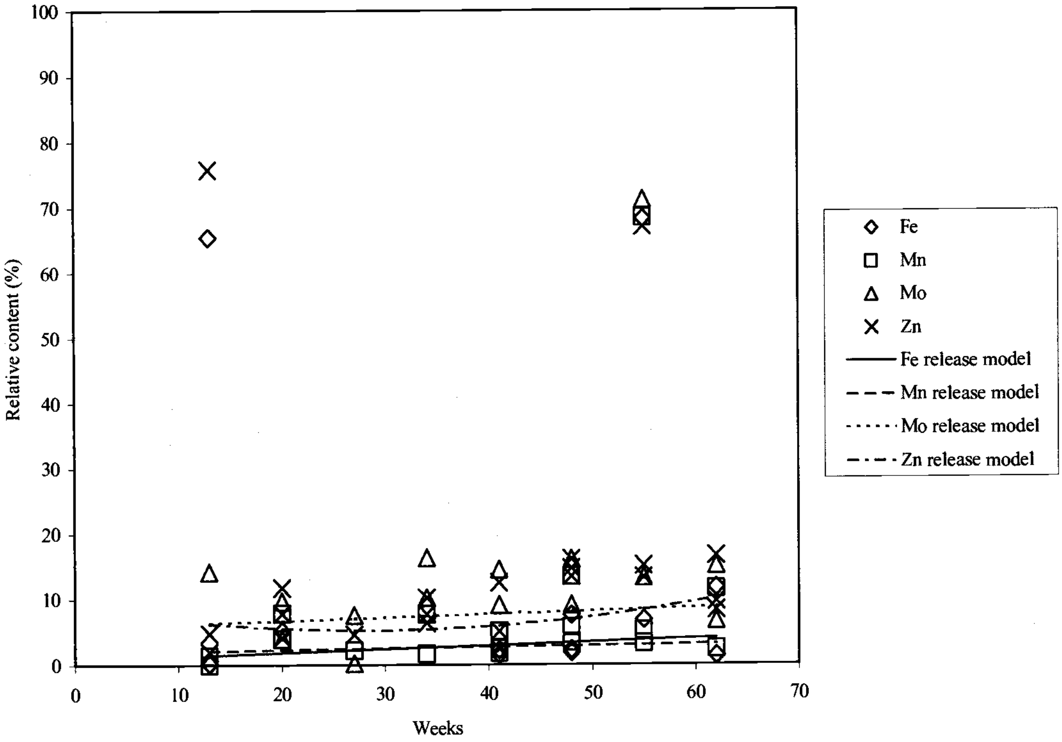

Figure IV.3a. Relative micronutrient release across time for fertilizer with a 3-4 months release period.

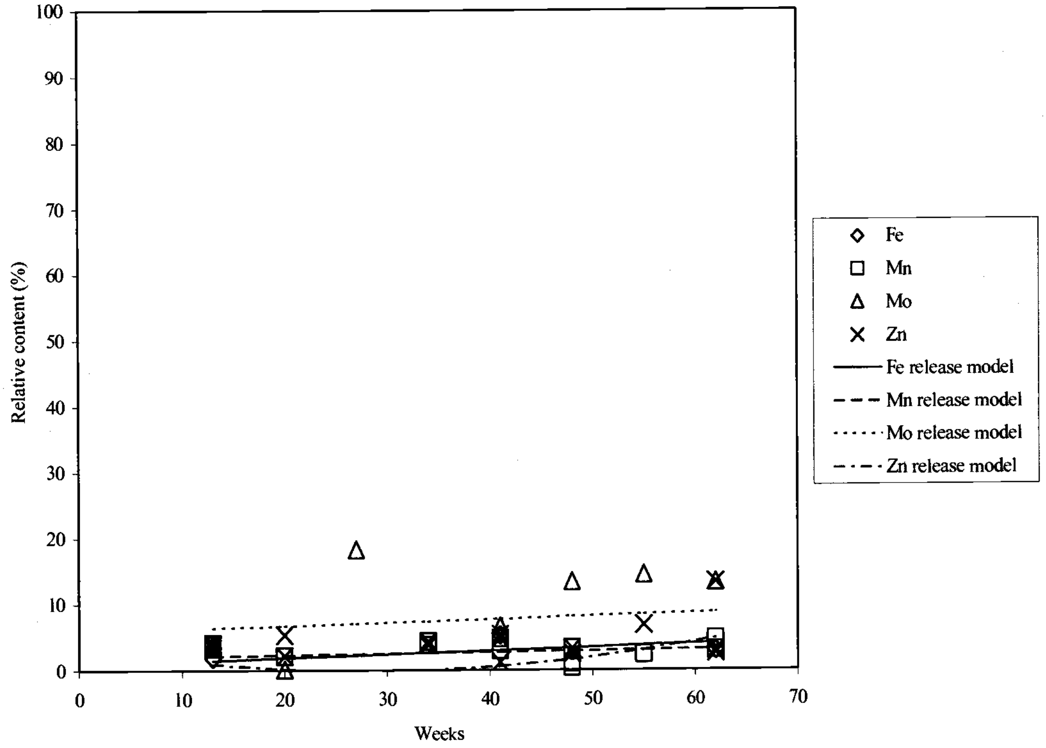

Figure IV.3b. Relative micronutrient release across time for fertilizer with a 5-6 months release period.

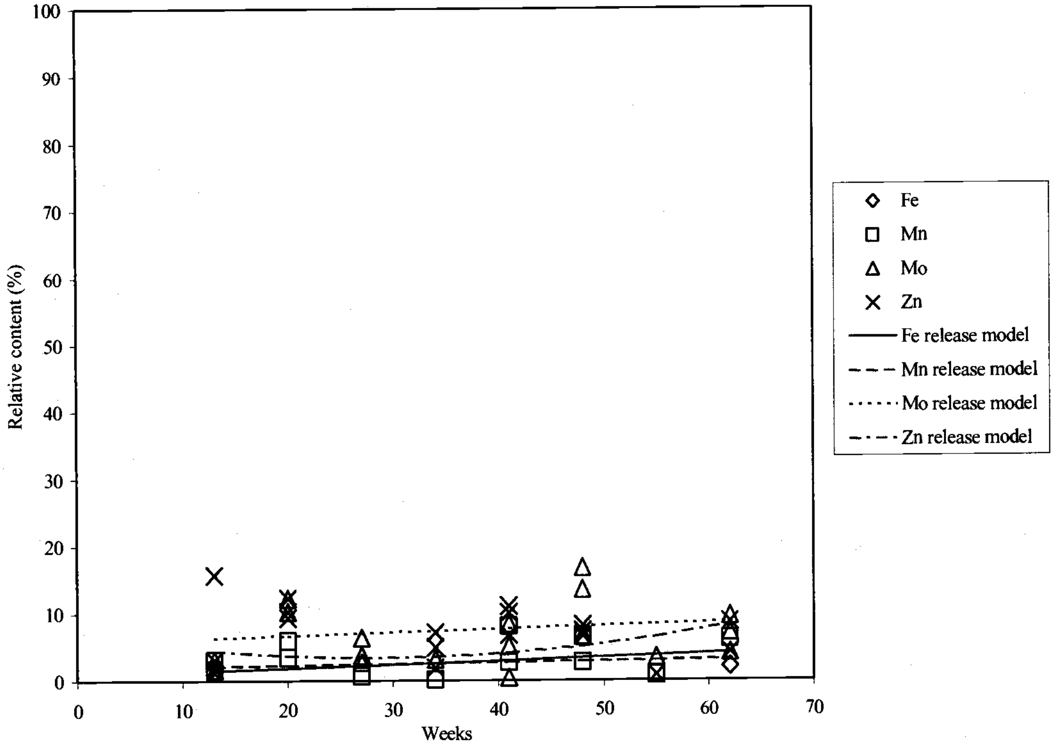

Figure IV.3c. Relative micronutrient release across time for fertilizer with a 8-9 months release period.

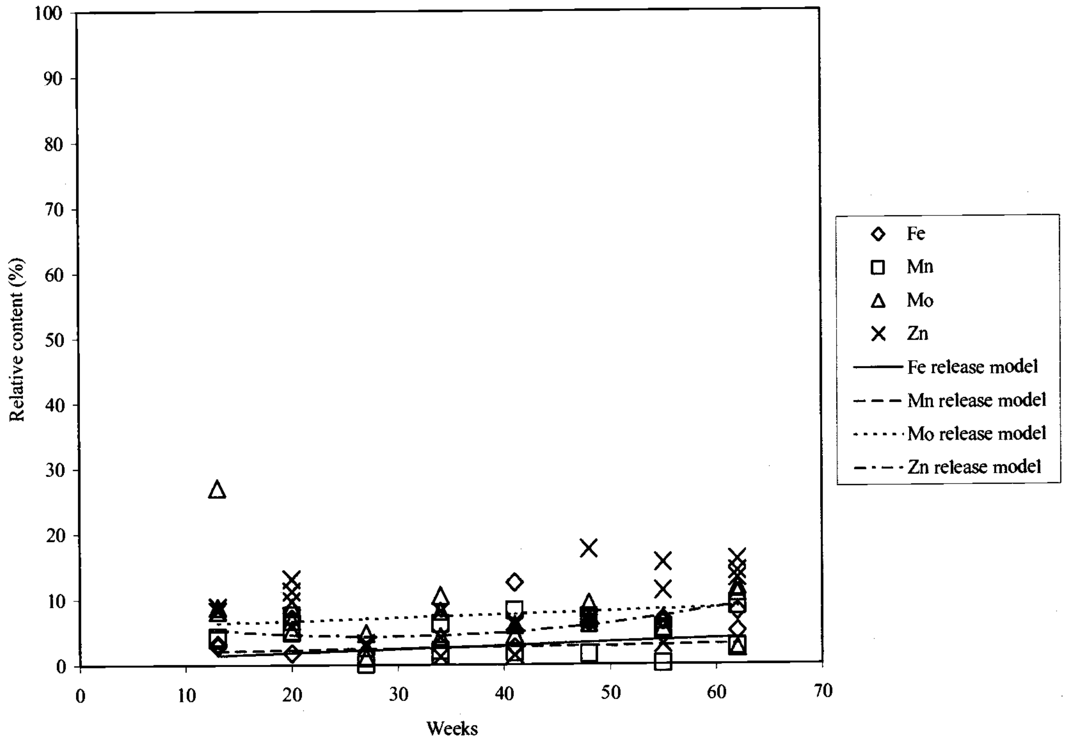

Figure IV.3d. Relative micronutrient release across time for fertilizer with a mix release period.

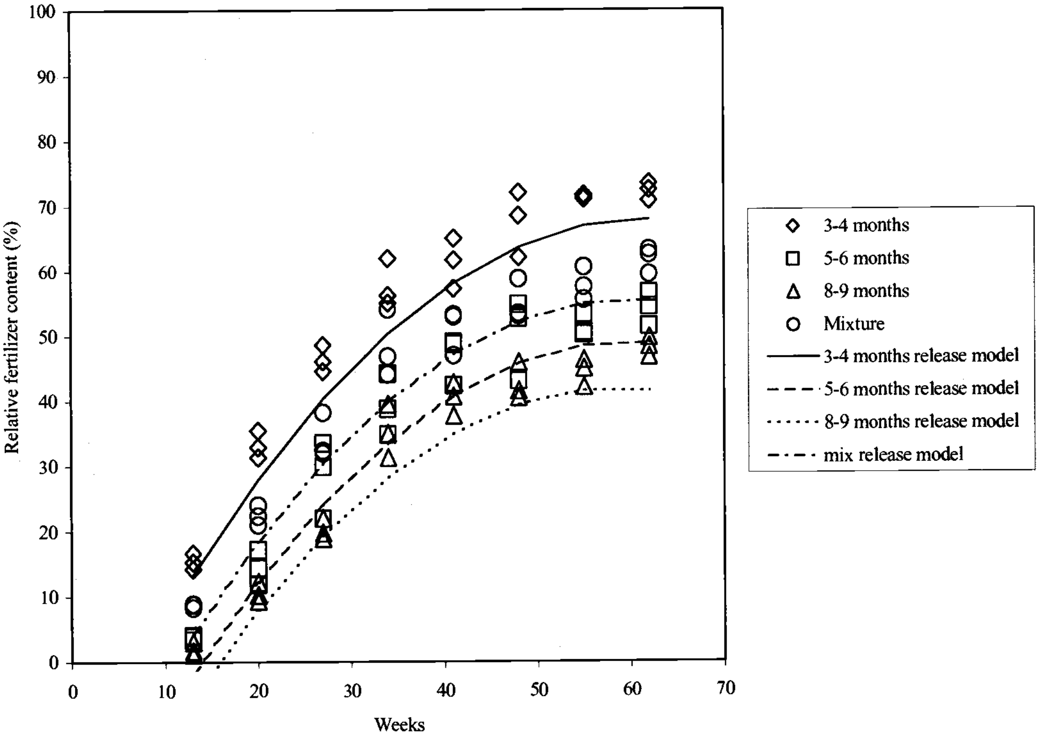

Figure IV.4. Relative fertilizer release content by weight across time for fertilizers with different release period.

Total nitrogen (N_2)

Nitrogen release was significantly affected by fertilizer release period ($p<0.0001$) and time ($p<0.0001$). Regardless of nominal release period, nitrogen release rate was the same among fertilizers ($p=0.3807$ for interaction). Fertilizer with the shortest release period (3-4 months) released 13, 14, and 22% more nitrogen at any point in time between weeks 13 and 62, than those with a release period of 5-6 months, the mixture, and 8-9 months, respectively (Figure IV.1).

Ammonia (NH_3)

The amount of ammonia released was significantly affected by fertilizer release period ($p<0.0001$) and time since the application ($p<0.0001$). Between the 13th and 62nd weeks since the application, all fertilizers released at the same rate ($p=0.3499$), and the fertilizer with the longest release period (8-9 months) released 5, 12, and 23% less ammonia than those with a release period of 5-6 months, the mixture, and 3-4 months, respectively. At the end of the experiment only between 62 and 85% of initial ammonia content was released (Figure IV.1). Using the model developed for ammonia, it was estimated that 44 weeks (10 to 11 months) after applying the fertilizer with a release period of 3-4 months were required to deliver 80% of ammonia.

Nitrate (NO_3)

Both fertilizer release period ($p<0.0001$) and time since application ($p=0.0025$) significantly affected the amount of nitrate released into the soil. The interaction between release period and time was not significant ($p=0.1589$). Between weeks 13 and 62, the different fertilizers delivered nitrate at the same rate. Nitrate release of fertilizer with an 8-9 month release period was 4, 9, and 20% less than that of the mixture, 5-6 months release period and 3-4 months release period, respectively. Only between 68 and 89% of nitrate was released 62 weeks after establishing this experiment (Figure IV.1).

Phosphorus (P)

Phosphorus release depended on fertilizer release period and time since the application ($p<0.0001$). Fertilizer with the shortest release period (3-4 months) released the most phosphorus and that with the slowest release period (8-9 months) the least (Figure IV.1). Only 22 to 38% of initial phosphorus content was released at the time of the last sampling.

Potassium (K)

The interaction between fertilizer release period and time since application was significant ($p=0.0102$) for potassium release. Depending on the release period of the fertilizer, 51 to 74% of initial potassium content was delivered 62 weeks after establishing the experiment (Figure IV.1).

Magnesium (Mg)

Magnesium release depended on fertilizer release period and time since application ($p<0.0001$). Fertilizer with the nominal release period of 3-4 months released magnesium at a higher rate than all other fertilizers (Figure IV.1). At the end of the study, only between 17 and 19% of initial magnesium content was released.

Sulfur (S)

Both fertilizer release period ($p<0.0001$) and the number of weeks since application ($p<0.0001$) affected sulfur release. Sulfur release rate between weeks

13 and 62 was estimated to be 0.67% per week for the four different fertilizers (Table IV.5). At the same point in time within this range, fertilizer with a nominal release period of 3-4 months delivered 9, 11, and 22% more sulfur than those with a 5-6 months release period, the mixture, and 8-9 months release period, respectively. At the time of the last sampling, only between 28 and 50% of initial sulfur content was effectively released from the prills (Figure IV.1).

Iron (Fe), manganese (Mn) and molybdenum (Mo)

For these three micronutrients, regardless of fertilizer release period and the number of weeks since the application, the amount of nutrient released did not differ significantly from one another ($p>0.05$). Approximately 4% of iron, 4% of manganese, and 9% of molybdenum was released by the end of this experiment (Figure III.3).

Zinc (Zn)

Zinc relative release content was only affected by fertilizer release period ($p=0.0008$). The interaction between time since application and fertilizer release period was not significant for this nutrient release (p=0.0736). Between the 13th and 62nd week since application, fertilizer with the shortest release period (3-4 months) released approximately 1, 2, and 5% more zinc than the mixture, 8-9 month release, and 5-6 month release period, respectively. After completing this experiment, only 5 to 10% of the initial zinc content was released from the fertilizer prills (Figure III.3).

DISCUSSION

Fertilizers compared in this study were manufactured by Simplot® using a technology developed by Pursell Technologies, Inc, known as "reactive layer coating" in which two reactive monomers are polymerized as they are applied to the fertilizer particles in a continuous drum. With this technology, nutrients release by osmotic diffusion at a rate controlled by the thickness of the coating (Goertz 1993). The different fertilizer release periods tested in this experiment were effective to a greater or lesser extent in delaying the delivery of certain nutrients such as ammonia, nitrate, phosphorus, potassium, sulfur, magnesium, and zinc. For all these nutrients, the fertilizer with the shortest release period (3-4 months manufacture rating) released the most nutrients at any point in time between weeks 13 and 62, while that with the longest release period (8-9 months manufacture rating) released the least. On the other hand, regardless of fertilizer release period and time since application, iron, manganese and molybdenum release was unaffected (Figure IV.3).

Results obtained from this study showed a rapid release of nutrients shortly after application. This is evident by looking at the slopes of the curves of the nutrients that exhibited a curvilinear release pattern, such as ammonia, phosphorus and potassium. In general, steeper slopes are obvious until the 35th week, after which they decline. These results agree with results of previous studies (Huett 1997a, Huett 1997b, Huett and Morris 1999, Huett and Gogel 2000) that there is a faster release of nitrogen compounds (NH_3 and NO_3) than other elements such as potassium and phosphorus (Figure IV.1).

Assuming that these fertilizers were incorporated into the soil close to a seedling root system at the time of establishing a forest plantation in winter, we might expect to provide the seedling with an adequate nitrogen supply during the first 6.5 months (28 weeks) after planting. This coincides with the period of time when seedlings develop new roots to become established and start growing. Depending on the fertilizer nominal release period used, soil and growing conditions, nitrogen supply may be extended even into the second growing season. It would be desirable, however, to also provide nutrients other than nitrogen to promote early seedling growth, which was not accomplished with the fertilizers tested in this study.

Fertilizer release periods observed in this study for the different fertilizers, differed somewhat with the release periods specified by the manufacturer. Among macronutrients, nitrogen compounds (NH_3 and NO_3) and potassium were the nutrients delivered at highest amounts during the 14 months (62 weeks) after application. For the same period of time, less than 50% of phosphorus, magnesium and sulfur, and less than 10% of all other nutrients were released. This may explain the lack of response in foliar nutrient concentration other than nitrogen found in various fertilization outplanting studies (1999 NTC annual report). Nominal release periods specified by manufacturers are established at a base temperature of 21°C, which was not representative of maximum average soil temperatures at the study site (Table IV.6). Only during July and August, soil temperatures reached 21°C.

Table IV.6. Monthly average soil temperatures at the study site and monthly rainfall at Corvallis, OR.

Date	Weeks since fertilizer application	Average soil temperature °C	Maximum soil temperature °C	Monthly rainfall (mm)
Feb-00	0	-	-	151
Mar-00		7.6	10.9	88
April-00		11.4	24.4	41
May-00	13	13.7	18.5	70
June-00	20	17.6	18.9	30
July-00		19.5	20.6	4
Aug-00	27	20.1	21.1	0
Sept-00		17.2	18.2	14
Oct-00	34	13.1	13.7	75
Nov-00	41	7.8	9	70
Dec-00		6	9.2	108
Jan-01	48	5.5	6.2	36
Feb-01	55	5.7	6.2	28
Mar-01		7.9	8.5	71
April-01	62	9.4	10.3	55

Similarly, soil moisture content may have slowed down nutrient release from the fertilizers. During the winter of 2001, monthly rainfall was considerable lower average (Table IV.6). The mechanism by which nutrients are released from polymer-coated, controlled-release fertilizers requires the diffusion of water vapor from the surrounding soil through the coating into the fertilizer. Water vapor condenses inside the prill, dissolves the particles, and builds enough hydrostatic pressure to expand the micropores of the coating through which fertilizer solution flows outward (Goertz 1993). It has been suggested that water-vapor diffusion into the fertilizer is the process that limits fertilizer release rate (Kochba et al. 1990). More rapid release rates of polymer-coated, controlled-release fertilizers have been measured in soils between 50 and 100% of field capacity than in similar soils with 25 and 0% of field capacity. In the latter conditions, there was no nutrient release at all (Kochba et al. 1990).

Soil pH may also have played an important role in reducing release of phosphorus, iron, manganese, zinc, and molybdenum from the fertilizer prills. The soils of the experimental site had a pH of 5.6 (Table IV.2), which is considered acid. Under these acidic conditions, phosphorus particles tend to be adsorbed to other mineral nutrients such as iron and aluminum to form insoluble compounds such as hydroxyapatite, variscite, strengite and vivianite (Havlin et al. 1999, Mengel and Kirkby 2001). Since magnesium, sulfur, and all the micronutrients were present in lower amounts than phosphorus within the fertilizer prills, it is reasonable to believe that part of these nutrients were adsorbed to phosphorus particles forming insoluble compounds. Thus only the phosphorus portion that was not adsorbed with the metals was able to be dissolved by water and diffused from the fertilizer, leaving the insoluble metal-phosphate compounds inside the prill membrane. Unfortunatelly for this study, nutrient analysis did not determine the characteristics of the compounds present in the fertilizer prills.

CONCLUSIONS

In general, fertilizer with shorter release period tended to deliver nutrients more rapidly than fertilizer with longer release period. Fertilizer release period did not affect the delivery of iron, manganese and molybdenum.

Nominal fertilizer release periods established by the manufacturer are not representative of nutrient delivery periods when controlled-release fertilizer are used in the field where they are exposed to a wide range of soil temperature, moisture, and pH. They should only be used as a reference of fertilizer characteristics.

Although further investigation is required, fertilizer mixtures that include phosphorus and metals such as iron, manganese, zinc, and molybdenum may not be suitable for use in acid soils, because part of the phosphorus may be adsorbed to the metals and form insoluble compounds.

This study had a significant impact in the manufacturing process of controlled-release fertilizers by Simplot®. This company already changed the phosphorus delivery mechanisms within their controlled-release fertilizers by incorporating phosphorus alone into a separate prill within the N-P-K fertilizer.

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CHAPTER V GENERAL CONCLUSIONS

This thesis confirmed that the use of high quality Douglas-fir bareroot seedlings, determined by the size of their root system improved reforestation success by increasing both seedling survival and growth rates during the initial establishment stages of a forest plantation.

Simplot Polyon® (19-6-12) and Osmocote Plus® (15-9-11) CRF's, applied to 1+1 Douglas-fir seedlings at the time of planting should be used with caution on sites with a prolonged dry season. In both outplanting studies I found that application of both products to the rooting zone of 1+1 Douglas-fir seedlings, stimulated shoot and diameter growth during the first growing season at the expense of restricting root development, producing seedlings with high shoot-root ratios. When exposed to drought during the second growing season, seedling survival and growth was significantly reduced relative to unfertilized seedlings in the root-volume experiment (Chapter II) and surface and dibbled fertilizer placements (Chapter III).

This thesis also demonstrated that nominal release periods of different Simplot Polyon® CRF's specified by the manufacturer of the fertilizer did not coincide with the nutrient release observed when they are applied in the field and should only be used as a reference. Among nutrients within fertilizer prills, nitrogen is released faster and in higher amounts than all other nutrients, affecting nutritional balance of seedlings when applied close to the root system in reforestation operations. Thus further research is recommended on the development of controlled-release fertilizers to deliver nutrients in balanced amounts through the growing season to match nutrient demand by the seedling without significantly restricting root development.

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