OPTIMUM FERTILIZATION OF HYBRID POPLAR PLANTATIONS IN COASTAL BRITISH COLUMBIA

by

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ABSTRACT

The principles of optimum nutrition were examined in a short-rotation intensive-culture (SRIC) hybrid poplar plantation near Sayward, B.C. One-year-old SRIC hybrid poplar (*Populus trichocarpa* x *P. deltoides*) were fertilized with N or NPK applied once, in 3 equal additions, or in 3 incremental additions. Total loading rates were 225 kg N/ha, 75 kg P/ha and 75 kg K/ha. Height and diameter growth increased after fertilization, with NPK generally providing the best response after two growing seasons. Application timing did not affect growth. Two-year-old hybrid poplar were fertilized with N, NP, NPK or NPKS. Total loading rates were 225 kg N/ha, 75 kg P/ha, 75 kg K/ha and 15 kg S/ha. Height and diameter growth were highest after one growing season in trees fertilized with NPKS. One-month-old poplar stecklings were fertilized with 5 nutrient combinations (N, NK, NP, NKP or NKPCaMg) at 4 rates (0, 150, 300 or 450 kg N/ha). Loadings were based on 100N:70K:13P:7Ca:7Mg. Biomass, leaf area and foliar nutrient concentrations were measured after 17 weeks. Foliar nutrient concentrations and contents increased after fertilization. Additional nutrients, in combination with N, increased steckling biomass, but application rate did not. Growth responses to 5 organic wastes and NPK fertilizer were compared in a second pot bioassay. Biomass, leaf area and foliar nutrient concentrations were measured after 17 weeks. The greatest growth response was to organic wastes, particularly fish-wood compost. Application of these results to SRIC hybrid poplar nutrition are discussed.

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INTRODUCTION

Poplar Management

The genus *Populus* comprises fast-growing trees that respond well to management in native stands (Van Cleve and Oliver 1981) and in intensively managed plantations (Anderson 1977; Heilman et al. 1972; McLaughlin et al. 1987). *Populus* species produce biomass at higher rates than most north-temperate woody species (Dickman et al. 1992). The high level of biomass per unit land area, and the relatively short rotation length of managed *Populus* stands, make them attractive for the production of veneer, composite wood products, pulp and paper, forage, and energy (Adams and Taylor 1986).

Crosses between poplar species (genetic hybrids) have demonstrated exceptional vigour (Stettler et al. 1988). Hybrid poplars have considerable potential in forestry because they are easily cloned; desirable traits such as growth rate, low susceptibility to disease, branching habit, and wood characteristics can be manipulated (McLennan and Mamias, 1992). The primary end use of hybrid poplar is pulp fibre. Poplar fibre is brighter than conifer fibre, which significantly lowers the cost of producing high value printing papers. When mixed with softwood kraft pulp, it is suitable for book, computer, offset printing and other high quality paper products (Clayton 1968). In British Columbia there are at present more than 2000 ha of hybrid poplar plantations. This is likely to increase as the landbase for harvestable forests shrinks and the demand for forest products increases.

Understanding the nutritional requirements of *Populus* species is essential for designing effective management regimes. The importance of manipulating site fertility as a component of management regimes is increasing throughout the Pacific Northwest. The basic ways of managing site fertility are to increase nutrient input and to decrease nutrient removal (Hansen 1986). Because *Populus* spp. can produce large amounts of biomass during a limited time on a limited land area, they are also capable of removing large amounts of nutrients from the site. The nutritional requirements of poplars can be met through inorganic fertilization (Safford and Czapowskyj 1986, Van Cleve and Oliver 1981), organic fertilization (Carlson 1992; McIntosh et al. 1984; Thomas et al. 1994), thinning (Perala and Laidly 1989) and N retention by a cover crop

(Blackmon 1977; McLaughlin et al. 1985). Poplar management can be divided into two areas: management of native stands, and management of plantations.

Native Stands

Frequently, native stands are mixtures of several broadleaved species. Managing them involves fertilization and thinning. Fertilization supplies required nutrients, and thinning reduces competition from non-crop or same-crop trees. Schmitt et al. (1981) suggested that fertilization of native hardwood stands can decrease rotation length by increasing the biomass of fertilized stands beyond unfertilized levels. This would achieve a target biomass or tree size in a shorter time. A short rotation length in *Populus* is desirable not only for the associated economic gains, but also for wood quality, because reduced rotation lengths allow less time for disease establishment.

Perala and Laidly (1989) evaluated the effects of thinning and N fertilization on a mixed stand of quaking aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marsh.), balsam fir (*Abies balsamea* (L.) Mill.) and balsam poplar (*Populus balsamifera* L.). Ammonium nitrate (168 kgN/ha) was applied to 5- and 10-year-old saplings alone and in combination with removal of non-crop species. There was a substantial increase in aspen height and diameter in response to thinning, and a slight increase in response to thinning plus fertilization. Nitrogen fertilization alone provided little measurable benefit. In Maine, Schmitt et al. (1981) applied N, P and lime to a 22-year-old mixed forest with bigtooth aspen, quaking aspen, red maple (*Acer rubrum* L.) and paper birch in the overstorey, and red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* L. Mill.) in the understorey. After 3 years, fertilization increased total aboveground N and P content and biomass production of bigtooth aspen and paper birch by more than 150%. Ten-year growth responses were measured by Safford and Czapowskyj (1986). All of the species present responded to N, and the aspens in particular responded to N+lime. Fertilization with N and P increased individual quaking aspen tree size, but it also increased mortality as compared to the control and N+lime treatments, resulting in a net decrease in basal area. Therefore, N seemed to accelerate mortality (which also occurred in the control stands) and lime reduced it (Safford and Czapowskyj 1986). In explanation, Safford and Czapowskyj (1986) suggested that N application increased the rate of self-thinning through competition for available resources, resulting in the elimination of weaker trees from the stand. The reduction in quaking aspen basal area in the presence of competing species, and the accelerated reduction with N fertilization, could explain the findings of Perala and Laidly (1989). They found that the basal area of quaking aspen stands increased with removal of non-crop or competing trees of the same and different species (thinning), and that N fertilization increased basal area only with thinning.

In a study near Fairbanks, Alaska, Van Cleve and Oliver (1981) found that N fertilization significantly increased the biomass of quaking aspen on a burned site. Phosphorus fertilization increased biomass to a lesser extent, and K fertilization resulted in a slightly lower ($p > 0.05$) biomass than the controls. A large growth response resulted from application of N and P, suggesting that the N addition caused an increased P demand which could not be met by soil reserves. Nitrogen use efficiency was high in untreated and K fertilized plots, despite the general reduction in growth measured in the K fertilized plots (Van Cleve and Oliver 1981). Quaking aspen is extremely sensitive to moisture stress (Perala and Laidly 1989). The reduced growth in the K fertilized plots may have resulted from exacerbated moisture stress due to an increase of salts in the soil solution, following KCl application in a semiarid climate (Van Cleve and Oliver 1981). Fertilization with KCl also decreased the soil biological activity which would have affected N mineralization. The result was a limitation of growth but a greater amount of biomass produced per unit leaf area (Van Cleve and Oliver 1981) i.e. a higher nitrogen use efficiency (NUE) or a higher amount of biomass produced for each unit of N used.

Plantations

It is apparent from investigations into the nutritional requirements of *Populus* spp. growing in native stands that many factors interact to affect productivity, such as stand species composition, genetic variability of the crop trees, and site. Much of this variability can be reduced by growing poplar in short-rotation, intensive-culture (SRIC) plantations. These plantations have rotations of 15 years or less, and consist of single species, single clone stands of genetically superior trees planted on well prepared and intensively managed sites. The use of genetically identical clones results in a reduction of the between-tree variability seen in native stands. Trees are planted at regular intervals, fertilized, and cultivated or treated with herbicides for weed control. Plantation spacing controls inter-tree competition, and weed control reduces competition for moisture from the minor vegetation (Heilman 1972, McLaughlin et al. 1987).

Inorganic Fertilization

Fertilization of SRIC poplar plantations has been shown to increase productivity. Heilman et al. (1972) evaluated the response of black cottonwood (*Populus trichocarpa* Torr. and Gray) in short rotations to 3 spacing alternatives and 3 fertilization regimes. The highest yields in the first year were at the closest spacing (0.3 x 0.3 m) and with the addition of N, P, and K. Spacing and fertilization did not affect yield in the second season, however, they did affect mortality which was greatest at the closest spacing (Heilman et al. 1972). Recent trends in SRIC plantations have led away from short term coppice plantations, toward rotations of 7 years or more (Heilman and Stettler 1990).

Ammonium nitrate applied to SRIC eastern cottonwood (*P. deltoides* Bartr.) in Mississippi doubled the yield in the year of application and in the year following (Blackmon 1977). In Washington, application of 167 kg N/ha/yr as ammonium nitrate in the second, third and fourth growing seasons resulted in a 24% increase in dry weight of hybrid clones of *P. trichocarpa* x *P. deltoides* (TxD) (Heilman and Xie, 1993). This was the result of a 40% increase in dry weight at the end of year 3 and an 8% increase in dry weight at the end of year 4.

Fertilization With Organic Wastes

An alternative to inorganic fertilizers is the use of organic wastes as forest fertilizers. Organic wastes can supply N, P, and K and a variety of other macro and micronutrients. In theory, because much of the nutrients are in organic form, they should be made available to the plant slowly, through mineralization, over an extended period. Large growth responses to sewage sludge applications have been measured in forests of coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Cole et al. 1984), white spruce (*Picea glauca* (Moench) Voss) (Gagnon 1973), loblolly pine (*Pinus taeda* L.) (McKee et al. 1986), Corsican pine (*Pinus nigra* var. *maritima* (Ait.) Melville) (Moffat et al. 1991), and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (Bayes et al. 1987). Fertilization trials with fish silage and sewage sludge, applied to chlorotic cedars on a cedar-hemlock cutover on northern Vancouver Island, resulted in increased height and diameter growth (McDonald et al. 1994). Sewage sludge applied to chlorotic cedar, hemlock and amabalis fir at a nearby site also resulted in increased tree growth (Weetman et al. 1993).

Increased yields have also been observed with organic waste applications to SRIC poplar plantations. Carlson (1992) reported high yields of hybrid poplar trees in demonstration plots near Vernon, BC, following application of sewage effluent. However, because they were demonstration plots there were no controls with which to compare growth in the treated plots. Application rates increased through the growing season, and over several growing seasons coinciding with increased tree requirements. At the time of the report, a total of 158 kg N/ha, 60 kg P/ha and 120 kg K/ha had been applied in the fifth growing season. Application of organic wastes to poplar plantations has also involved solid wastes. Thomas et al. (1994) reported 20-30% increases in growth of TxD hybrid poplars in a plantation in coastal British Columbia fertilized with municipal sewage sludge. Application of pulp and paper sludge to a TxD poplar plantation in Washington resulted in a tripling of tree growth (Henry and Harrison, unpublished report). SRIC plantations are well suited to organic waste use because the trees are regularly spaced and cultivated between rows which allows for easy application.

Nutrient Retention

The proportion of applied N recovered by the trees in a plantation is often less than 20%, unlike agricultural crops which average >50% recovery (McLaughlan et al. 1987). McLaughlan et al. (1987) used cover crops to enhance N retention in an irrigated SRIC poplar plantation. Fertilization of TxD hybrids with 112 kg N/ha/yr for 4 years resulted in significant increases in tree biomass on plots with a ground cover of native weeds or trefoil, as compared with fertilized, bare-ground plots. Growth of trees in the ground-cover plots was lower than in the bare-ground plots during the first three years. But by the end of the fourth growing season, total tree biomass in the ground-cover and fertilized plots was greater than in the bare-ground and fertilized plots. The change between year 3 and 4 represented a shift from a cover-crop dominated system to a tree dominated system. At the end of 2 years, most of the applied N was recovered in the minor vegetation, but at the end of 4 years, most was recovered in the trees. There was a large reduction in the below-ground biomass of the minor vegetation and a corresponding increase in tree biomass. Recovery of N from the cover-crop system was 44 - 51%, compared with 15% from the bare-ground plots (McLaughlan et al. 1987). Irrigation eliminated competition for moisture from the minor vegetation, therefore the benefits of N retention by the minor vegetation could be utilized. When moisture is a limiting factor, the benefits of N retention by the ground cover can be overridden by the negative effects of competition for moisture with the crop trees. Therefore, in non-irrigated plantations the approach has been to control the minor vegetation through the use of herbicides or cultivation.

Nutrient Removal and Nutrient Use Efficiency (NUE)

The amount of nutrients removed by hybrid poplars varies with the individual clone. Nutrient removals in the bole and branches of 4-year-old *Populus* harvested in the dormant season were reported by Heilman (1992) (Table 1). This shows the degree of variability within the genus *Populus* and among clones of the same species. Similarly, the nitrogen use efficiency (NUE) or amount of biomass produced per unit of nitrogen, also varies. Several black cottonwood clones, TxD clones and a Robusta (Euramerican hybrid) clone (*P. deltoides* x *P. nigra*) were irrigated and fertilized with 225 kg N/ha in the third and fourth growing seasons (Heilman and Stettler 1986). Two of the TxD hybrids produced the highest biomass, but a black cottonwood clone had the highest NUE.

Table 1: Nutrient removals in dormant season harvest of *Populus* at 4 years of age.

Material	Age	Biomass (Mg/ha)	Nutrient content in above-ground boles and branches (kg/ha)			
			N	P	K	Ca
Black cottonwood	4	29-72	95-223	14-34	-	80-205
Eastern cottonwood	4	27-34	101-128	18-22	92-118	203-262
Hybrid (TxD) poplar	4	44-111	241-420	41-105	-	159-288
Hybrid poplar	4	37	213	31	86	126

from Heilman (1992)

Optimum Nutrition

In agriculture, potentially limiting nutrients are applied once at the start of the growing season and repeated annually. In contrast, forest fertilizers are applied only once, or every few years. The proportion of the applied nutrients taken up by tree crops is typically less than 30% and is often only 10-20% of the amount applied (Binkley 1986). Most of the applied nutrients are immobilized in microbial biomass and soil organic matter, and a proportion can be lost from the soil system through volatilization and leaching. Increases in tree growth after single, large fertilizer applications are temporary, usually lasting only 5-10 years (Binkley 1986).

In tree nurseries, nutrients are usually applied once, at the start of the season, or split into several equal doses and applied as top dressings during the season (Imo and Timmer 1992). Potential problems arising from these practices include an initial nutrient toxicity due to an excess of nutrients, and a deficiency at later stages when the supply no longer meets the nutrient requirements of the plant (Imo and Timmer 1992). These problems may be greater with single than with split applications. However, because conventional regimes involve the use of several equal doses to supply a total loading adequate for plant growth, a surplus of nutrients is supplied to the seedlings at the start of the growing season and there may be a deficit at the end (Figure 1). A nutrient supply which more closely matches plant demands would provide better nutrition and reduce nutrient waste.

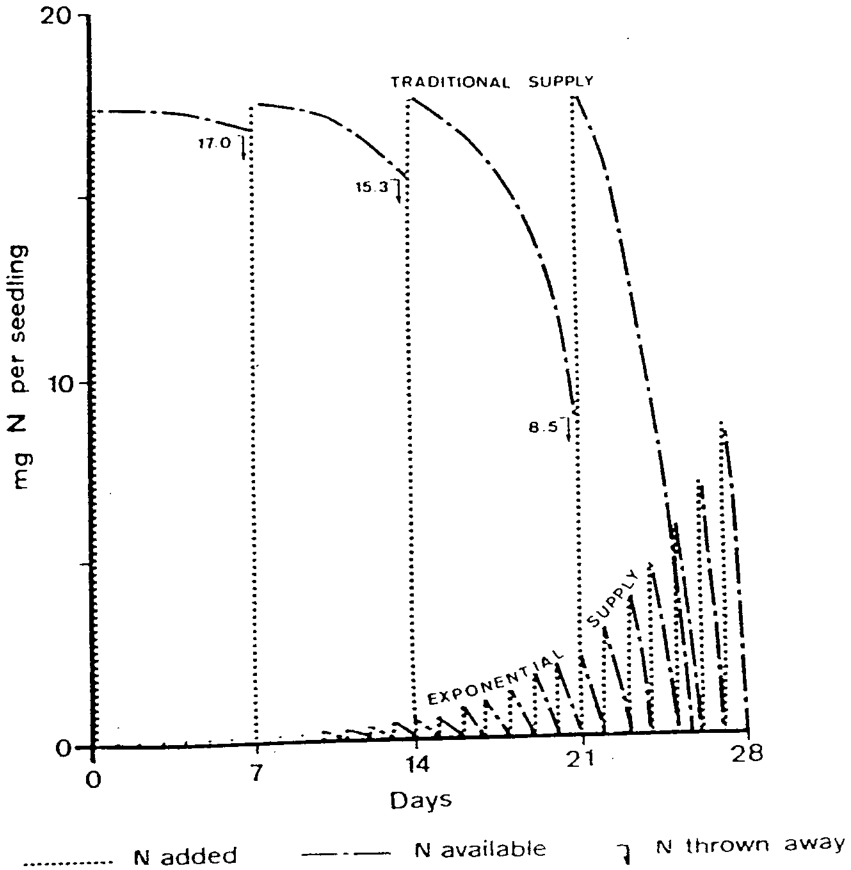

Figure 1: Comparison between traditional and exponential supply of nitrogen. mg N per seedling = N available to the seedlings; N thrown away = supplied N not used by the seedlings but available. Growth rate and nitrogen consumption rate are assumed to be equal for the two systems. In the traditional method, the nutrient solution is changed once a week, making 17.5 mg N available per seedling each time. During the week, the growing seedlings diminish the remaining amount of available nitrogen, slowly in the beginning and more and more rapidly later on. By the fourth week the amount of nitrogen supplied satisfies consumption only for about 4.5 days and the rest of the week no nitrogen is available. With the exponential supply (here shown as daily amounts) the amount of nitrogen is always the same as consumed. (from Ingestad 1977)

Deficiencies or toxicities of some nutrients may also result from an imbalance in nutrient supply after conventional fertilization. Ingestad and Kahr (1985) observed luxury uptake of phosphorus, potassium, calcium and magnesium when nitrogen limited growth of Scots pine (*Pinus silvestris* L.), lodgepole pine (*Pinus contorta* Dougl. ex Loud) and Norway spruce (*Picea abies* Karst.). Brockley (1992) observed that nitrogen additions to lodgepole pine stands in the interior of British Columbia may induce or aggravate S deficiencies. Similarly, Teng and Timmer

(1990) found that high phosphorus treatments induced Zn and Cu deficiencies in hybrid poplar clones.

Problems encountered in conventional fertilization can be overcome by applying the principles of optimum nutrition. Crops are repeatedly fertilized with small additions of nutrients, which more closely match plant uptake than single large additions. The principles of optimum nutrition theory developed by Ingestad in 1971 can be outlined as follows: (i) nutrient concentrations in the rooting medium must be adequate for uptake and must be maintained throughout the growing season, (ii) the ammonium/nitrate ratio within the rooting medium must be suitable, and (iii) nutrients must be maintained in the plant in the required proportions (Ingestad 1974). The latter two conditions provide the circumstances required for the maintenance of the first condition. The maintenance of optimum proportions of nutrients leads to the development of steady-state nutrition in which both tissue nutrient concentrations, and plant growth rate remain stable over time (Ingestad and Agren 1992). Stable nutrient concentrations in optimum proportions, at maximal growth, are achieved through fertilization regimes which are synchronized with plant requirements (Ingestad 1977). In contrast, conventional nutrient regimes are characterized by a rapid increase in foliar nutrient concentrations, followed by a gradual decline due to dilution (Timmer et al. 1990).

The optimal nitrogen concentration is the lowest internal nitrogen concentration which concurs with the maximum relative growth rate (Ingestad and Kahr 1985). N is then taken as 100 and the remaining macro and micronutrients added to the growing medium in fixed proportions (Ingestad 1987). Table 2 provides a list of nutrient ratios present in plants at optimum steady-state nutrition and maximum growth rate. Figure 2 illustrates the relationship between nutrient supply and growth or yield (Ingestad 1977). Optimum yield is achieved only when nutrient supply falls into the 'required supply' area of the curve.

Table 2. Proportions by weight of some nutrient elements (N=100) present in plants at optimum steady state nutrition and maximum growth.

Proportions by weight of some nutrient elements ($N = 100$) present in plants at optimum steady state nutrition and maximum growth; the required relative levels of the other necessary nutrient elements have also been estimated (Ingestad, 1979b)

Plant	K	P	Ca	Mg	Reference
Betula pendula	65	13	7	8.5	Ingestad, 1971
Vaccinium species	50	13	7	8.5	Ingestad, 1973a
Cucumis sativus	75	13	9	9	Ingestad, 1973b
Pinus silvestris	45	14	6	6	Ingestad, 1979b
Picea abies	50	16	5	5	Ingestad, 1979b
Picea sitchensis	55	16	4	4	Ingestad, 1979b
Pinus nigra	50	20*	5	4	Ingestad, 1979b
Larix kaempferi	60	20*	5	8.5	Ingestad, 1979b
Tsuga heterophylla	70	16	8	5	Ingestad, 1979b
Pseudotsuga taxifolia	50	30*	4	5	Ingestad, 1979b
Wheat, barley, oats, rye	80	17	5	5	Ingestad and Stoy, 1982
Salix species	72	14	7	9.5	Ericsson, 1981b
Alnus incana	50	18	5	9	Ingestad, 1980, 1981
Populus simonii	70	13	7	7	Jia and Ingestad, 1984
Paulownia tomentosa	75	20	8	9	Jia and Ingestad, 1984

*Luxury uptake probably involved (see Ingestad, 1979b).

from Ingestad (1987)

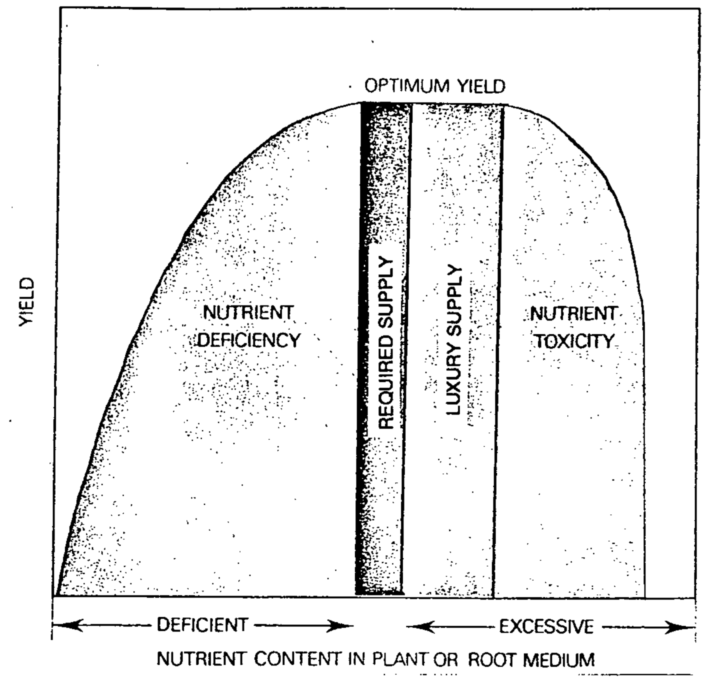

Figure 2: Effect on yield of increasing relative contents of a nutrient in the plant or root medium. The plateau of maximum yield is reached with the required nutrient supply and luxury nutrient supply. Excessive range includes both luxury supply and toxic supply. (from Ingestad 1974)

The driving force of growth at sub-optimum and optimum nutrition is the relative addition rate, based on the predetermined optimum internal nutrient ratios (Ingestad et al. 1981). Ingestad et al. (1981) found that relative growth rate was linearly correlated with relative addition rate up to the point of optimum nutrition. Therefore it is not specifically the concentration of nutrients in the growing medium which is the driving force of plant nutrition, but the nutrient flow which enters the plant. The relative addition rate can be regarded as a nutrient flux density or, the amount of nutrients available to the plant per units of time and area. In contrast, supra-optimum nutrition is caused by the external nutrient concentrations within the growing medium, not the relative addition rate. As the addition rate increases beyond optimum nutrition, the nutrients are not taken up in proportion to the additions. Nutrients accumulate in plant tissues and concentrations in the growing medium increase as the plant cannot use all of the nutrients supplied (Ingestad et al. 1981).

Steady-State Nutrition

During the seedling stage, plant growth is exponential. Therefore, the nutrients consumed per unit of time increase with increasing biomass (Ingestad and Lund 1986). It follows that the amount of nutrients supplied to the plant should also increase exponentially to compensate for those nutrients used. Application of a constant addition rate (R_a) has shown that the relative growth rate (R_g) becomes almost constant, and equals R_a during the exponential growth phase. R_a is linearly correlated with R_g. This is the principle of steady-state nutrition, in which R_a is equal to the relative uptake rate (R_u) and R_g (Ingestad and Lund 1986). However, it should be clearly stated that steady-state nutrition does not necessarily mean optimum nutrition. Optimum nutrition is the maximum point at which the relative addition rate is linearly correlated with relative growth rate (Ingestad 1981). Steady-state nutrition can occur at any point along that line. Another way of defining optimum nutrition is, the lowest internal nitrogen concentration at which the highest relative growth rate is still achieved (Ingestad and Kahr 1985). Steady-state nutrition can occur at internal nitrogen concentrations below this point.

Ingestad (1977) suggested that deficiency symptoms are a result of an unstable or changing nutrient stress rather than a constant stress. Stress symptoms in *Betula verrucosa* Ehrh appeared with rapidly changing internal nutrient status; these symptoms disappeared once the seedlings had adapted to new, lower nitrogen addition levels. In a similar set of trials, Ingestad and Kahr (1985) used various nitrogen addition rates with Scots pine, lodgepole pine and Norway spruce. Seedlings were established under optimum conditions for a pre-treatment period, followed by an adjustment period, and then a growth period during which growth was controlled by the various nitrogen addition rates. All seedlings encountered a lag phase during which they showed deficiency symptoms while adjusting to their specific nutrient regime. This was subsequently followed by steady-state nutrition at all rates. Needles turned green again, the internal nutrient concentrations stabilized, and the root:shoot ratio stabilized at a level in keeping with the treatment.

Optimum Nutrition in Practice

Nursery Trials

Ingestad worked with nutrient solution techniques in which the solution was a vector for transport of the nutrients to the roots (Ingestad and Lund 1986). Solution culture is not a practical method for production in the field, but it illustrates the need to tailor fertilization practices to plant requirements. In nursery trials with peat media, Timmer and Armstrong (1987b) measured red pine (*Pinus resinosa* Ait.) seedling growth in response to a conventional fertilization regime which supplied the seedlings with a recommended dose twice weekly over a 12-week period. Alternative treatments were an equal dosage, a half-rate dosage, and a one-quarter-rate dosage applied exponentially over the same period. The seedlings which were supplied with one-quarter of the recommended rate in an exponential fertilization regime yielded the best growth (Timmer and Armstrong 1987b).

Timmer and Armstrong (1987a) observed that induced deficiencies of a single element in red pine seedlings decreased uptake of other elements, even when they were supplied in ample quantities. This agrees with one of the conditions of optimum nutrition, that nutrients must be present in the plant in the required proportions. If the plant requires an optimal ratio of nutrients for optimal growth, deviation from that ratio will affect growth. It therefore follows that changes in any of the existing tissue nutrient concentrations will affect the current ratio, which will also influence uptake and growth whether nutrients are in optimum proportions or not.

Seedling roots in a soil or soil-like medium have limited access to nutrients due to their limited penetration of the growing medium. By supplying container-grown mesquite (*Prosopis chilensis* Mol.) seedlings with an initially elevated rate of nutrient solution, followed by a traditional exponential regime, Imo and Timmer (1992) were able to induce steady state nutrition 4 weeks sooner than with the pure exponential regime; this allowed the plants to maintain vigorous growth and nutrient uptake for a longer period (Imo and Timmer 1992).

The importance of exponential fertilization regimes in greenhouse or nursery production lies in their potential to improve growth as compared with conventionally fertilized seedlings, as well as possibly improving outplanting performance in the field. Additionally, the potential to use a decreased amount of fertilizer would lower production costs, and reduce waste of fertilizer and potential for seedling damage from high levels of fertilizer salts in the growing medium. The major drawback to such a regime would be that it is complex, involving changing rates and frequent applications. In nursery practice this could easily be accomplished through use of computerized systems of fertilizer injected into the irrigation water (fertigation).

Field Trials

The use of optimum nutrition principles in the field presents a more complex problem involving a highly variable growing substrate (the soil), limitations such as site access, application costs, and prediction of tree growth response. Tamm (1991) outlined optimum nutrition experiments conducted in Sweden with Norway spruce. Four levels of N were applied on a yearly basis and 3 levels of P, with or without K and micronutrients, were applied every 3 years. Application rates were highest in the first 3 years of the experiment, decreased in the following 7 years, and decreased again in the next 10 years. Ingestad (1987) proposed that addition rates be reduced as the trees grew older because fertilization would increase the leaf and root biomasses to the maximum, which would in turn maximize litter returns to the soil. As internal cycling and nutrient return through litter input became of increased importance, the dependance on fertilization to maintain growth would decrease. In practice, this management regime resulted in steady state conditions with respect to nitrogen supply, foliar concentration levels, foliar production, and growth of the spruce (Tamm 1991). The internal nutrient concentrations of the trees yielding the highest growth rates approached the theoretical Ingestad ratios (Ingestad 1987). A similar set of experiments was initiated with Scots pine in 1974, however, this time irrigation was introduced (Ingestad 1987). Fertilizer was injected into the irrigation water (fertigation) and distributed on the plots 5 days a week during the growing season. There was a substantial growth increase in response to both the fertilization and fertigation treatments (Ingestad 1987). Axelsson (1985) summed up the gains from the yearly fertilization trials in Sweden as having the potential to increase mean annual increment of pine by 300% and spruce by 150%.

The use of sewage effluent to irrigate forages and forested land near Vernon, B.C. has resulted in a fertigation system able to synchronize nutrient application with uptake requirement. The trees were irrigated with 30 cm of sewage effluent in the first growing season, increasing to 75 cm in year 5. The plantation was irrigated weekly supplying 158 kg N, 60 kg P, and 120 kg K /ha in year 5. Nutrients were supplied throughout the growing season, and application rates increased on a yearly basis as tree demand increased. This approximates Ingestad's concept of supplying the plant with all of its required nutrients as needed. Monitoring of relative growth rate and foliar nutrient concentrations is required to confirm that the fertilization regime has achieved steady-state conditions.

It may not be practical to fertilize field sites on a weekly or monthly basis if fertigation is not an option. However, the theories of optimum nutrition can be applied on a yearly basis as illustrated by the Swedish trials with Norway spruce. There are several field experiments in North America in which tree growth has improved through practical application of the principles of optimum nutrition. Ten-year results of 45-year-old jack pine (*Pinus banksiana* Lamb.) fertilized with three nitrogen levels, with or without P and K, at 2 year intervals indicated a sustained positive growth response to the lowest nitrogen level (56 kg/ha/2 years) used (Weetman and Fournier 1984). van Miegroet et al. (1994) fertilized a 1-year-old American sycamore (*Platanus occidentalis* L.) plantation with a total of 450 kg N/ha as urea over a 3-year period. Treatments included a single application in the first year; an even split of 150 kg N/ha applied each year for 3 years; applications of 50 kg N/ha 3 times per year for each of 3 years; and annual incremental doses of 50, 150 and 250 kg N/ha. Stem biomass production was greatest for the annual incremental doses, which increased as tree requirement increased (van Miegroet et al. 1994).

Because the use of optimum nutrition practices are management-intensive, the capital costs of these regimes are higher than costs of conventional fertilization practices. However, the potential gains in product quality and quantity are very high, and may be realized very quickly with a fast-growing, nutrient-demanding species such as hybrid poplar, growing in SRIC plantations.

Thesis Objectives

In this study, I tested the potential for applying the principles of optimum nutrition to increase the growth of hybrid poplar in SRIC plantations. Four major questions were addressed in four trials. (1) Which nutrients are required for optimum growth of hybrid poplar? This was addressed in two field trials and one nursery trial, which tested hybrid poplar growth response to different nutrient combinations. (2) At what addition rate should the nutrients be applied? This question was addressed by a nursery trial which tested nutrient application rates as well as nutrient combinations. (3) At what timing or frequency should fertilizer be applied within a growing season? The trial used to address this question tested the effects of three fertilizer application frequencies on tree height and diameter growth. (4) Do organic wastes have potential as fertilizers for hybrid poplar? This final question was addressed by a pot trial testing hybrid poplar growth response to five different organic wastes as compared with inorganic fertilizer and untreated controls.

STUDY AREA AND SITE DESCRIPTION

Field Trials

The site chosen for the 1993 and 1994 field trials was a clonal evaluation site established by MacMillan Bloedel Limited in 1992. It is located at Sayward, B.C. on the east coast of Vancouver Island in the Coastal Western Hemlock (CWH) biogeoclimatic zone. The climate is characterized as cool mesothermal with cool summers and mild winters (Meidinger and Pojar 1991). Weather data was obtained from the Environment Canada weather station at Chatham Point, at which only precipitation data were available (Table 3).

Month	Precipitation (mm) 1993	Precipitation (mm) 1994
January	198.5	247.6
February	24.9	372.7
March	246.3	201.1
April	409.4	171.3
May	230.5	82.5
June	116.5	159.8
July	111.1	not available
August	124.8	not available
September	6.4	not available
October	125.3	not available
November	209.0	not available
December	375.1	not available
Total	2177.8	1235.0

Table 3: Mean monthly precipitation for 1993 and 1994 at Chatham Point, near Sayward, B.C.

Prior to cultivation, the site was occupied by red alder (*Alnus rubra* Bong.). A small proportion of the site had also been a farm field. The current study was entirely on the alder site. The alder was harvested in 1991, and the site was windrowed and cultivated. 60 cm cuttings of 4 hybrid poplar clones were planted at staggered 3 x 3 m spacings in the spring of 1992.

For the purposes of this investigation, two different clones were used in the 1993 and 1994 fertilization trials: clone 1 was used for the 1993 trial at sites 1, 2 and 3; clone 2 was used for the 1994 trial at site 4 (Figures 3 and 4). The sites were on an alluvial floodplain. Soil characteristics of each site were as follows (Table 4):

Site	Depth	% Total N	% Carbon	C/N	C.E.C.
1	0-15 cm	0.31	7.09	22.87	38.26
	15-30 cm	0.27	5.90	21.85	38.61
2	0-15 cm	0.15	3.73	24.87	27.70
	15-30 cm	0.09	2.52	28.00	23.87
3	0-15 cm	0.32	6.66	20.81	39.54
	15-30 cm	0.25	5.00	20.00	36.33
4	0-15 cm	0.36	6.34	17.61	38.71
	15-30 cm	0.31	5.10	16.45	38.32

Table 4: Soil characteristics of sites 1, 2 and 3 (trial 1) and site 4 (trial 2).

Nursery Trials

The 1993 and 1994 nursery trials were conducted at the University of British Columbia Forest Nursery on the UBC campus at Vancouver, BC. The site is in the CWH biogeoclimatic zone. The climate is characterized as cool mesothermal with cool summers and mild winters (Meidinger and Pojar 1991). Weather data were obtained from the Vancouver Airport weather station (Table 5).

Month	Temp. (°C) 1993	Precipitation (mm) 1993	Temp. (°C) 1994	Precipitation (mm) (1994)
March	7.4	115.2	7.2	103.2
April	10.0	126.9	14.3	65.0
May	14.7	100.8	18.0	39.6
June	15.8	72.2	15.0	70.5
July	16.4	34.3	18.5	27.4
August	17.6	19.0	18.5	18.0
September	14.8	2.1	15.7	65.6

Table 5: Mean monthly temperatures and precipitation from March to September of 1993 and 1994 at the Vancouver Airport, Vancouver, B.C.

Figure 3: Sayward study site: clone 1, used in trial 1, is located at sites 1, 2 and 3; clone 2, used in trial 2, is located at site 4. (MacMillan Bloedel Limited)

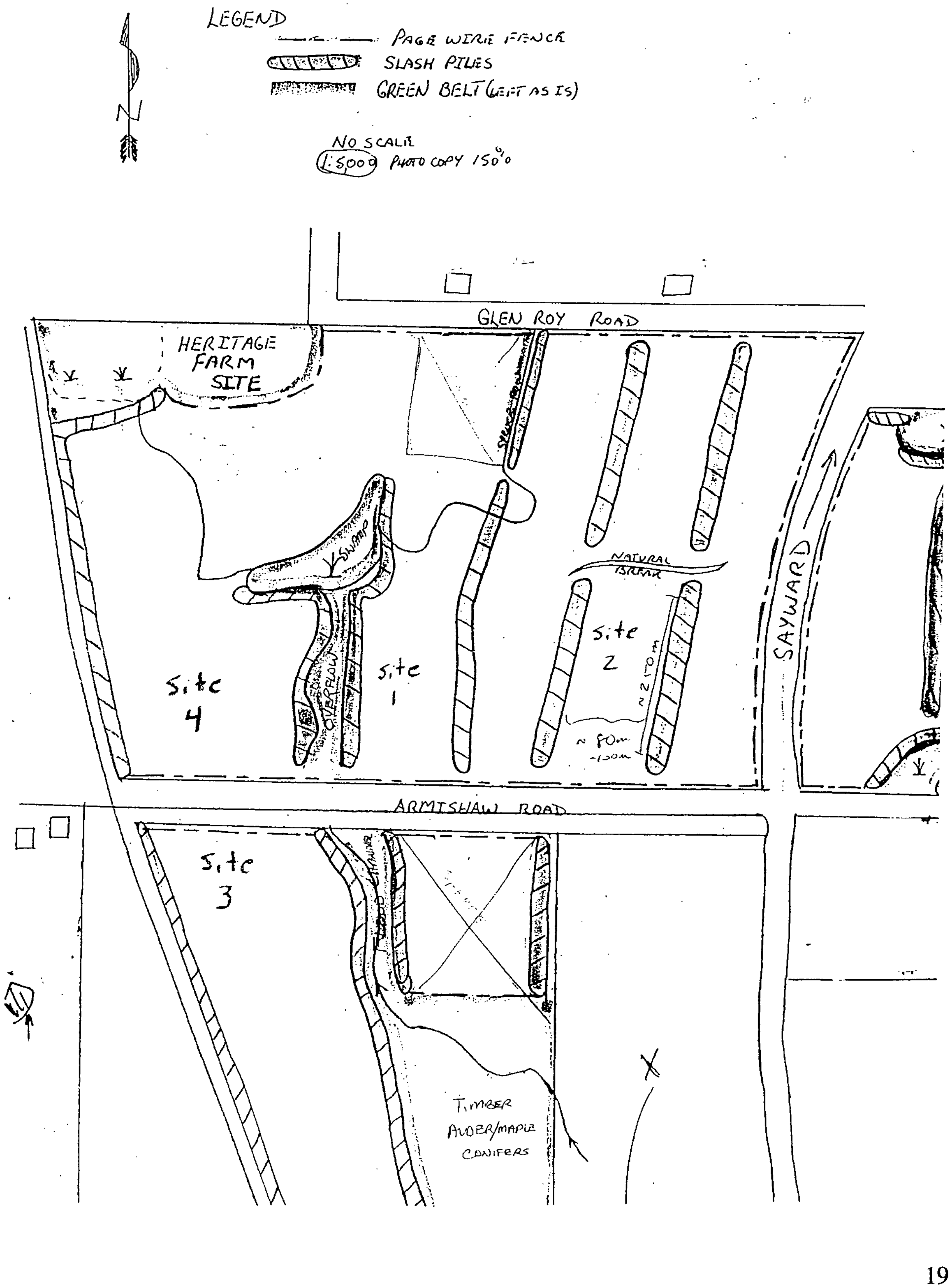

Figure 4: Sayward study site: clone 1, used in trial 1, is located at sites 1, 2 and 3; clone 2, usied in trial 2, is located at site 4.

METHODS

Field Trials

Trial 1: Tree growth response to application timing and nutrient combination

Seven fertilizer regimes were applied to a plantation of cloned SRIC (short-rotation intensive-culture) hybrid poplar entering their second growing season. The numbered clone used was a TxD (*Populus trichocarpa* Torr. and Gray x *P. deltoides* Bartr.) clone (clone 1), produced from a hybridization between *P. trichocarpa* from Granite Falls, WA and *P. deltoides* from Illoos, IL. The trial was arranged in a randomized complete block design with each of the 7 treatments randomly allocated within each block. Experimental units (plots) were 20 x 20 m with an inner 15 x 15 m sample area, and 10 m non-treated buffer zones. The seven treatments were as follows: a non-treated control, N applied once in the spring @ 225 kg/ha, N applied in three equal doses at 6 week intervals (75, 75, and 75 kg/ha), N applied in incremental doses at 6 week intervals (50, 75, and 100 kg/ha), N+P+K applied once in the spring @ 225 kg N/ha, 75 kg P/ha, and 75 kg K/ha, N+P+K applied in three equal doses at 6 week intervals (75, 75, 75 kg N/ha, 25, 25, 25 kg P/ha, and 25, 25, 25 kg K/ha), and N+P+K applied in three incremental doses at 6 week intervals (50, 75, 100 kg N/ha, 15, 25, 35 kg P/ha, and 15, 25, 35 kg K/ha). Nitrogen was applied as ammonium nitrate, phosphorus as triple super phosphate and potassium as muriate of potash. The plots were fertilized by hand and cultivated with a discer immediately after fertilization. Later during the season, they were disced twice more and rotovated once to control competing vegetation.

Height and basal diameter (diameter at 5 cm above junction with the cutting) were measured on 22 to 25 sample trees in each plot in April and November of 1993. The 1993 annual growth increment was calculated as the difference between the two measurements. Dbh (diameter at 1.3 m above the ground) was measured in May and October of 1994. Height was remeasured in October 1994. The 1994 annual growth increment was calculated as the difference between the 1993 and 1994 measurements.

Samples of the most recent fully expanded terminal leaf were collected from 10 trees randomly selected from each plot in each of June, July, and August. The most recent fully expanded terminal leaf was defined as having a size consistent with older leaves and having lost its red coloration. Samples were dried at 70^{o}C for 24 hrs and ground to pass a 2-mm mesh screen. Foliar N, P, and K concentrations were measured from samples collected in June and July. Concentrations of all macronutrients and micronutrients were measured in foliage samples collected in August.

Total N, P, K, Ca, Mg, Mn, Cu, Zn, Fe and Al were determined by using a wet oxidation with an H_2SO_4 and H_2O_2 digest, followed by colorimeteric analysis for N and P, and atomic absorption spectrophotometry for K, Ca, Mg, Mn, Cu, Zn, Fe and Al. 250 mg of foliage were placed in digestion tubes and 5 ml of H_2SO_4 was added to each. The tubes were mixed, heated to 420°C for 1 minute and cooled for 5 minutes. 5 ml of H_2O_2 were added to each tube. Samples were digested at 420°C for 45 minutes, after which 50 ml of distilled water was added while mixing in a vortex mixer. Samples were cooled and diluted to 75 ml with distilled water. For N and P analysis the samples were run undiluted on an RFA 300 (autoanalyser - colorimetric analysis). For Mn, Fe, Zn and Cu determination, the samples were run undiluted through the atomic absorption spectrophotometer. For Ca and Mg, the samples were diluted by a factor of 10 with La_2O_3, which acted as a releasing agent, and then run. Samples were diluted by a factor of 10 with NaCl for K determination, and with KCl for Na determination. Total S was measured by a Fisher Sulfur Analyser, Model 475, which combusts the sample and converts all forms of S to SO_2 which is then absorbed into solution and S concentration measured. For SO_4-S determination, samples were boiled with 0.01N hydrochloric acid for 20 minutes, and centrifuged for 10 minutes at 5000 rpm. 5.0 ml of the supernatant were transfered to 25 ml volumetric flasks and diluted to volume. The SO_4-S was then digested at 115°C with a reducing mixture of hydriodic acid, formic acid and hypophosphorus acid. They were then run on the spectrophotometer.

Trial 2: Tree growth response to nutrient combination

Five fertilization regimes were applied to a second TxD clone (clone 2) in May 1994 at the start of the plantation's third growing season. Clone 2 is also product of a hybridization between *P. trichocarpa* from Granite Falls, WA and *P. deltoides* from Illoos, IL. Experimental design was a 5x5 latin square in which each row and column contained each treatment. Plots were 18 x 18 m with 9-m untreated buffer zones. 25 sample trees were measured in an inner 12 x 15 m plot. The five regimes were as follows: a non-treated control; N; N+P; N+P+K; and N+P+K+S. N was applied at 225 kg/ha, P @ 75 kg/ha, K @ 75 kg/ha and S @ 15 kg/ha. Nitrogen was applied as ammonium nitrate, phosphorus as triple super phosphate, potassium as muriate of potash, and sulphur as ammonium sulphate. The plots were fertilized by hand and cultivated with a springtooth cultivator immediately prior to and after fertilization. They were cultivated twice during the growing season and rotovated once.

Height and dbh were measured in May and October of 1994. Growth increment was calculated as the differences between the two measurements.

Samples of the most recent fully expanded terminal leaf were collected from 5 trees randomly selected from each plot in each of June, July, and August. Samples were dried at 70°C for 24 hrs and ground to pass a 2-mm mesh. Foliar N, P, and K concentrations were measured from samples collected in June and July. Foliar concentrations of all macronutrients and micronutrients were measured from samples collected in August.

Nursery Trials

Trial 3: Steckling growth response to fertilization rates and nutrient combinations

Soil was collected from the SRIC hybrid poplar plantation near Sayward in April 1993, seived to 5 mm, and 2 kg d/w placed in each of 100 2-gallon pots. Fifteen-cm-long cuttings of a third TxD clone were soaked 40 hours before planting to induce bud swelling. Clone 3 is a product of a hybridization between *P. trichocarpa* from Chilliwack, BC and *P. deltoides* from Stoneville, MS. Cuttings were planted at the UBC Forest Nursery July 1 and placed under 30% shade cloth for 4 weeks to reduce heat stress while rooting. 500 ml of water was added weekly in the first 4 weeks, 750 ml in the following week, and 500 ml twice per week for the remaining 12 weeks. The stecklings (rooted cuttings) were pruned to one shoot in the 4th week and fertilized at the end of 8 weeks. The trial was arranged in a completely randomized design with 5 replicates per treatment. Five nutrient combinations (N, N+K, N+P, N+K+P, N+K+P+Ca+Mg) at 4 application rates (0, 150, 300 and 450 kg N/ha) were used. Nutrient loadings were based on the ratio 100N : 70K : 13P : 7Ca : 7Mg (Table 6) (Jia and Ingestad 1984).

	Loading							
	@ 0 kgN/ha		@ 150 kgN/ha		@ 300 kgN/ha		@ 450 kgN/ha	
Element	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot
N	0	0	150.0	0.47	300.0	0.93	450.0	1.40
K	0	0	103.0	0.32	210.0	0.65	315.0	0.98
P	0	0	19.5	0.06	39.0	0.12	58.5	0.18
Ca	0	0	10.5	0.03	21.0	0.07	31.5	0.10
Mg	0	0	10.5	0.03	21.0	0.07	31.5	0.10

Table 6: Total loadings of N, P, K, Ca and Mg applied to TxD stecklings at 4 application rates, based on the ratio 100N : 70K : 13P : 7Ca : 7Mg.

N was supplied as ammonium nitrate, K as muriate of potash, P as triple super phosphate, Ca as calcium chloride and Mg as magnesium chloride. The fertilizer was crushed and the nutrient mixes were watered in with 500 ml water/pot.

Steckling diameter, 5 cm above the junction with the cutting, and height were measured after 17 weeks. All stecklings were then harvested at the junction with the cutting, and leaf area of each was measured using a LI-3100 Area Meter (LI-COR Inc.). Stems and leaves were dried at 70^{o}C, weighed and ground to pass a 2-mm mesh. Stem samples were composited by treatment, and concentrations of N, P, K, Ca and Mg were measured. Foliar N, P, K, Ca and Mg concentrations were measured for each treatment and replicate.

The steckling roots were harvested 2 weeks later. They were washed, dried at 70^{o}C, weighed and ground to pass a 2-mm mesh. Samples were composited by treatment and concentrations of N, P, K, Ca and Mg were measured.

Trial 4: Steckling growth response to organic fertilization

Soil was collected from the SRIC hybrid poplar plantation near Sayward, British Columbia in April, 1994. At UBC, 2.2 kg of soil d/w was placed in each of 112, 2-gallon nursery containers. Cuttings of two TxD clones were used: clone 4 is a product of a hybridization between *P. trichocarpa* from Orting, WA and *P. deltoides* from Texas; clone 5 is a product of a hybridization between *P. trichocarpa* from Chilliwack, BC and *P. deltoides* from Stoneville, MS. Steckling growth response to five organic waste treatments was compared with the growth responses to an untreated control and an inorganic fertilizer. Each of the seven treatments (Table 7) was replicated 8 times in a completely randomized design for each of the two clones.

Treatment	% N	Rate (g /pot)	N Loading (g N/pot)	N Loading (kg N/ha)
Control	-	-	-	-
Inorganic	34.50	2	0.70	225
Biosolids	2.72	171	4.65	1500
Fish Silage	3.66	127	4.65	1500
Fish Compost	1.69	275	4.65	1500
Pig Manure	1.20	388	4.65	1500
Straw	1.19	125	1.49	480

Table 7: Fertilizer treatments used in trial 4: N concentration, amount of material added per pot, loading of N per pot and rate of N per hectare.

Inorganic N was applied as ammonium nitrate, P as triple-super-phosphate (75 kg/ha), and K as muriate of potash (75 kg/ha). Anaerobically digested, dewatered sewage sludge (biosolids) was obtained from the Greater Vancouver Regional District's Lions Gate treatment facility. Total P was 1.3 %. Fish silage was obtained from a fish farm on Northern Vancouver Island, and consisted of ground salmon offal and morts ensiled in sulphuric acid. The fish compost was obtained from PacBio Ltd. located at Oyster River, B.C., in conjunction with the UBC Research Farm. The product was produced from fish silage composted with fir and cedar sawdust and wood chips. Total P and K were 1.37 and 0.35 %, respectively. The pig manure was obtained from Britco Export Packers Ltd. in Langley, B.C. and included a straw component. Total P and K were 1.05 and 1.48 %, respectively. The straw was a cereal grain straw obtained from the UBC Research Farm. Total P and K were 0.14 and 1.37 %, respectively. Addition of the organic wastes, excluding straw, was based on a loading rate of 225 kg available N/ha, assuming approximately 15% of total N would be available. Due to the physical bulk of the straw, it was added at a 1:1 volume ratio with the soil.

The straw, compost, pig manure, and sewage sludge were mixed with the 2.2 kg of soil in plastic bags and placed in 2-gallon pots. Four holes were punched in the bottom of the bags for drainage. The fish silage and inorganic fertilizer were dissolved in 200 ml of water which was mixed with the soil volume in plastic bags and then placed in pots. 200 ml of water was also supplied to each pot of the other treatments.

15-cm cuttings of each clone were soaked for 40 hrs prior to planting to induce bud swelling. The cuttings were planted June 12 and placed under 30% shade cloth for 4 weeks to reduce heat stress while rooting. The stecklings were pruned to one shoot in the 5th week. 500 ml of water was supplied to the stecklings each week.

Steckling diameter, 5 cm above the junction with the cutting, and height were measured after 17 weeks. All stecklings were then harvested at the junction with the cutting, and leaf area of each was measured using a LI-3100 Area Meter (LI-COR Inc.). Stems and leaves were dried at 70^{o}C, weighed and ground to pass a 2-mm mesh. The teckling roots were harvested 5 days later, washed, dried at 70^{o}C and ground to pass a 2-mm mesh. Stem and roots samples were composited by treatment, and percent N, P, K, Ca, and Mg was measured. Foliar N, P, K, Ca, and Mg were measured for each treatment and replicate. Data from clone 5 was not used in this report due to an extremely high mortality rate.

Statistical Tests

All data were analysed using SPSS for Windows release 6.0 (SPSS Inc.). All data sets were tested for homogeneity of variance using Levene's test or Cochran's-C test. Differences between treatments in Trials 1 and 2 were tested for significance with analysis of covariance and Bonferroni's multiple range test. Differences between treatments in Trials 3 and 4 were tested for significance using one-way analysis of variance (ANOVA) and Bonferroni's multiple range test or orthogonal contrasts. In instances where the ANOVA procedure indicated significance but Bonferroni's test did not, Duncan's test was used. Correlation coefficients were determined to investigate the relationships between height and diameter growth, and foliar N and P concentrations in the field. Significance level for all tests was $p < 0.05$ unless otherwise stated. Details of the analyses can be found in the Appendix.

FIELD TRIALS

Trial 1: Tree growth response to application timing and nutrient combination (clone 1)

Results

During the first growing season after fertilization (1993) of TxD hybrid poplar entering the second growing season, both height and diameter growth were greatest in the NPK once treatment, and least in the control and N incremental treatments (Figure 5 & Figure 6). There were no growth advantages to splitting the application of NPK and a slight disadvantage to splitting the application of N incrementally. However, due to large variability within and between plots these differences were not significant. In 1994, two growing seasons after fertilization, mean dbh increment was significantly greater in trees amended with the NPK incremental treatment than in trees amended with the N incremental or N even split treatments. (Figure 7). The same trend was apparent in height growth (Figure 8), but the differences were not significant due to large block x treatment interactions (Appendix).

Foliar concentrations of N, P, Cu and Ca, measured in August 1993 after 1 growing season, were significantly different between treatments (Table 8).

Treatment	N %	P %	Cu ppm	Ca ppm
control	3.03 (0.40) b	0.33 (0.07) b	8.5 (2.1) b	0.60 (0.04) a
N Once	3.52 (0.22) ab	0.35 (0.07) ab	9.9 (1.8) ab	0.57 (0.01) ab
N Even	3.49 (0.16) ab	0.38 (0.07) ab	10.8 (0.8) a	0.50 (0.03) ab
N Incremental	3.27 (0.25) b	0.31 (0.08) b	9.1 (0.7) ab	0.58 (0.06) ab
NPK Once	3.54 (0.22) ab	0.40 (0.06) ab	9.1 (1.3) ab	0.52 (0.02) ab
NPK Even	3.53 (0.14) ab	0.37 (0.05) ab	9.4 (1.0) ab	0.51 (0.02) ab
NPK Incremental	3.96 (0.18) a	0.45 (0.07) a	10.4 (1.0) ab	0.48 (0.05) b

Table 8. Foliar nutrient concentrations of hybrid poplar fertilized with different nutrient combinations and application timings. Each value is the mean (followed by the standard deviation (s.d.)) of 70-75 trees. Means followed by the same letter within a column are not significantly different ($p > 0.05$) as determined by analysis of variance and Bonferroni's test.

Foliar N concentrations were higher in trees fertilized with the NPK incremental regime than the N incremental regime or the control. Foliar P concentrations were also higher in trees treated with the NPK incremental regime, than in control trees or those treated with the N incremental regime. Cu was higher in trees treated with the N even split regime than in control trees, and foliar Ca was higher in the control trees than in the NPK incremental trees. Potassium, Mg, Mn, S, Fe, Zn and SO_4-S concentrations did not differ between treatments. There were no significant differences in foliar nutrient concentrations in the second year after fertilization.

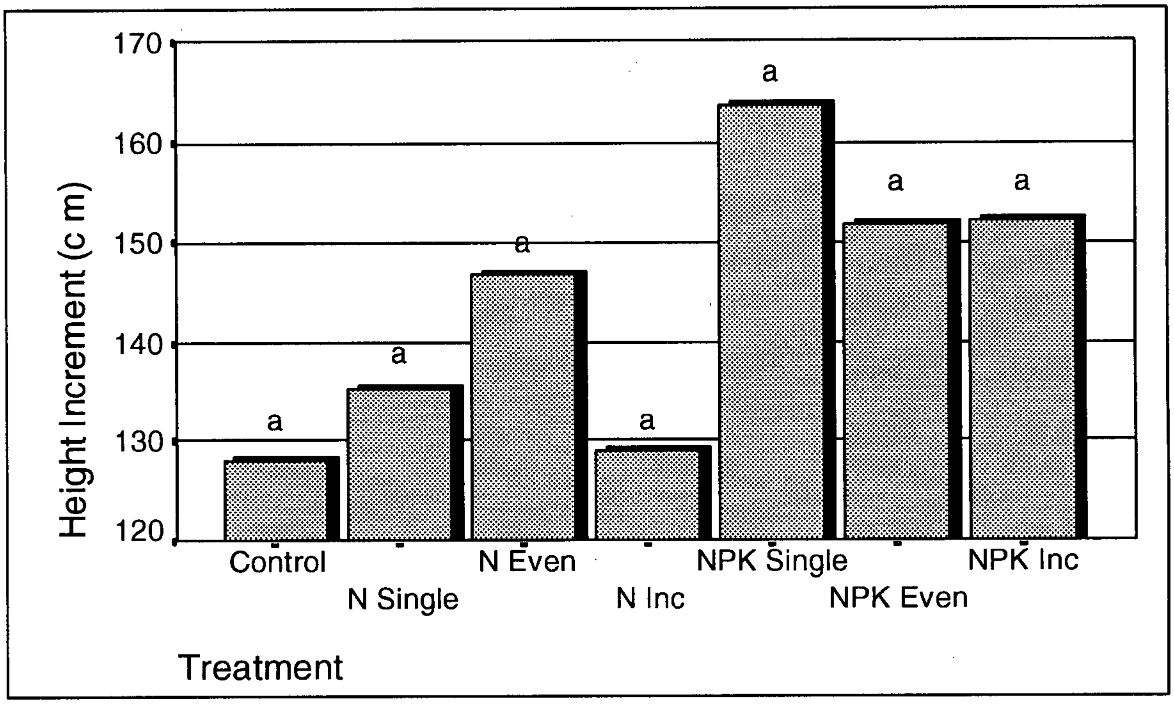

Figure 5: Height growth (1993) of hybrid poplar fertilized with different nutrient combinations and application timings. Each bar represents the mean of 70-75 trees. (Trial 1, clone 1)

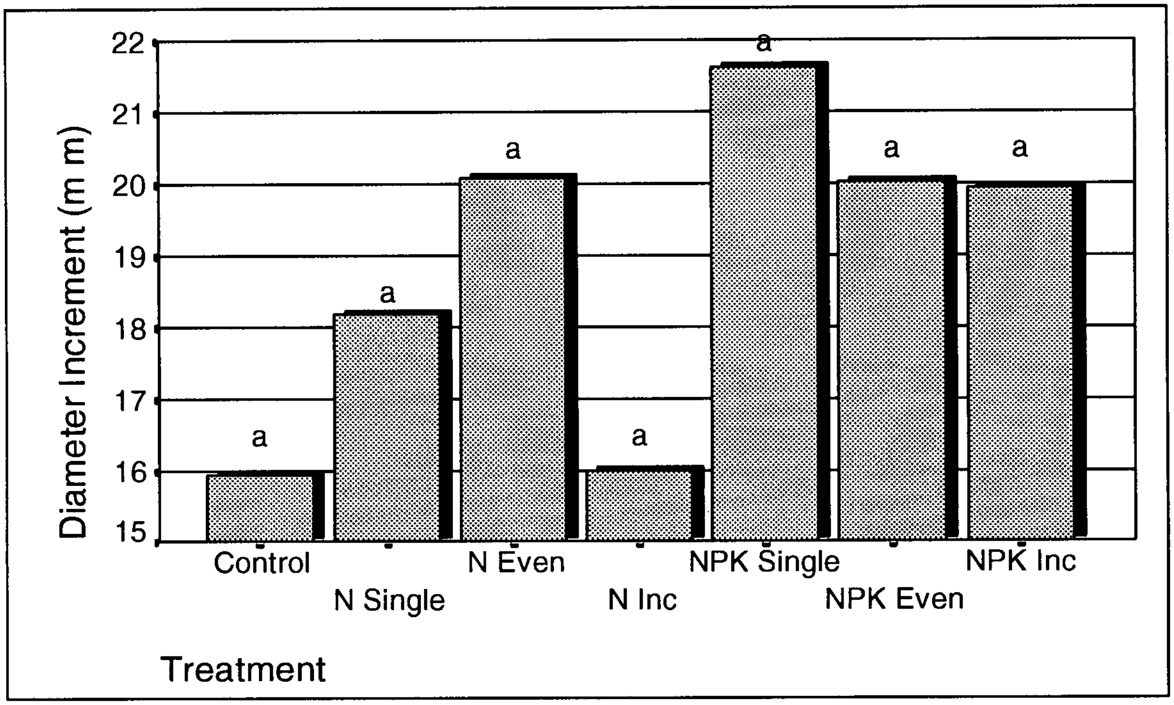

Figure 6: Diameter growth (1993) of hybrid poplar fertilized with different nutrient combinations and application timings. Each bar represents the mean of 70-75 trees. (Trial 1, clone 1)

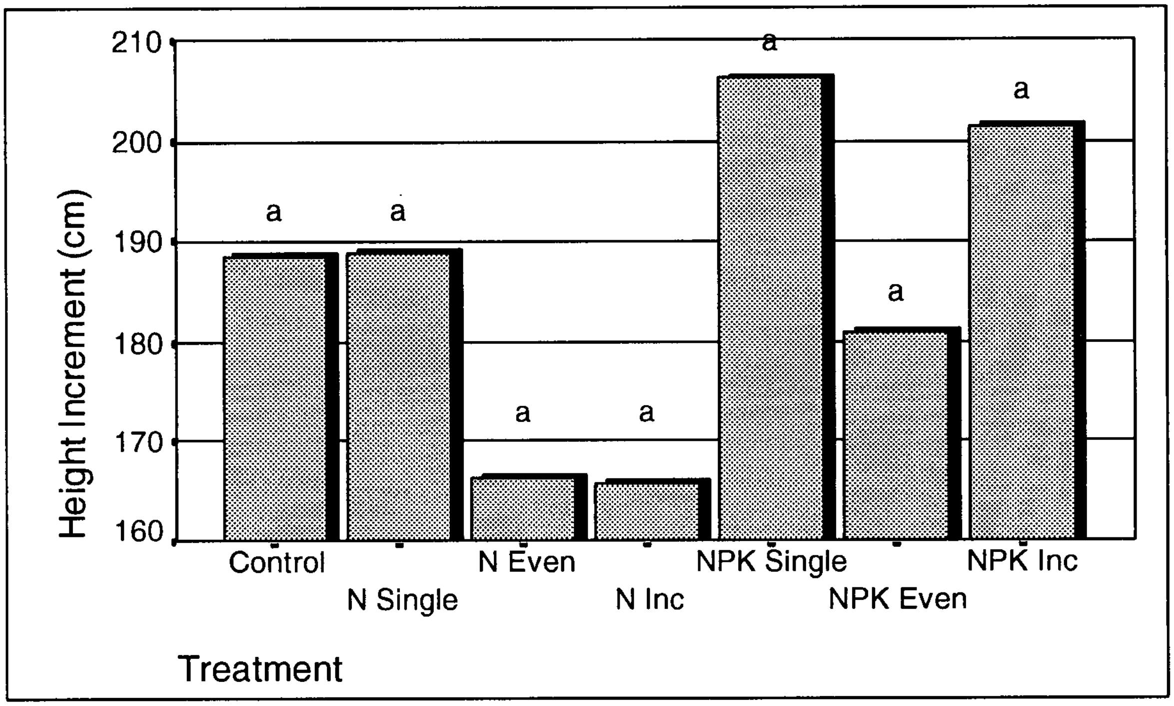

Figure 7: Diameter growth (1994) of hybrid poplar fertilized with different nutrient combinations and application timings. Each bar represents the mean of 70-75 trees. Bars labelled with the same letter are not significantly different ($p > 0.05$) as determined by analysis of covariance and Bonferroni's test. (Trial 1, clone 1)

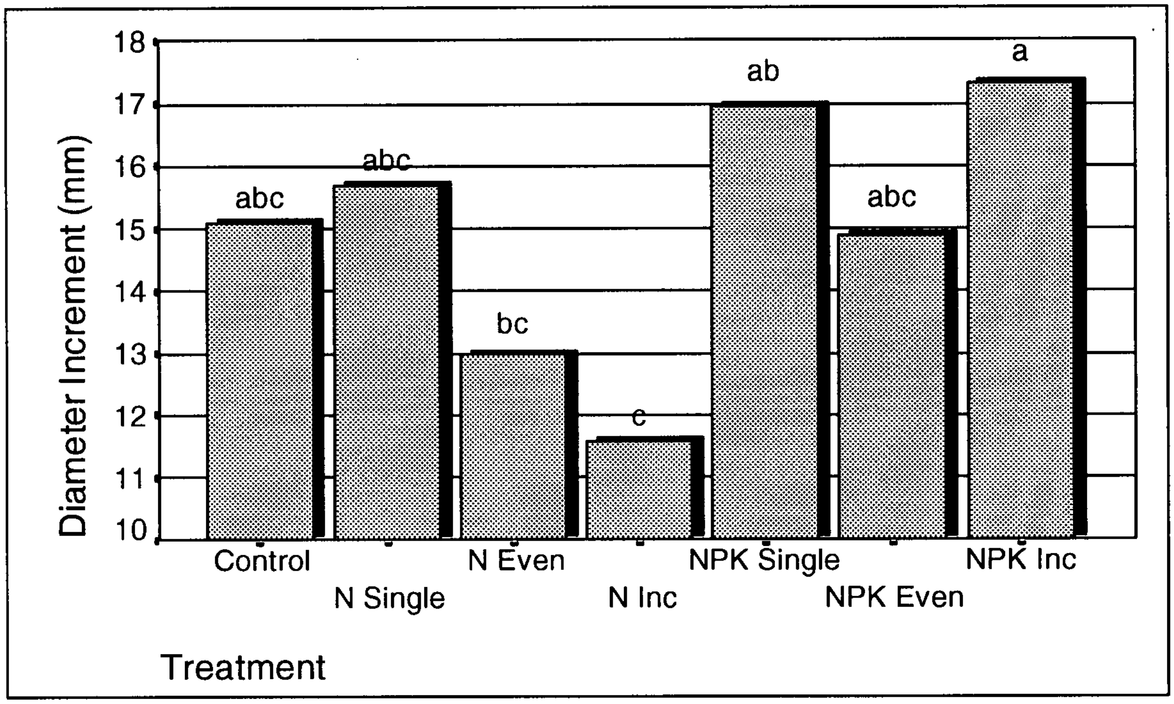

Figure 8: Height growth (1994) of hybrid poplar fertilized with different nutrient combinations and application timings. Each bar represents the mean of 70-75 trees. (Trial 1, clone 1)

Discussion

In general, the increments in height and diameter in the first and second growing seasons after fertilization were greater in trees fertilized with N+P+K than in those fertilized with N alone. However, only diameter growth in the second growing season showed any significant differences. Growth in the NPK single treatment was greater than in the N even or N incremental treatments, and the NPK incremental treatment was greater than the N incremental treatment. Therefore, nutrients in addition to N may be important to hybrid poplar nutrition at this site. This would be in keeping with the principles of optimum nutrition, that supplying plants with a mixture of nutrients in the required proportions rather than a single most limiting element more closely matches nutrient supply to plant requirements (Ingestad 1974). By matching supply to requirements, instances of nutrient deficiency, luxury uptake and toxicity are less likely to occur, resulting in greater plant growth. By applying a combination of nutrients, secondary deficiencies can be avoided, which prevents the occurrence of related growth limitations (Prescott and Weetman 1994). In this trial, the presence of secondary nutrient limitations could be predicted from the foliar concentrations as more N and P were taken up in trees treated with N+P+K, than in those treated with N alone, even though the total loading rates were the same.

Matching nutrient supply to plant requirements also refers to frequency of nutrient application. Plant demand increases during the growing season, and therefore, split applications should more closely match plant needs than a single large application. Frequent, small applications of nutrients which increase as plant need increases have resulted in greater growth than conventional fertilization in nursery trials (Imo and Timmer 1992, Timmer and Armstrong 1987b). The results from this field trial do not support this hypothesis. They indicate that a single large application at the start of the growing season was as good at promoting tree growth as several applications in even or increasing amounts through the growing season. Successful examples of optimum nutrition in field trials have used multiple applications over a number of years rather than during a single growing season. In the original optimum nutrition trial with Norway spruce in Sweden, N was applied annually and P, K and micronutrients every 3 years (Ingestad 1987). van Miegroet et al. (1994) tested 5 different N application regimes in a short-rotation sycamore plantation. Regimes tested were: an untreated control; a single application of 450 kgN/ha shortly after planting; annual applications of 150 kgN/ha for 3 years; 50 kgN/ha 3 times a year for 3 years; and, an annually increasing application of 50 kgN/ha in year 1, 150 kgN/ha in year 2 and 250 kgN/ha in year 3. The last regime resulted in the greatest amount of biomass produced. These findings suggest that matching nutrient application to plant demand over several growing seasons will increase growth. The findings from trial 1 suggest that splitting fertilizer applications to match nutrient application to plant demand during a single growing season will not increase growth.

Fertigation (injection of fertilizer into the irrigation water) trials in which there are continuous applications of nutrients throughout the growing season, have resulted in substantially higher growth responses than single applications. In Sweden, a complete mix of nutrients was distributed in the irrigation water to Scots pine 5 days/week during the growing season (Ingestad 1987). The result was a 300% increase in mean annual increment (Axelsson 1985). Moisture requirements also increase in the same pattern, so supplying the trees with moisture reduces plant stress and makes the nutrients available to the roots, which enables full utilization of the applied nutrients.

The growth responses measured in the trial at Sayward may be related to moisture supply as well as nutrient supply. The project site received about 413 mm of rain in April, 244 mm in May, 113 mm in June and 111 mm in July. Fertilizer was applied in April, June and July of 1993. Dry conditions in June and July may have limited the trees' abilities to take up nutrients applied at this time, thereby lessening the effects on growth of later additions. This is supported by foliar nutrient concentrations measured in June and July (Table 9).

Treatment	June N (%)	July N (%)	August N (%)
Control	2.18 b	2.31 B	3.03 a
N Single	2.86 a	2.78 A	3.52 ab
N Even	2.42 ab	3.01 A	3.49 ab
N Incremental	2.48 ab	2.69 AB	3.27 b
NPK Single	2.76 a	3.03 A	3.54 ab
NPK Even	2.45 ab	2.94 A	3.53 ab
NPK Incremental	2.58 ab	2.76 A	3.96 a

Table 9:. Foliar nutrient concentrations of hybrid poplar fertilized with different nutrient mixes and application timings. Each value is the mean (s.d.) of 70-75 trees. Means followed by the same letter within a column are not significantly different ($p > 0.05$) as determined by analysis of variance and Bonferroni's test (lower case letters) and Duncan's test (upper case letters).

Foliar N concentrations measured in June (after the April application) were higher in the trees treated with the N single application and the NPK single application than the control trees. Foliar N concentrations in July (after the June application) were higher in all treatments, except the N incremental, than in the control trees. Even though the even-split and incremental treatments received another fertilizer application, their foliar N concentrations were not higher than those of the single application. Foliar N concentrations measured in August (after the July application) were greater in trees fertilized with the NPK incremental regime than in the control and N incremental treatments. They were not however, greater than in the single applications, indicating that more N was not taken up by trees fertilized with multiple applications.

Hybrid poplars are a fast growing, nutrient and moisture demanding species. Plantations are cultivated until they close canopy, due to moisture competition with the minor vegetation (Kennedy 1984). In the spring, deciduous species mobilize stored nutrients to develop leaves for photosynthesis (Kozlowski et al. 1991). In this trial, a large quantity of N was immediately available in the spring with the single fertilizer application, as well as a large supply of moisture. If N levels were sufficient to meet plant requirements, less stored N would have been mobilized within the plant. The split treatments, which provided smaller initial amounts of nutrients, may have required the mobilization of larger quantities of stored nutrients. By the time of the next application in June, precipitation had decreased, potentially resulting in a lower shoot growth and a concomitant reduction in nutrient uptake and use. Or, because of the lower precipitation levels, the nutrients applied in June and July simply may not have been available to the trees. Hybrid poplar growth is greatly influenced by late season N uptake (Dykstra 1974). Therefore, lower growth would be expected in trees which had reduced access to soil N (due to moisture restrictions), and possibly stored N (due to previous mobilization).

Trial 2: Tree growth response to nutrient combinations (clone 2)

Results

During the first growing season after fertilization (1994) of hybrid poplars entering the third growing season, height and diameter growth were greatest in the N+P+K+S-treated trees, followed in decreasing order by the N+P+K, N+P and N treated trees (Figure 9 & Figure 10). The N+P+K+S (complete mixture) treatment resulted in significantly greater tree height and diameter growth than the control or N alone treatment.

Foliar concentrations of N, P and SO_4-S measured in August 1994, differed significantly between treatments (Table 10).

Treatment	N %	P %	SO_4-S ppm
Control	2.80 (0.30) b	0.33 (0.07) bc	1023.8 (115.3) a
N	3.23 (0.35) b	0.30 (0.07) c	883.8 (204.5) ab
N+P	3.42 (0.30) a	0.39 (0.04) ab	618.0 (169.3) b
N+P+K	3.57 (0.26) a	0.39 (0.03) ab	599.6 (76.2) b
N+P+K+S	3.76 (0.21) a	0.43 (0.06) a	658.8 (83.4) b

Table 10. Foliar nutrient concentrations of hybrid poplar fertilized with 4 nutrient combinations and a nontreated control. Each value is the mean (s.d.) of 110 trees. Means followed by the same letter within a column are not significantly different ($p > 0.05$) as determined by analysis of variance and Bonferroni's test.

Foliar N concentrations were increased when N was added in combination with additional nutrients. Foliar P concentrations declined ($p > 0.05$) when N was added but increased when P was added. The increase was greatest ($p < 0.05$) in the N+P+K+S-fertilized trees. Sulphate concentrations were significantly greater in the control trees than in the trees fertilized with nutrients in addition to N. Foliar sulphate levels decreased with addition of elements other than S to the soil, but addition of S only slightly elevated SO_4-S concentrations. There were no significant differences between treatments in concentrations of K, S, Mg and Ca. Figure 11 shows an aerial view of the trial. Each plot is labelled by treatment.

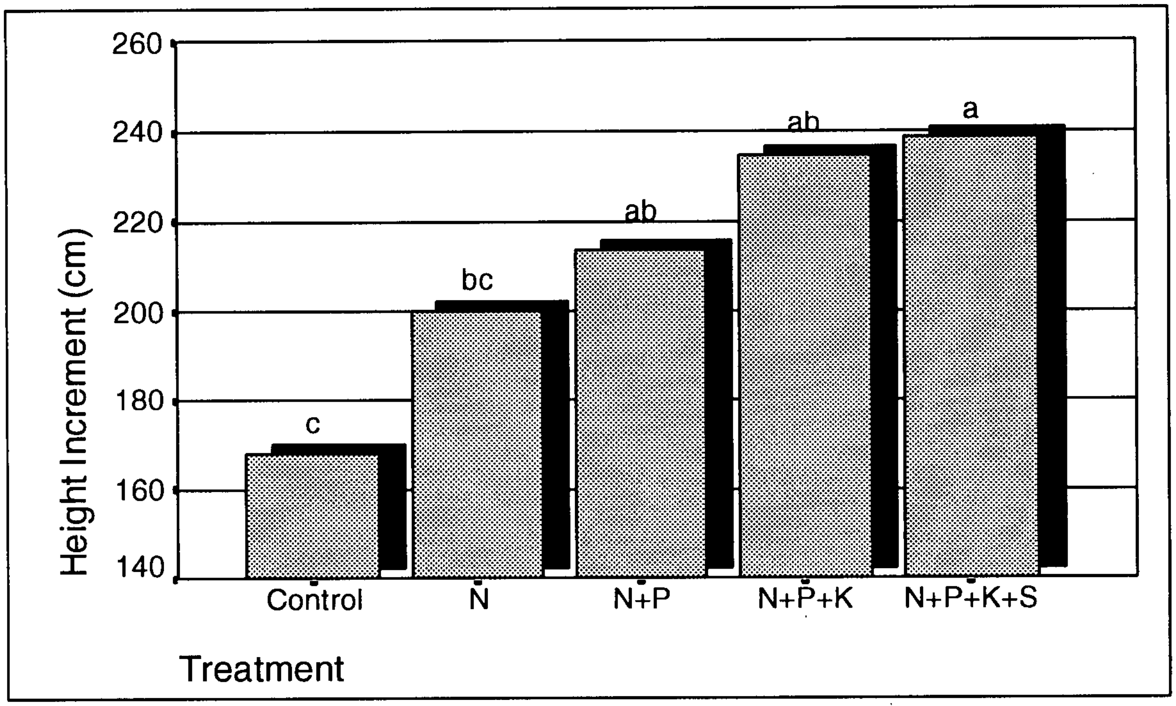

Figure 9: Height growth of hybrid poplar fertilized with 4 nutrient combinations and a nontreated control. Each bar represents the mean of 110 trees. Bars labelled with the same letter are not significantly different ($p > 0.05$) as determined by analysis of covariance and Bonferroni's test. (Trial 2, clone 2)

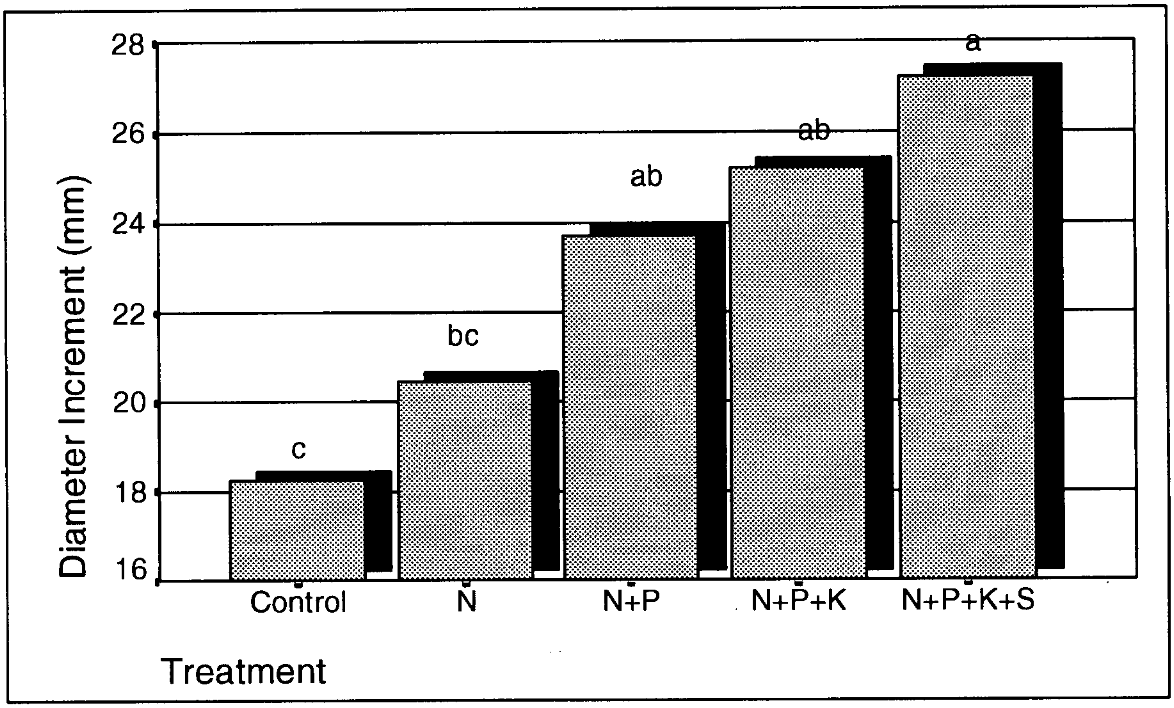

Figure 10: Diameter growth of hybrid poplar fertilized with 4 nutrient combinations and an untreated control. Each bar represents the mean of 110 trees. Bars labelled with the same letter are not significantly different ($p > 0.05$) as determined by analysis of covariance and Bonferroni's test. (Trial 2, clone 2)

NP	NPK	N	Control	NPKS
NPKS	NP	NPK	N	Control
NPK	Control	NP	NPKS	N
N	NPKS	Control	NP	NPK
Control	N	NPKS	NPK	NP

Figure 11: Aerial view of trial 2.

Discussion

Trial 2 was instigated to determine if the additional fertilization response measured in trial 1 was due to P or both P and K. As well, foliar S concentrations from trial 1 (Table 11) had indicated a consistent but insignificant decrease in foliar sulphate levels measured in all fertilized plots. Therefore S was added as a treatment to determine if it would provide an additional response.

Treatment	SO_4-S ppm
Control	1011.9
N Single	736.7
N Even	824.3
N Incremental	709.7
NPK Single	958.0
NPK Even	667.7
NPK Incremental	639.7

Table 11. Foliar SO_4-S concentrations of hybrid poplar fertilized with different nutrient combinations and application timings from Trial 1.

Overall, growth increased as the number of nutrients added increased. The N+P, N+P+K, and N+P+K+S treatments all resulted in significantly greater tree growth than the control. An additional response to N+P+K+S was measured, as both diameter and height growth were significantly greater than in the N treatment. Diameter and height growth in the N+P+K+S treatment were also greater than in the N+P+K and N+P treatments, but these differences were not significant. There has been very little work on S fertilization of poplars. Dr. R. van den Driessche (personal communication) noted that S nutrition is a problem in some locations on Vancouver Island, and that TxD hybrids in sand culture respond to applications of ammonium sulphate.

The response to P and S is predictable from the foliar concentrations. Foliar P declined when N was added, but increased when P was added. Foliar SO_4-S levels also decreased significantly with addition of nutrients other than S. Use of S in the fertilizer mixture resulted in a slight ($p > 0.05$) increase in SO_4-S concentrations, but they were still below control levels. A higher S application rate was needed to increase SO_4-S concentrations to the control levels.

Tree Age at Which to Fertilize

The question of the age at which these trees should be fertilized was not directly addressed in these experiments. However, other research has indicated that fertilizing in the third growing season is optimal. In Washington, Heilman and Xie (1993) found that tree growth response to urea application was greatest in the third growing season, and minimal in the second. Similarly, in Wisconsin, McLaughlin et al. (1987) also found the benefits of N fertilization to be greatest in the third growing season, and negligible in the first two. The TxD hybrids used in Trials 1 and 2 were fertilized in the second and third growing seasons respectively, but they were different clones, therefore direct comparisons are not possible. The clone fertilized in trial 2 (clone 2) was entering its third growing season and responded very well to fertilization. The clone fertilized in trial 1 (clone 1) was entering its second growing season and did not respond as much. These differences in response could be attributed to clonal characteristics or environmental influences in addition to age. However, MacMillan Bloedel Ltd. operationally fertilized all areas not included in this project when the trees were 3 years old, including sections of clone 1. Loading rate was 200 kgN/ha as urea. In July, the foliar concentrations of N, P and K for clone 1 fertilized at the start of year 2 and at the start of year 3 were as follows (Table 12):

Clone 1: 2-year-old trees fertilized at 2 years (1993)				Clone 1: 3-year-old trees fertilized at 3 years (1994)			
	N %	P %	K %		N %	P%	K%
N @ 225 kg/ha NH_4NO_3-N	2.78	0.23	1.57	N @ 200 kg/ha Urea	3.74	0.39	1.49

Table 12. Foliar N concentrations (July) of clone 1, fertilized at the start of the second and third growing seasons.

The foliar N and P concentrations of the trees fertilized in 1994 were higher than those fertilized in 1993, indicating that the trees took up more N when they were 3 years old than when they were 2 years old. This is visually illustrated in Figure 4. The yellow areas of the photo (sites 1, 2 and 3) were fertilized at the start of the 2nd growing season in 1993. The balance of the area was fertilized at the start of the 3rd growing season in 1994 (all green areas), including the remaining sections of clone 1 immediately surrounding each of sites 1, 2 and 3. Direct comparisons can not be made because of the different years in which fertilization took place and the different fertilizers used, but the values support the practice of fertilizing in the third growing season. These trials were fertilized during the 2nd growing season because no 3-year-old plantations were available in 1993 when the project was initiated.

Predicting Growth response from foliar nutrient concentrations

The optimal foliar nutrient concentrations of poplar were summarized by Ericsson et al. (1992). Depending on the species studied, the optimal concentrations were found to be about 2.9% N and 0.31% P. Foliar N and P concentrations of clone 1 were within this range during the year of fertilization and the year following fertilization. But the growth response was not as great as that of clone 2, which had N concentrations of 3.5% and greater. In trial 2, the correlation between N concentrations and height and diameter growth are significant at $p < 0.05$ (Table 13).

		Correlation Coefficient (r)	
		N concentration	P concentration
Trial 1	diameter	0.69	0.87
	height	0.62	0.86
Trial 2	diameter	0.55	0.67
	height	0.66	0.66

Table 13: Strength of the linear relationship between foliar nutrient concentrations and tree growth as calculated by Pearson's Correlation Coefficient. Correlations are significant at $p < 0.05$.

As foliar N concentrations increased, so did height and diameter growth up to approximately 3.4 - 3.6% N (Figure 12 & Figure 13). Heilman (1992) found that fertilization of T x D hybrids with nitrogen increased the foliar N concentration from 2.5% to 3.25%, with a corresponding 22% increase in bole dry weight at four years of age. A similar relationship was observed in trial 1 (Figure 14 & Figure 15), but there was a higher degree of correlation between P concentration and growth in this trial (Table 13). In both Trial 1 and Trial 2 optimal foliar P concentrations were approximately 0.36 to 0.40% (Figures 23 and 24). Phosphorus was not applied without N, so the correlation between P concentration and growth indicates that maximal growth response to N required addition of P to prevent secondary deficiencies. This is supported by the growth measured in trial 2. The N+P treatment resulted in significantly greater growth than the control, but the N treatment was similar to the control (Figures 9 and 10).

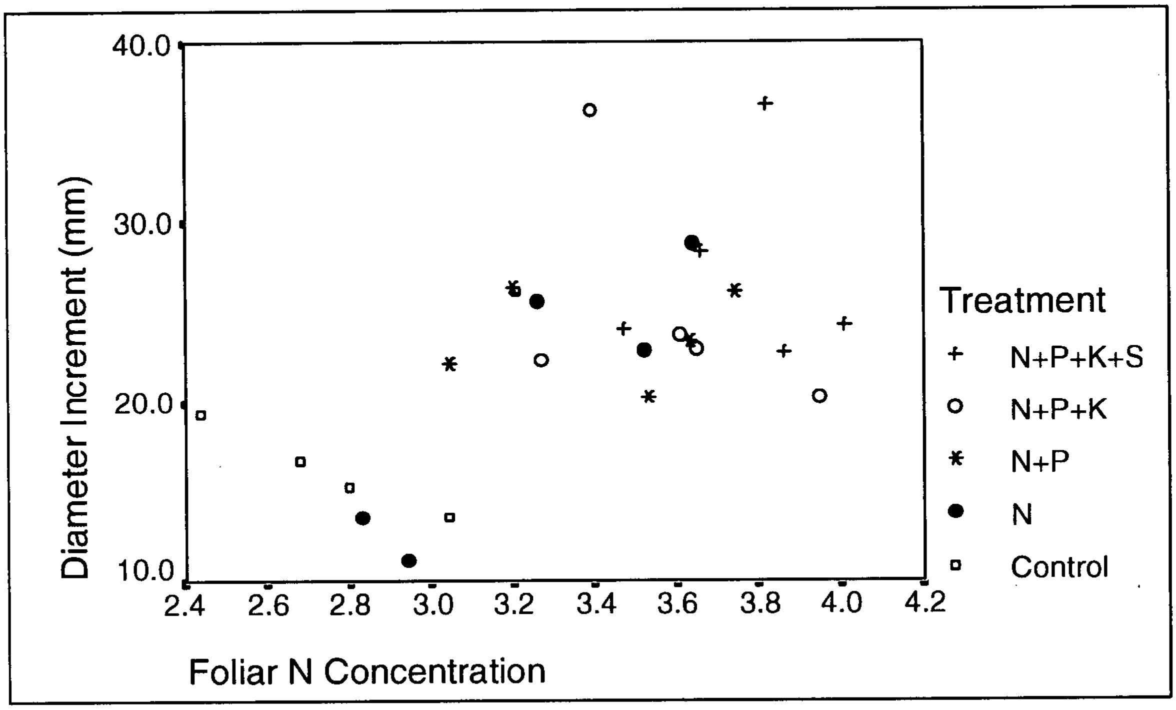

Figure 12: Relationship between foliar N concentrations and diameter growth (dbh) of hybrid poplar fertilized with 4 nutrient combinations and an untreated control. Each symbol on the graph represents one treatment plot (diameter increment = the mean of 22 trees; foliar concentration = one composite sample). (Trial 2)

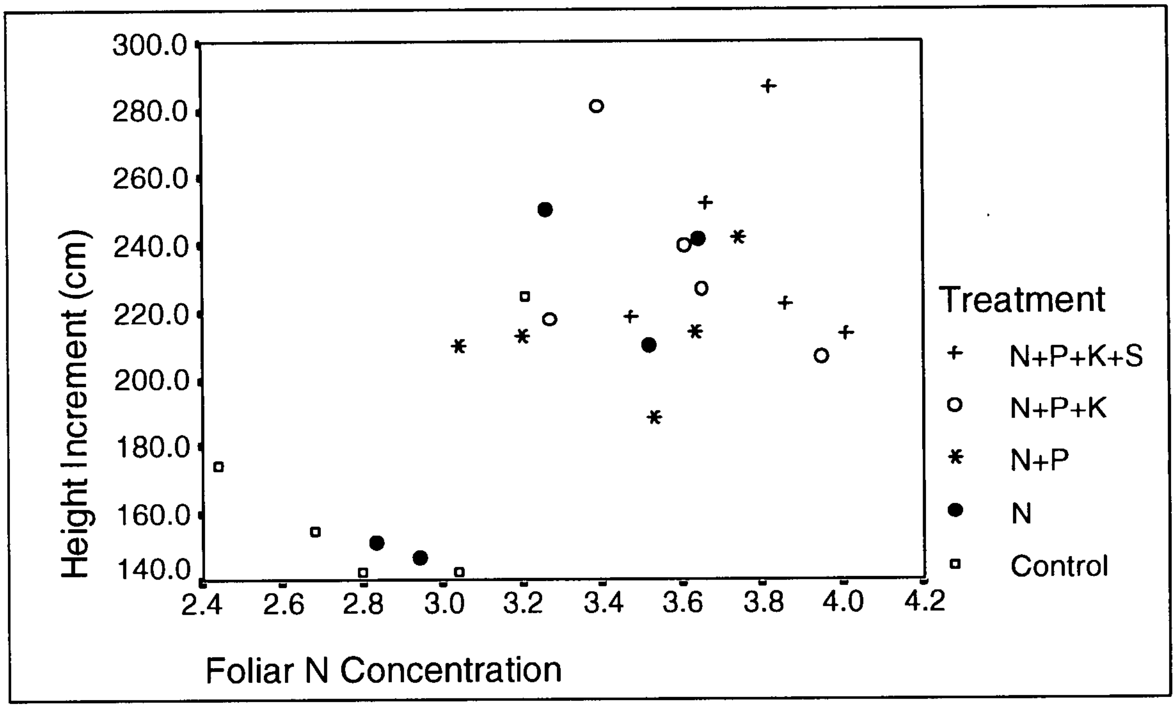

Figure 13: Relationship between foliar N concentrations and height growth of hybrid poplar fertilized with 4 nutrient combinations and an untreated control. Each symbol on the graph represents one treatment plot (height increment = the mean of 22 trees; foliar concentration = one composite sample). (Trial 2)

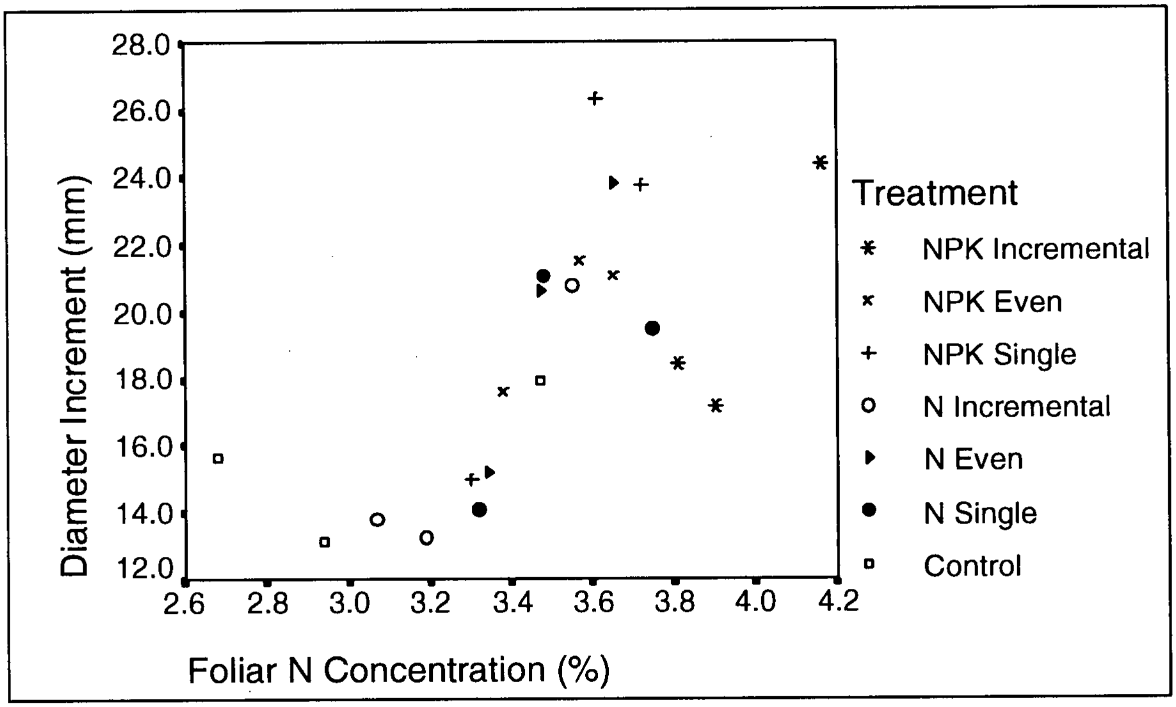

Figure 14: Relationship between foliar N concentrations and diameter growth of hybrid poplar fertilized with different nutrient combinations and application timings. Each symbol on the graph represents one treatment plot (diameter increment = the mean of 22 trees; foliar concentration = one composite sample).(Trial 1)

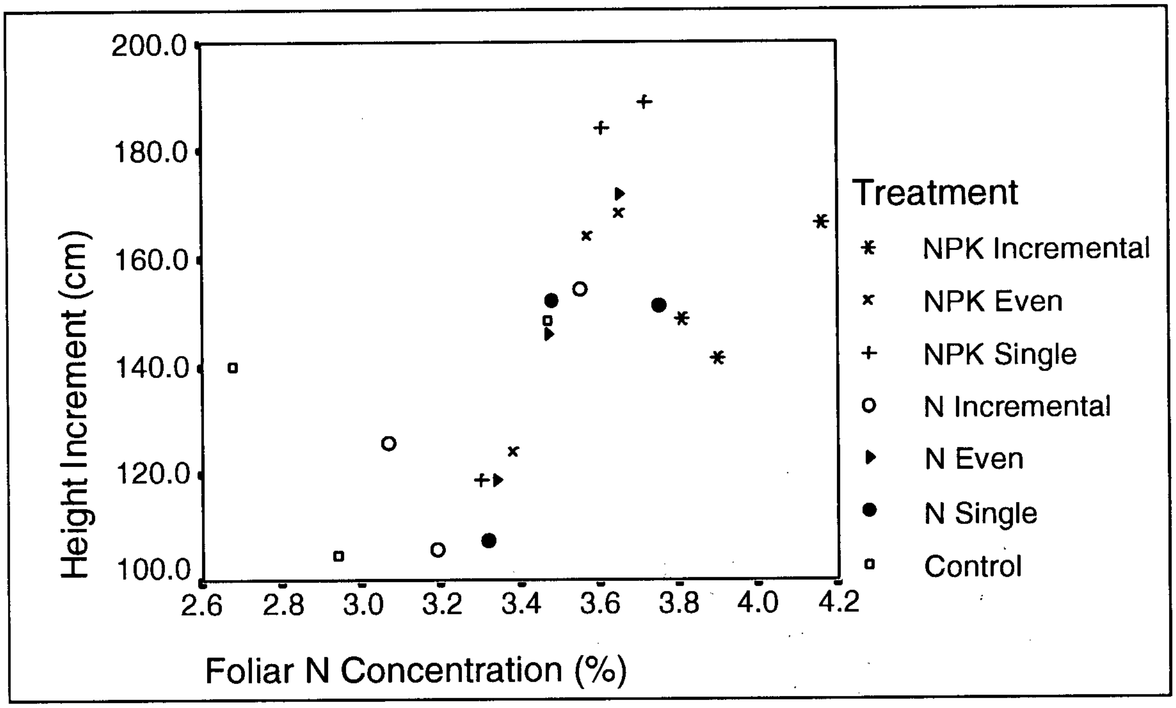

Figure 15: Relationship between foliar N concentrations and height growth of hybrid poplar fertilized with different nutrient combinations and application timings. Each symbol on the graph represents one treatment plot (height increment = the mean of 22 trees; foliar concentration = one composite sample). (Trial 1)

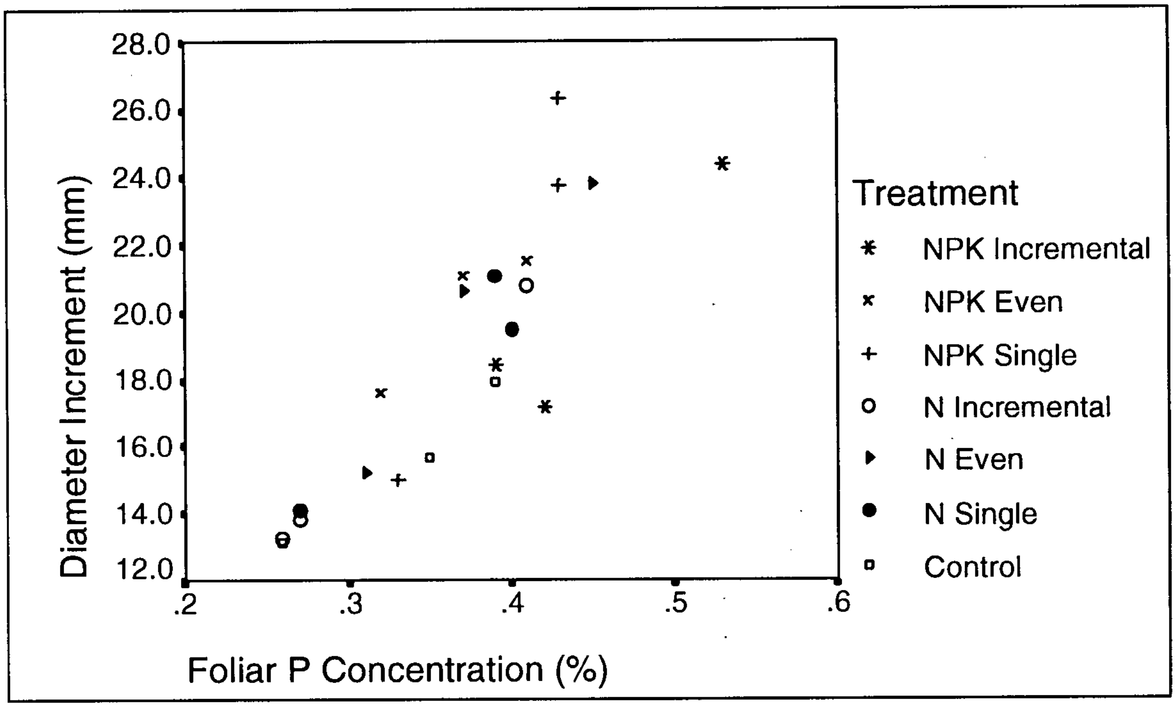

Figure 16: Relationship between foliar P concentrations and diameter growth of hybrid poplar fertilized with different nutrient combinations and application timings. (Trial 1)

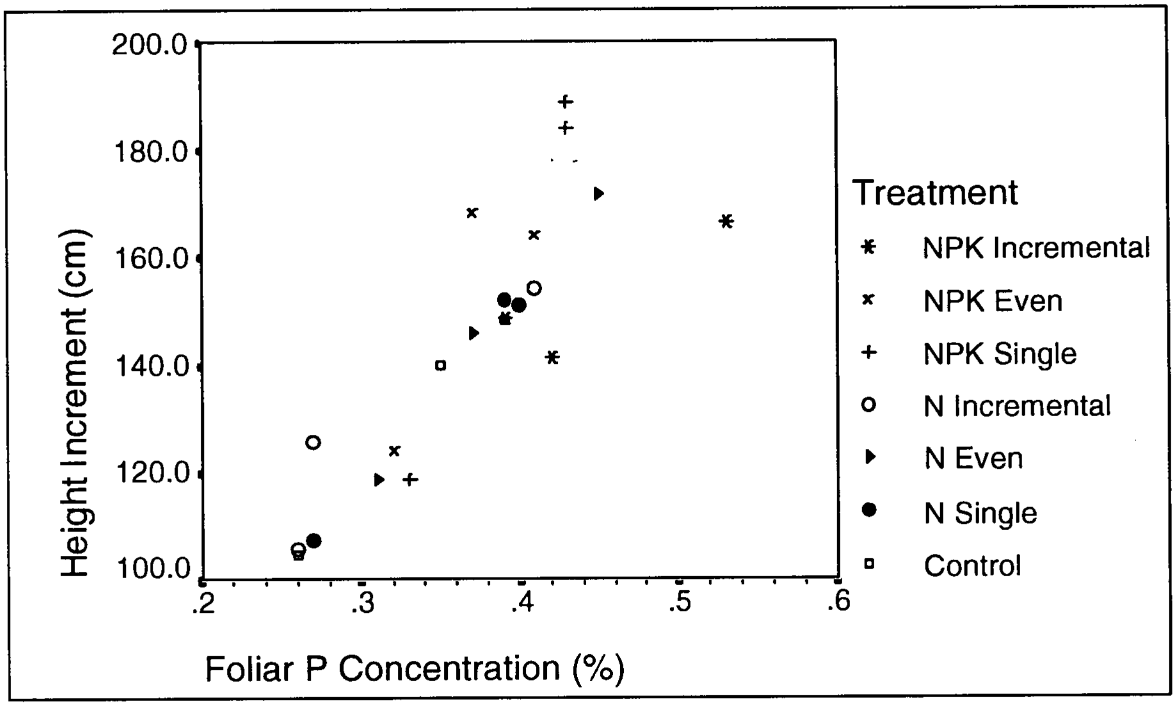

Figure 17: Relationship between foliar P concentrations and height growth of hybrid poplar fertilized with different nutrient combinations and application timings. (Trial 1)

NURSERY TRIALS

Trial 3: Steckling growth response to fertilization rate and nutrient combination (clone 3)

Results

Seventeen weeks after fertilization with 5 different nutrient combinations and 4 different application rates, there were no significant differences in steckling height or diameter among the treatments. However, total steckling biomass in the pots was greater in the N+K and N+P treatments than in the N alone treatment. Adding P+K or P+K+Ca+Mg did not affect total biomass further (Figure 18). Addition of N+P significantly increased root biomass over that of the N alone and complete mixture (N+P+K+Ca+Mg) treatments (Figure 18). Shoot dry weight was greater in the N+K treatment than in the N or complete mixture treatments (Figure 18). Application rate (0 - 450 kgN/ha) did not affect root or shoot biomass.

Foliar biomass was also affected by nutrient combination (Figure 19). Addition of K with N increased foliar biomass over the control and complete mixture. Addition of P with N, increased foliar biomass over that of the control but was statistically similar to the complete mixture. Leaf area was not affected by nutrient mix or application rate.

Foliar nutrient concentrations differed with respect to treatment (Table 14) and application rate.

Treatment	N %	P %	K %
N	2.60 (1.08) AB	0.09 (0.01) bc	1.47 (0.32) bc
N+K	2.23 (0.91) B	0.08 (0.01) c	1.76 (0.41) ab
N+P	2.61 (1.13) AB	0.09 (0.01) bc	1.36 (0.21) c
N+P+K	2.53 (1.05) AB	0.10 (0.02) ab	1.78 (0.33) ab
N+P+K+Ca+Mg	3.06 (1.27) A	0.11 (0.02) a	1.87 (0.40) a

Table 14: Foliar nutrient concentrations of hybrid poplar stecklings fertilized with 5 different nutrient combinations. Each value is the mean (s.d.) of 20 pots, 1 steckling/pot. Means followed by the same letter within a column are not significantly different ($p > 0.05$) as determined by analysis of variance and Duncan's test (upper case letters) or Bonferroni's test (lower case letters).

Foliar N concentration was higher in stecklings treated with N+P+K+Ca+Mg than in N+K trees.

Foliar P concentrations were also higher in the complete mixture than the N, N+K and N+P stecklings. Foliar K concentrations and contents (g) were highest in the treatments in which K was added. Foliar N concentrations were increased by adding N up to 150 kgN/ha, but there was no increase at rates greater than this (Figure 20). Foliar N content followed the same pattern (Figure 21). Foliar P concentrations were highest at the highest application rate whether P was added to the stecklings or not (Figure 22). There were no significant differences in foliar P content. Foliar K concentrations were significantly greater than the control at the highest application rate in both the N+K and N+P+K treatments (Figure 23). There were no significant differences in foliar K contents. Magnesium concentrations and contents significantly decreased with increasing fertilization rate only in the N+P+K treatment.

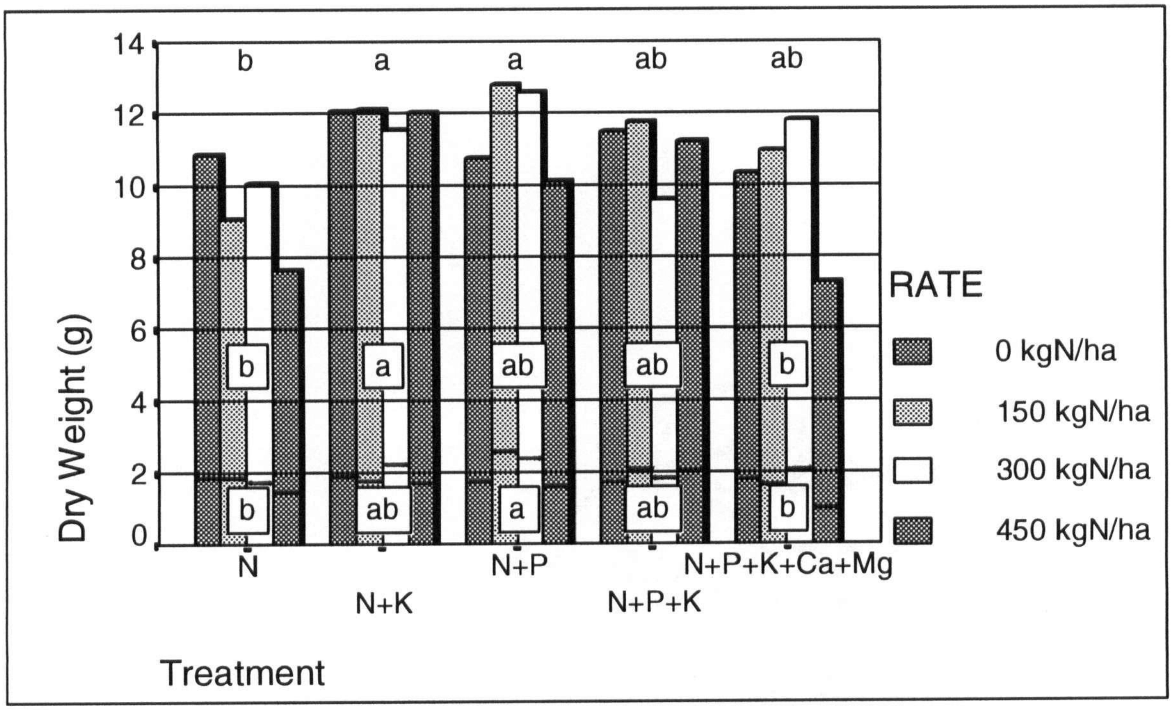

Figure 18: Root, shoot and total biomass of hybrid poplar stecklings fertilized with 5 nutrient combinations. Each group of bars represents the mean of 20 pots, 1 steckling/pot. Bar area below the lines = root biomass; bar area above the lines = shoot biomass; entire bar = total biomass. Groups of bars with the same letter are not significantly different ($p > 0.05$) as determined by orthogonal contrasts. (Trial 3, clone 3)

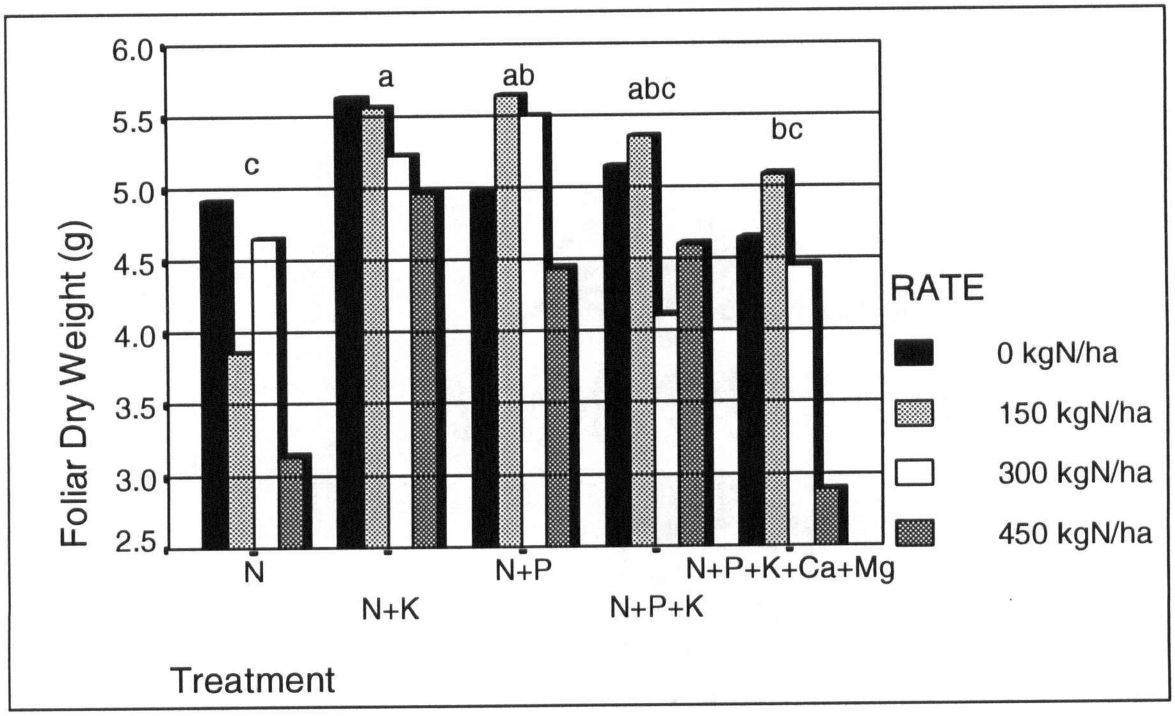

Figure 19: Foliar biomass of hybrid poplar stecklings fertilized with 5 nutrient combinations. Each group of bars represents the mean of 20 pots, 1 steckling/pot. Groups of bars with the same letter are not significantly different ($p > 0.05$) as determined by orthoganal contrasts. (Trial 3, clone 3)

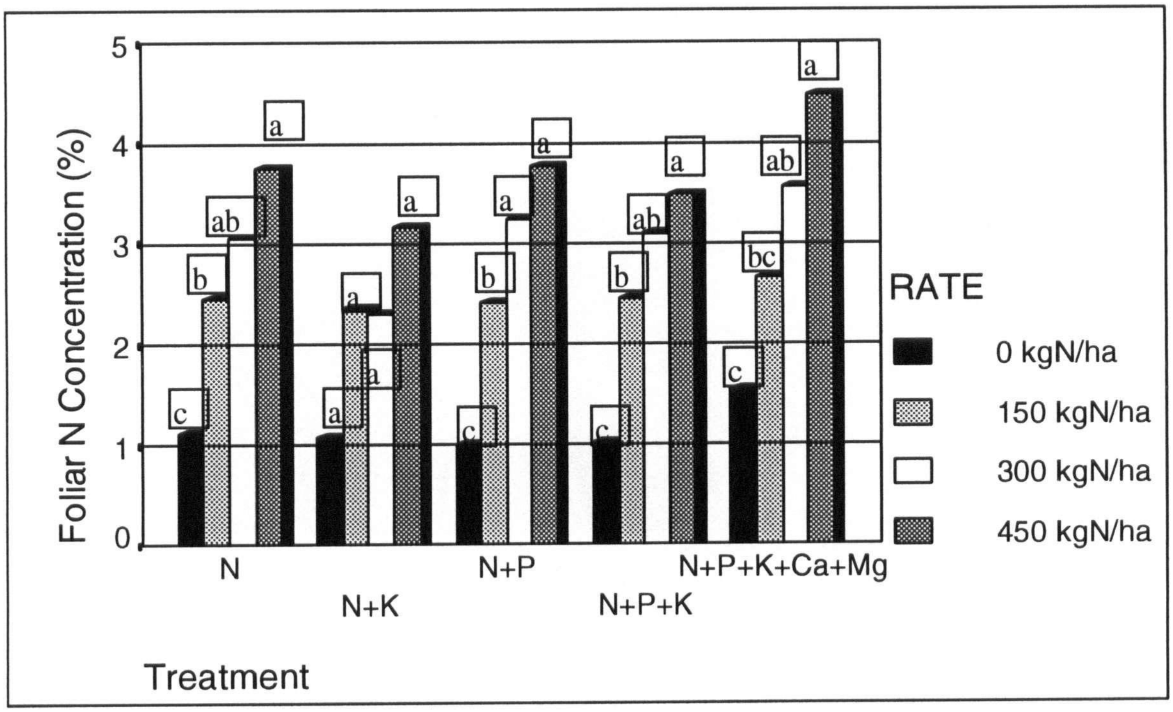

Figure 20: Foliar N concentrations of hybrid poplar stecklings fertilized with 5 nutrient combinations and 4 application rates. Each bar represents the mean of 5 pots, 1 steckling/pot. Bars labelled with the same letter within groups are not significantly different ($p > 0.05$) as determined by analysis of variance and Bonferroni's test. (Trial 3, clone 3)

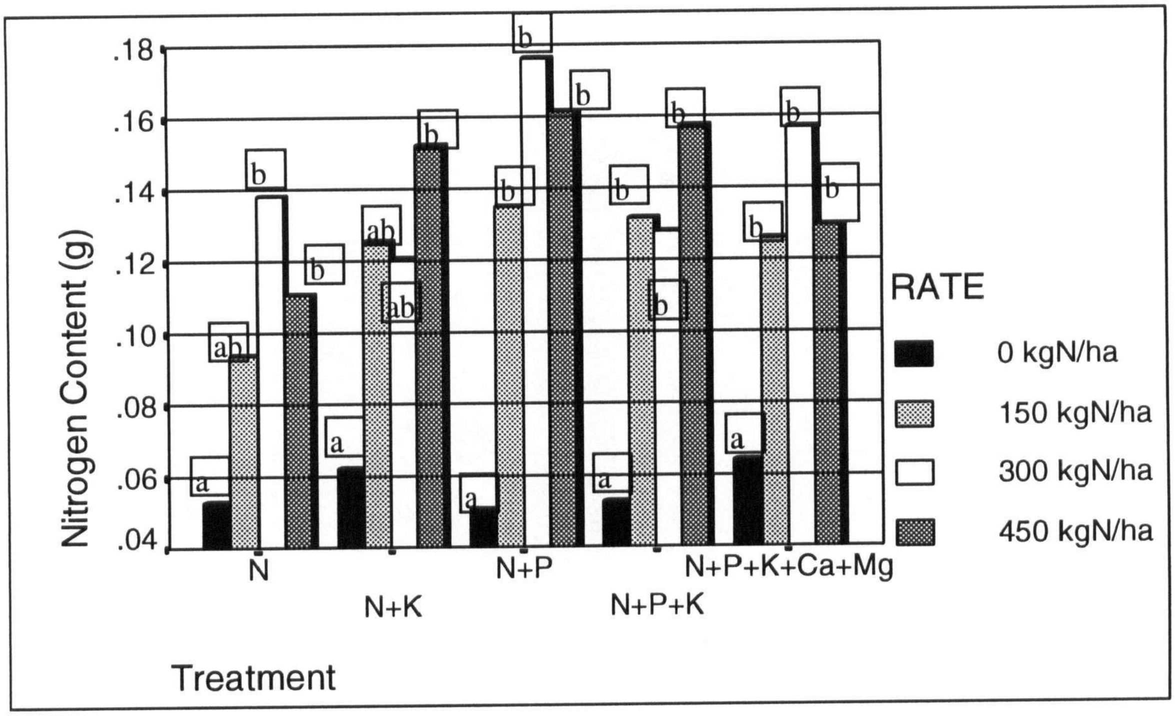

Figure 21: Foliar N content of hybrid poplar stecklings fertilized with 5 nutrient combinations and 4 application rates. Each bar represents the mean of 5 pots, 1 steckling/pot. Bars labelled with the same letter within groups are not significantly different ($p > 0.05$) as determined by analysis of variance and Bonferroni's test. (Trial 3, clone3)

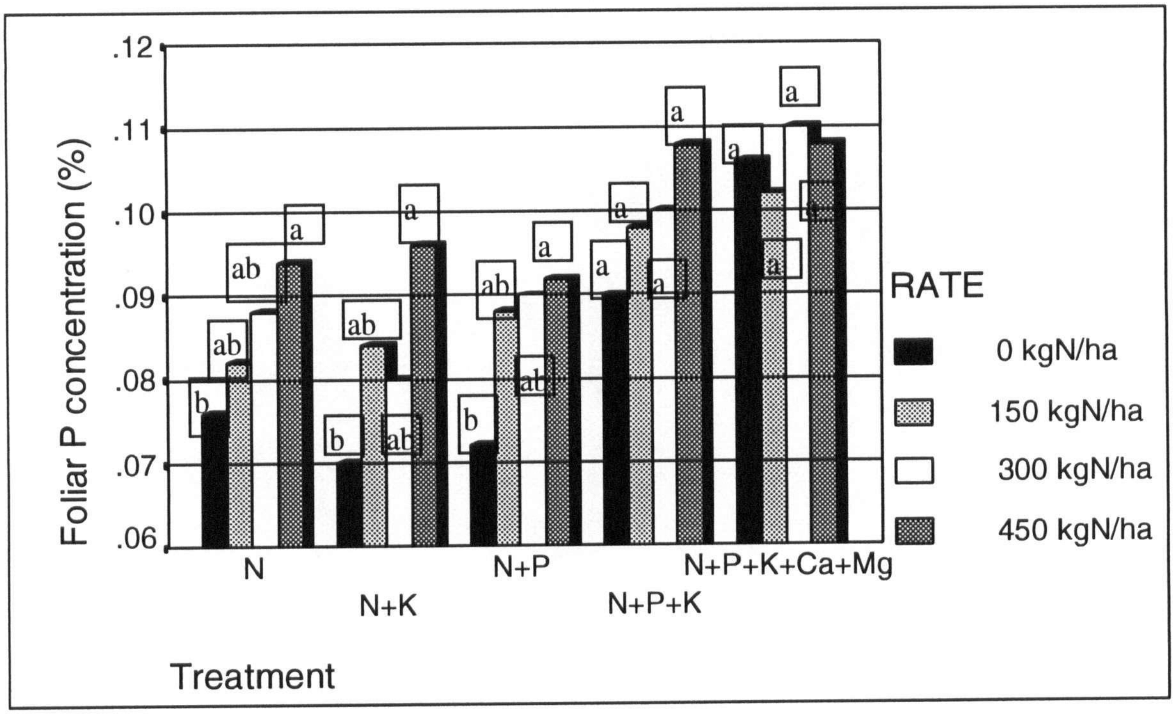

Figure 22: Foliar P concentrations of hybrid poplar stecklings fertilized with 5 nutrient combinations and 4 application rates. Each bar represents the mean of 5 pots, 1 steckling/pot. Bars labelled with the same letter within groups are not significantly different ($p > 0.05$) as determined by analysis of variance and Bonferroni's test. (Trial 3, clone 3)

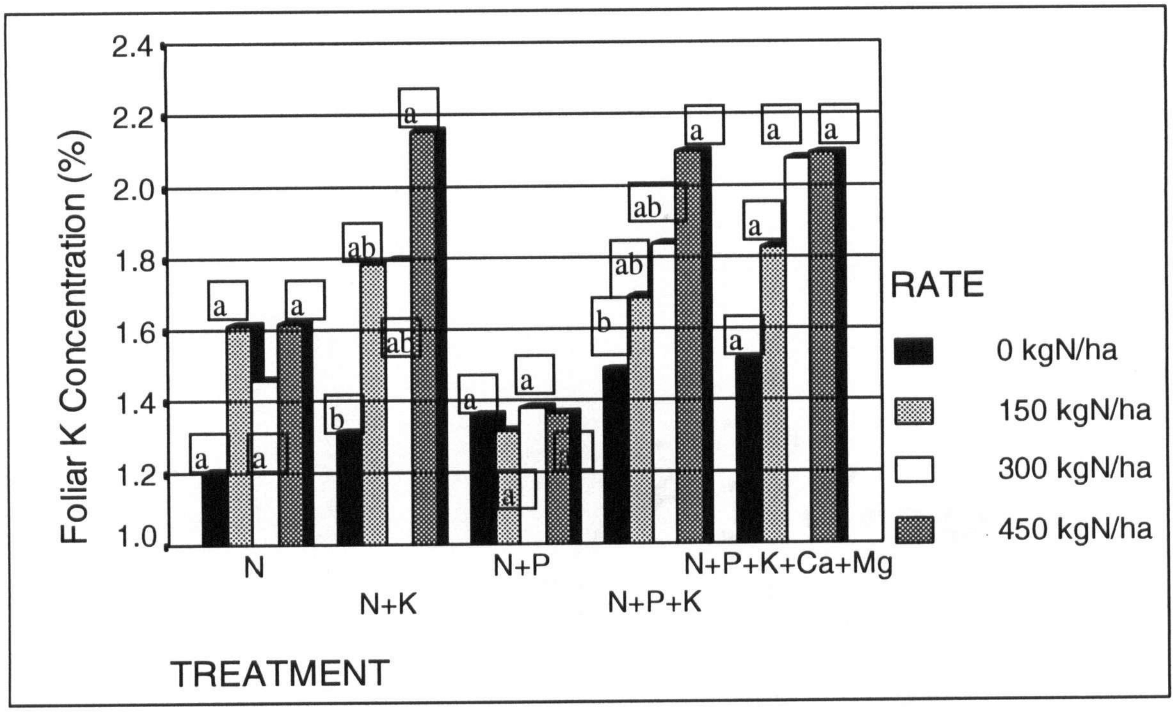

Figure 23: Foliar K concentrations of hybrid poplar stecklings fertilized with 5 nutrient combinations and 4 application rates. Each bar represents the mean of 5 pots, 1 steckling/pot. Bars labelled with the same letter within groups are not significantly different ($p > 0.05$) as determined by analysis of variance and Bonferroni's test. (Trial 3, clone 3)

Discussion

The lack of height, diameter and biomass growth response to different rates of fertilizer application in this pot trial, indicates that there was enough inherent fertility in the soil brought from Sayward to sustain growth of the stecklings for the 17-week trial.

Although there was no effect of fertilizer application rate on growth, there was an effect on foliar concentrations. Foliar N concentrations were consistently highest at the 450 kgN/ha rate, but there were no corresponding increases in biomass. Therefore, nitrogen was accumulating in the plants indicating they were not nitrogen limited. Accumulation, coupled with the decline of foliar biomass below control levels at the 450 kgN/ha rate, indicates that nitrogen toxicity may have occurred in these plants.

There were differences in growth between nutrient combinations, indicating an imbalance in nutrient supply. Total biomass was greater in the N+K and N+P treatments than the N treatment. The differences in total biomass reflect the differences in root and shoot biomass. Root biomass was greater in the N+P treatment than the N and complete treatments. Shoot biomass was greater in the N+K treatment than the N and complete treatments. Marschner (1986) estimated that the potassium requirement for optimal plant growth was 2 - 5% in the vegetative parts, fleshy fruits and tubers. Foliar K concentrations in this trial were within this range only in the N+K, N+P+K and the complete mixture treatments. Because growth increased only when P and/or K were added with N, we may surmise that the stecklings were not limited by N during the 17-week pot trial, and that they were more limited by P or K.

Trial 4. Steckling growth response to organic fertilization (clone 4)

Results

Total steckling biomass was greater in the compost-amended pots than in all other treatments except biosolids (Figure 24). Shoot biomass in the fish-compost treatment was greater than the control, inorganic, fish silage and straw treatments. Shoot biomass of the stecklings treated with pig manure and biosolids were intermediary. Root biomass was also greatest in the fish compost treated stecklings, followed by biosolids=pig manure=straw>control=inorganic >fish silage. Neither steckling height nor diameter was affected by type of fertilizer.

The general ranking of foliar biomass produced within the various regimes was as follows: compost>biosolids>pig manure>control>straw>fish silage>inorganic. Stecklings amended with compost had significantly more foliar biomass than those amended with inorganic fertilizer, fish silage and straw (Table 15). Foliar biomass of the control, manure and biosolids were intermediate. Leaf area followed a similar trend of compost>biosolids>pig manure> control>fish silage>straw>inorganic. Leaf area of the compost-amended stecklings was significantly greater than that of the control, inorganic-, fish silage- and straw-amended stecklings (Table 15).

Treatment	Foliar dry wt. (g)	Total leaf area (cm^2)
Control	4.65 (0.96) abc	499.16 (100.81) bc
Inorganic	2.24 (2.01) c	299.65 (250.67) c
Fish Compost	7.54 (1.17) a	878.56 (150.89) a
Fish Silage	3.34 (1.71) bc	435.38 (208.02) bc
Pig Manure	4.85 (3.81) abc	619.77 (404.03) abc
Biosolids	5.92 (1.12) ab	759.79 (136.68) ab
Straw	3.63 (1.27) bc	410.83 (129.84) bc

Table 15. Foliar biomass and leaf area of hybrid poplar stecklings amended with inorganic and organic fertilizers. Each value is the mean (s.d.) of 8 pots, 1 steckling per pot. Means followed by the same letter within a column are not significantly different ($p > 0.05$) as determined by analysis of variance and Bonferroni's test.

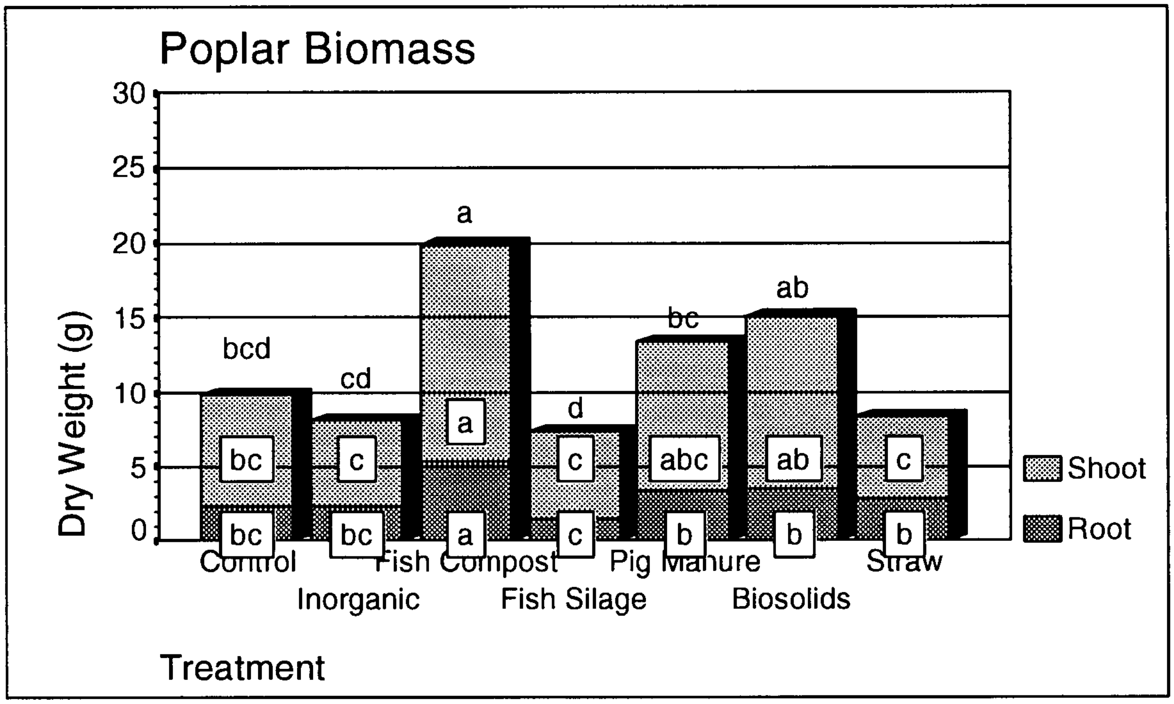

Figure 24: Root, shoot and total biomass of hybrid poplar stecklings ammended with inorganic and organic fertilizers. Each bar represents the mean of 8 pots, 1 steckling/pot. Bar area below the line = root biomass; bar area above the line = shoot biomass; entire bar = total biomass. Bars labelled with the same letters are not significantly different ($p > 0.05$) as determined by analysis of variance and Bonferroni's test. (Trial 4, clone 4)

Foliar concentrations of N, P, K, Ca and Mg all differed between treatments (Table 12), as did foliar nutrient contents (Table 13). Foliar N concentrations were highest in the inorganic, silage and manure treatments. Total foliar N contents (g) were highest in the compost, fish silage and pig manure treatments. Phosphorus concentrations were significantly higher in foliage of the pig manure and biosolids amended stecklings than the straw, fish silage and control trees. Phosphorus contents were also highest in the biosolids and manure treatments, as well as the compost treatment. Foliar K concentrations were significantly higher in the straw than in any of the other treatments, except compost. Potassium content was highest in the compost treatment, followed by the pig manure. Calcium contents were highest in the foliage of compost-amended stecklings. Magnesium concentrations and contents were highest in the biosolids-amended stecklings.

Treatment	N	P	K	Ca	Mg
control	1.33 (.14) b	.09 (.01) d	1.39 (.12) d	.97 (.10) abc	.24 (.02) b
N+P+K	2.75 (.32) a	.24 (.05) ab	1.52 (.17) d	1.15 (.33) ab	.22 (.03) bc
fish compost	1.80 (.40) b	.26 (.02) ab	2.45 (.34) ab	1.17 (.09) a	.15 (.01) d
fish silage	3.26 (.42) a	.18 (.03) bc	1.68 (.13) cd	.90 (.08) bc	.18 (.02) dc
pig manure	2.84 (.86) a	.31 (.10) a	2.14 (.46) bc	.78 (.08) c	.26 (.03) b
biosolids	1.60 (.15) b	.28 (.03) a	1.62 (.29) d	1.12 (.17) ab	.35 (.03) a
straw	1.34 (.32) b	.14 (.04) cd	2.71 (.12) a	.91 (.13) bc	.20 (.02) c

Table 16. Foliar nutrient concentration of hybrid poplar stecklings fertilized with inorganic fertilizer and organic wastes. Each value is the mean (s.d.) of 8 pots, 1 steckling/pot. Means followed by the same letter within a column are not significantly different ($p<.05$) as determined by analysis of variance and Bonferroni's test.

Treatment	N	P	K	Ca	Mg
control	.061 (.010) bc	.004 (.001) b	.062 (.013) b	.045 (.007) bc	.011 (.002) bc
N+P+K	.093 (.036) abc	.006 (.004) b	.054 (.023) b	.041 (.022) bc	.007 (.003) bc
fish compost	.133 (.021) a	.020 (.003) a	.196 (.045) a	.089 (.014) a	.011 (.002) bc
fish silage	.122 (.025) a	.007 (.003) b	.063 (.017) b	.034 (.009) c	.007 (.003) bc
pig manure	.133 (.057) a	.015 (.007) a	.120 (.091) ab	.042 (.024) bc	.014 (.007) b
biosolids	.094 (.016) b	.017 (.003) a	.096 (.026) b	.065 (.010) b	.021 (.004) a
straw	.047 (.014) c	.005 (.001) b	.099 (.034) b	.032 (.007) c	.007 (.002) c

Table 17. Foliar nutrient content (g) of hybrid poplar stecklings fertilized with inorganic fertilizer and organic wastes. Each value is the mean (s.d.) of 8 pots, 1 steckling/pot. Means followed by the same letter within a column are not significantly different ($p<.05$) as determined by analysis of variance and Bonferroni's test.

Discussion

Stecklings fertilized with organic wastes generally had the highest biomass and nutrient uptake. This supports the theory that plant growth benefits more from a mixture of nutrients than application of a single limiting element, or 2 or 3 elements. As well, organic wastes have the potential to release nutrients over an extended period of time, potentially matching nutrient supply with plant demand. Because most of the N in organic wastes is organic N, the rate of N mineralization and the amount of potentially mineralizable N are important factors. If the rate of N mineralization and the amount of mineralizable N are large enough, plant requirements can be met without the use of supplemental fertilizers. However, not enough is known about these factors to make accurate predictions. Chai and Tabatabai (1986) measured the mineralization rate of N from soil ammended with organic wastes during a 26-week period. The organic wastes included 4 different sewage sludges, 4 animal manures and 4 plant residues. In general, N mineralization of the sludge- and manure-amended soils was slow in the first 12 weeks, followed by a rapid increase during weeks 12 to 26. Total amounts of N mineralized were from 156 - 668 mgN/kg of sludge-amended soil, and 176 to 617 mgN/kg of manure-amended soil. The total amount of N mineralized differed greatly between the source of organic waste used, and the soil it was applied to (Chai and Tabatabai 1986). An earlier study by Epstein et al. (1978) showed that raw sewage sludge lost a lot of N through denitrification and immobilization, digested sludge had a net N mineralization pattern similar to native soil organic N, and the N in composted sludge was not easily mineralized. The variability of the organic wastes in these studies and others illustrates the need for an index against which specific organic wastes can be ranked as potential fertilizers. Douglas and Magdoff (1991) found a significant correlation between Walkley-Black N and amount of N mineralized from 19 different organic wastes. Further studies are required to determine its value as an N availability index in the field.

A second advantage to using organic wastes is the improvement of some physical properties of the soil including porosity, water-holding capacity and bulk density (Gallardo-Lara and Nogales 1987). In Maryland, McIntosh et al. (1984) found hybrid poplar ceased growth in

July or August, but with compost application, growth continued into October. They suggested that as well as greater N availability in the compost-amended plots, moisture availability was also higher. This would alleviate moisture stress, and improve nutrient uptake. Similarly, Epstein et al. (1976) found that application of 240 t/ha of compost to a silt loam soil increased soil moisture availability over that of the control, and Bengston and Cornette (1973) measured increased water holding capacity in compost-treated slash pine plantations in Florida.

Even though the stecklings were supplied with 500 ml of water per week, moisture may have been a limiting factor in the pot trial. Steckling growth increased from June to August, with a simultaneous decrease in precipitation from 70.5 mm in June to 18 mm in August. Treatments with organic matter added produced higher amounts of plant biomass than those that did not have organic matter added. The exception to this was the straw treatment which produced very little biomass. Within the compost, manure and biosolids treatments there was no relationship between the organic matter added and the total steckling biomass. Therefore, although moisture retention may have influenced steckling growth, it was not the only factor involved.

Total biomass, shoot biomass and root biomass were highest in the compost-treated stecklings. This was followed by stecklings treated with biosolids and pig manure. Several experiments have shown large plant growth responses to compost application in nursery environments and in the field. Angle et al. (1981), measured an increased growth rate of turfgrass to compost application in the field which was attributed to increased levels of available nutrients. A nursery study by Jellum and Kuo (1990) compared growth of silage corn and a grass mixture in four different fish composts, two biosolids composts, one cow manure compost and an inorganically fertilized (NPK) soil. Biomass of corn grown in the fish composts was comparable to that of corn treated with biosolids, manure and inorganic fertilizers. Biomass of the grass mixture was greatest in the fish compost treatments (Jellum and Kuo 1990). One of the field trials most applicable to this project involved the use of composted municipal sewage sludge and hybrid poplar (*P. deltoides* spp. and *P. angulata* x *P. trichocarpa*) (McIntosh et al. 1984). The compost was applied at 0, 150 and 300 Mg/ha. Stecklings were grown in pots containing their respective treatments for 5 months and then planted into the field in the same treatment sites. The compost was 1.36% N, 2.6% P, 0.18% K, 8.4% Ca and 1.6% Mg. Heights of hybrid poplar grown in the compost-amended plots were significantly greater than those grown in the control plots. This was partly due to trees in the compost-amended plots growing 1 to 2 months longer than those in the control plots. The extended growth period of the compost-ammended trees was attributed to a greater water holding capacity of the soil (McIntosh et al. 1984), although moisture was not addressed in the study.

In this experiment, foliar N concentrations were highest in the inorganic, silage and manure treatments, but biomass in the inorganic and silage treatments were similar to the control. This indicates that some of the added N was not being used for growth, suggesting luxury consumption. Foliar N concentrations of compost-treated plants were similar to the controls, but foliar N contents and foliar biomasses were higher, therefore the N taken up was used for steckling growth. In general, shoot growth is more sensitive to nutrient stress than root growth (Friend et al. 1990), therefore more carbon per unit of carbon fixed in the plant is used for root growth in low fertility soils than in high fertility soils (Hinckley et al. 1992). Friend et al. (1990) studied Douglas-fir seedling growth in response to severely deficient, moderately deficient and non-deficient N conditions. Total dry weight was lowest in the severely stressed seedlings. However, shoot growth was proportionally lower than root growth indicating a higher sensitivity. Because much of the nutrients applied in the organic wastes were in unavailable forms, it would be expected that root growth of the organic waste-ammended stecklings would be higher than root growth of the inorganic treatment. The compost-ammended stecklings produced the highest root biomass, followed by biosolids=pig manure=straw>control= inorganic>fish silage. But, the compost-ammended stecklings also produced the highest shoot biomass. This could be explained by looking at the mechanisms of carbon distribution over time. Increased carbon gain by the roots due to stress conditions acting on the shoot, increase root growth (Hinckley et al. 1992). This provides a positive feedback, because root growth increases result in interception of an increased amount of soil resources which partly alleviates foliar stresses (Hinckley et al. 1992). Alleviation of foliar stresses enables shoot growth to resume until stress conditions halt or decrease shoot growth rate once more, resulting in an increased amount of carbon being shifted to the roots. Through the continuing action of this mechanism, both shoot and root growth would benefit over a period of time.

In trial 4, KCl-extractable N was greatest in the inorganic and silage treatments. As would be expected from this, foliar N concentrations were also highest in inorganic and silage-amended stecklings. However, foliar biomass was as low as the control; therefore, the additional N was not being used for growth. A similar situation occurred in trial 3, in which there was a decreased growth response to N alone as compared to the N+K and N+P treatments. Nitrogen was not limiting. The soil to which the fertilizer amendments were added was brought from Sayward for both trials. Because N was not limiting we can surmise that the soil contained enough N to meet plant requirements during the 17 weeks of each trial. In trial 4, there was a growth response to the organic amendments. Because nitrogen was not limiting in either trial, the increased growth would have been due to factors other than N such as additional nutrients or moisture. Trial 3 tested a range of nutrient combinations added with N. A slight increase in biomass was measured in response to the addition of P and/or K with N, but the magnitude of the response was not as great as that measured in trial 4 with compost and biosolids. Therefore, it may be hypothesized that the moisture holding capacity of the organic amendments used in trial 4 significantly influenced growth. The moisture holding capacity of organic ammendments may be very beneficial in the field, especially on sites with low native organic matter or in dry areas. The use of compost and biosolids needs to be tested in field trials and compared to inorganic fertilization to examine their efficacy as plantation fertilizers.

SUMMARY AND CONCLUSIONS

Evaluation of the growth responses and foliar nutrient concentrations of the trees at the Sayward site and in the nursery trial indicate that fertilization with at least N and P is desireable. Indications from the height and diameter growth in the field are that growth response increased as the number of nutrients added increased. In trial 1, the overall best growth response was with NPK and in trial 2 the best growth response was with NPKS. The foliar nutrient concentrations focus importance on N and P nutrition. In trial 1, more N and P were taken up in the NPK treatment than in the N alone treatment. Foliar P concentrations in trial 2 decreased slightly ($p > 0.05$) when N alone was added but increased when both N and P were added. Additionally, there were significant correlations between foliar N and P concentrations and height and diameter growth. Because P was not applied without N, the correlation between P concentration and growth indicates that maximal growth response to N required P addition to prevent secondary deficiencies.

Results of the pot trial testing fertilization rate and nutrient combination indicated that P or K may have been limiting. Addition of P or K with N increased steckling biomass as compared to stecklings treated with N alone. Likewise, addition of S at the Sayward site, in combination with N and P, may also prevent secondary deficiencies. In trial 1 foliar SO_4-S levels decreased ($p > 0.05$) with fertilizer addition. In trial 2 the same trend was observed with a slight increase in SO_4-S when S was added as a component of the fertilizer mixture. Each added nutrient increased tree growth as compared with the controls ($p > 0.05$) and NPKS provided an additional growth response over N alone ($p < 0.05$). The results from these experiments are limited to one site, therefore fertilization trials with combinations of N, P, K and S across a range of sites should proceed before operational applications can be recommended.

The results from trial 1 indicated that there were no additional responses to splitting fertilizer applications during a growing season. This may have been confounded by low summer moisture levels. However, at this site a single application of fertilizer in the spring not only resulted in the equivalent growth of several applications, but would also reduce operational costs associated with site re-entry. Increasing the rate of fertilizer application over a 3- to 4-year period as tree growth increases may increase the biomass harvested at the end of the rotation. However, the potential gains from such a regime would have to be tested and compared with the associated operational costs.

The question of optimal tree age at which to fertilize was not directly addressed in this experiment. However, other trials suggest that the third growing season is optimal for fertilization (Heilman and Xie 1993, McLaughlin et al. 1987). The foliar nutrient concentrations measured in this trial support fertilizing in the third growing season. Trees in trial 1 were fertilized in the 2nd growing season; the resulting foliar N and P concentrations were within the published optimal ranges. Trees of the same clone fertilized in the third growing season, at the same sites, took up more N and P and exceeded the optimal ranges. Heilman (1992) had previously measured an increase in biomass associated with an increase in foliar N concentrations beyond the published optimal levels. Correlation analysis in this experiment indicated that an increase in growth was linearly associated with an increase in foliar N and P concentrations. It can be estimated that at this site optimal foliar N was approximately 3.4%, and foliar P was approximately 0.40%. Few growth advantages were measured beyond these levels.

The benefits of organic wastes as fertilizers include potentially increasing the amounts of available nutrients to the plant, providing a range of nutrients, increasing soil moisture retention and providing an alternate disposal method for the organic wastes. In this trial hybrid poplar stecklings responded well to the use of biosolids and fish-wood compost as fertilizers; further testing in field trials is recommended.

Because of their accelerated growth rate, hybrid poplars can produce large quantities of marketable biomass in a very short time. But also, because of their accelerated growth rate, they require nutrient additions to reach their maximum potential growth. This trial indicated that TxD clones at this site responded to N, P and S. Growth responses measured in other studies with different clones, at different sites have been variable. The nutritional requirements of a range of clones needs to be determined across a range of sites for maximum growth to be achieved. From this data set, predictive diagnostic techniques could be calibrated and tested for potential utility, resulting in an increase in the efficiency of fertilizer use.

One of the last, but most pertinent questions with respect to SRIC plantations is their sustainability. Removal of biomass and nutrients during repeated harvests of SRIC plantations have the potential to degrade soil and lead to productivity declines after several rotations. White (1974) studied nutrient removal with whole-tree harvesting practices in 6-9-year-old stands of native and plantation eastern cottonwood. His results indicated possible site degradation through removal of N, P and K after a few rotations. Van Veen et al. (1981) also found a N deficit when calculating the nitrogen and energy balance in a 5-year-old SRIC TxD plantation. If site degredation occurs, and the degree to which management practices can offset it needs to be addressed. Specifically, the role of inorganic and organic fertilizers in maintaining soil organic matter and nutrient supply in plantations needs to be determined.

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APPENDIX

The following abbreviations apply for the analysis of covariance (ANCOVA) tables: Source = source of variation; SS = sum of squares; DF = degrees of freedom; MS = mean square; E. Error = Experimental Error; and S. Error = Sampling Error.

Table 18: ANCOVAs for hybrid poplar diameter growth in Trial 1. Values in the table are adjusted for the covariate(s), initial diameter (1993 and 1994) and initial height (1994).

	Basal Diameter (1993)				DBH (1994)			
Source	SS	DF	MS	F	SS	DF	MS	F
Block	289917	2	144958	10.9*	1575	2	788	17.3*
Treatment	107099	6	17850	1.4	1155	6	192	4.2*
E. Error	158679	12	13223	7.1*	547	12	46	2.8*
S. Error	916942	489	1875		7653	475	16	
Total	2355693	510			20576	497		

* significant at $p < 0.05$

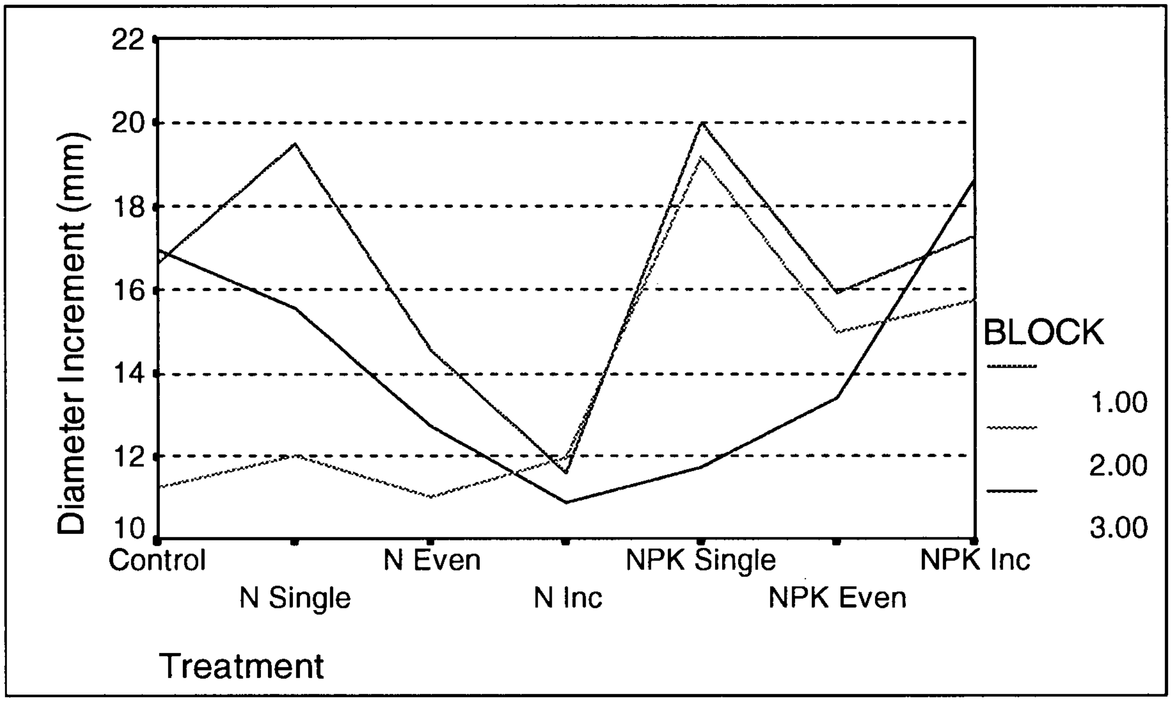

Figure 25: DBH growth (1994) of hybrid poplar fertilized with different nutrient combinations and application timings -block x treatment interactions. (Trial 1)

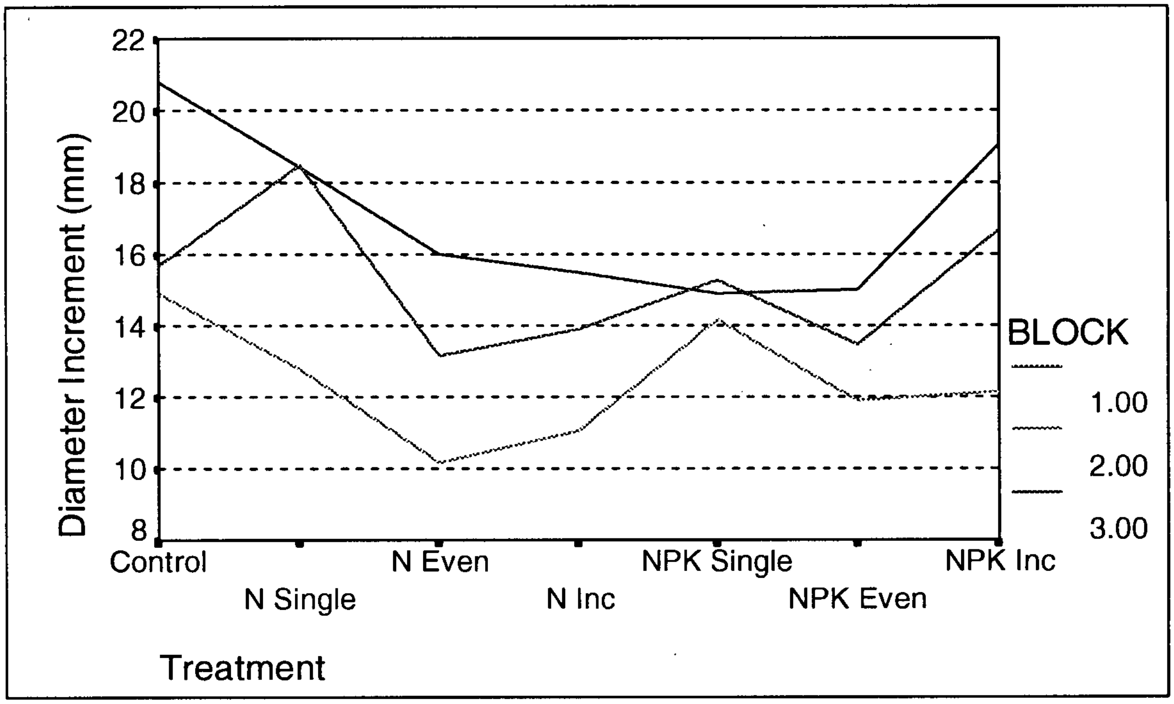

Figure 26: DBH growth (1994) of hybrid poplar fertilized with different nutrient combinations and application timings -block x treatment interactions. Values on the graph are adjusted for initial height and diameter. (Trial 1)

Table 19: ANCOVAs for hybrid poplar height and diameter growth in Trial 2. Values in the table are adjusted for the covariate(s), initial diameter (dbh, height) and initial height (dbh).

	DBH				Height			
Source	SS	DF	MS	F	SS	DF	MS	F
Treatment	6432	4	1608	7.5*	393150	4	98288	12.0*
Row	2973	4	743	3.5	124888	4	31222	3.8*
Column	1174	4	293	1.4	59434	4	14859	1.8
E. Error	2562	12	215	11.5*	98009	12	8167	7.4*
S. Error	10237	548	19		606591	549	1105	
Total	41804	574			1650741	574		

* significant at $p < 0.05$

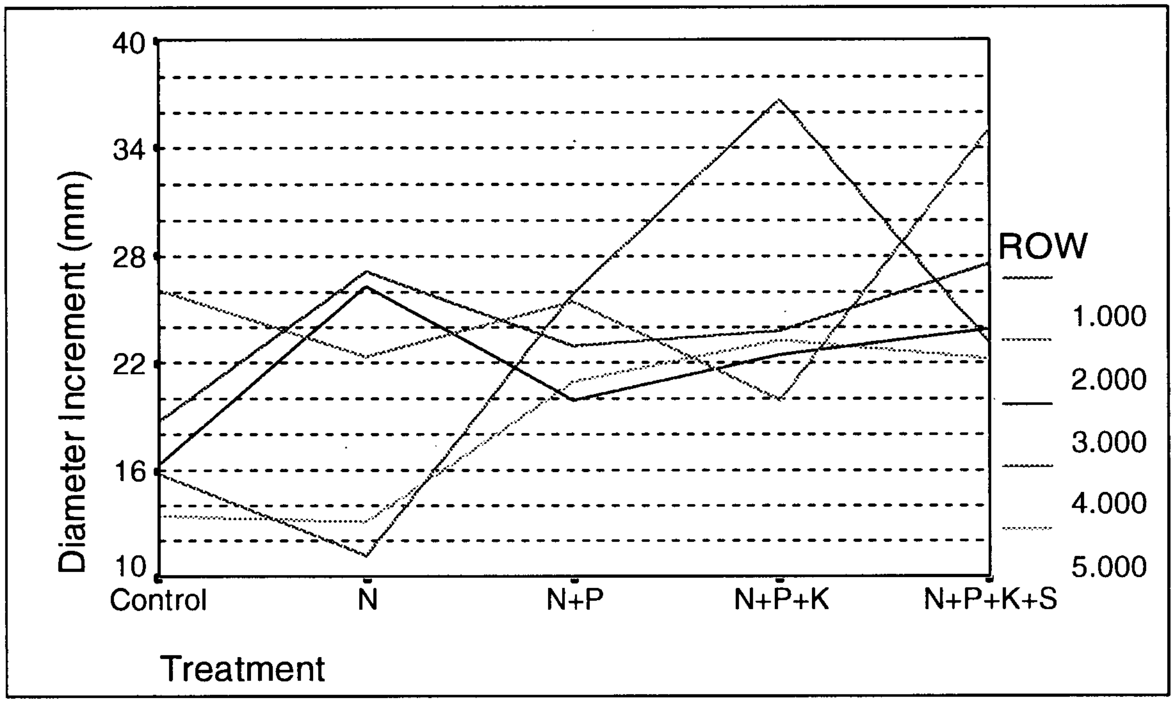

Figure 27: DBH growth of hybrid poplar fertilized with 4 nutrient combinations and an untreated control -block x treatment interactions. (Trial 2)

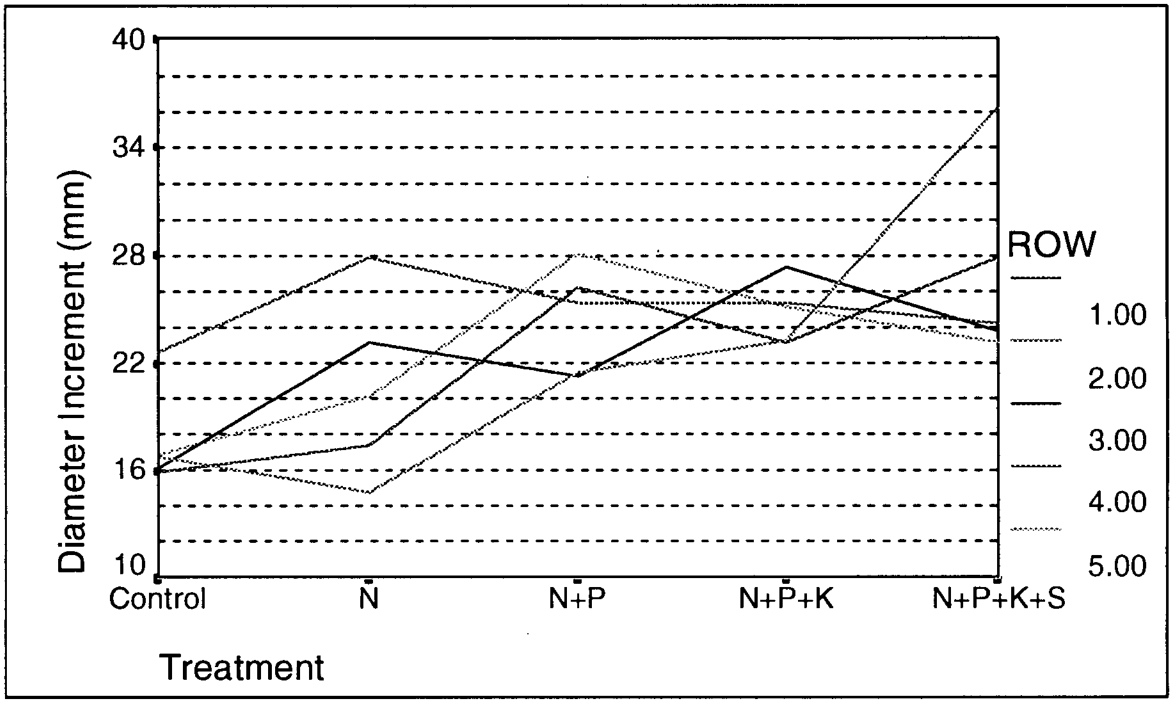

Figure 28: DBH growth of hybrid poplar fertilized with 4 nutrient combinations and an untreated control -block x treatment interactions. Values on the graph are adjusted for initial height and diameter. (Trial 2)

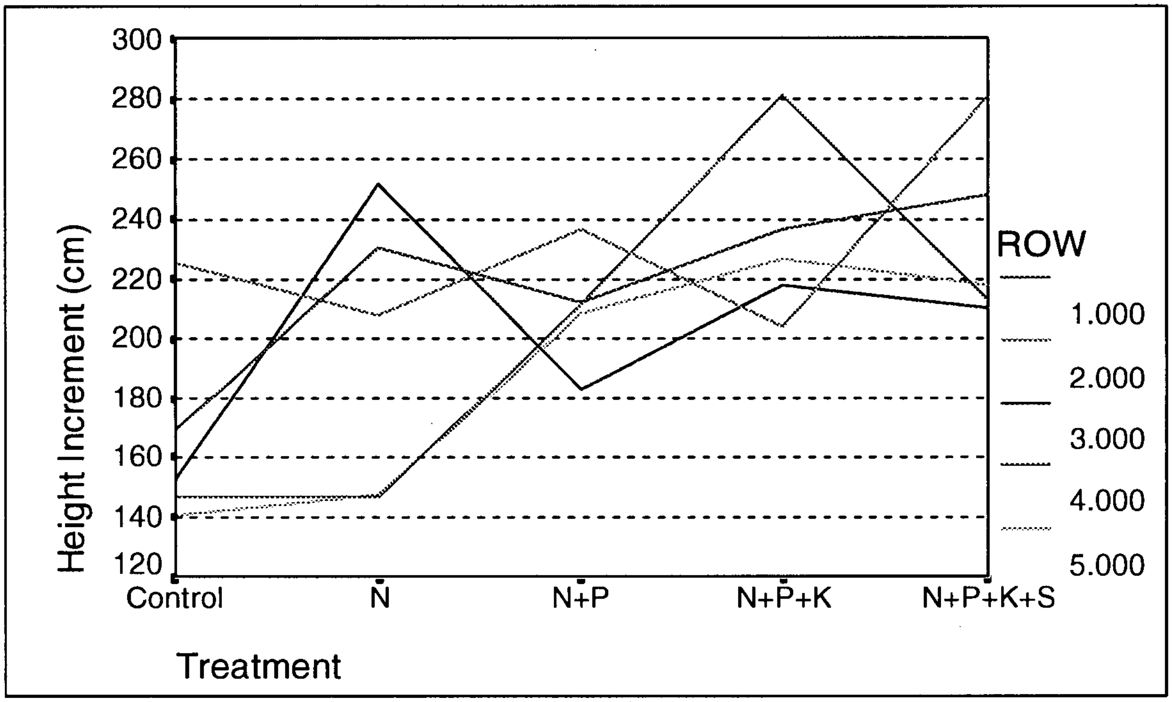

Figure 29: Height growth of hybrid poplar fertilized with 4 nutrient combinations and an untreated control -block x treatment interactions. (Trial 2)

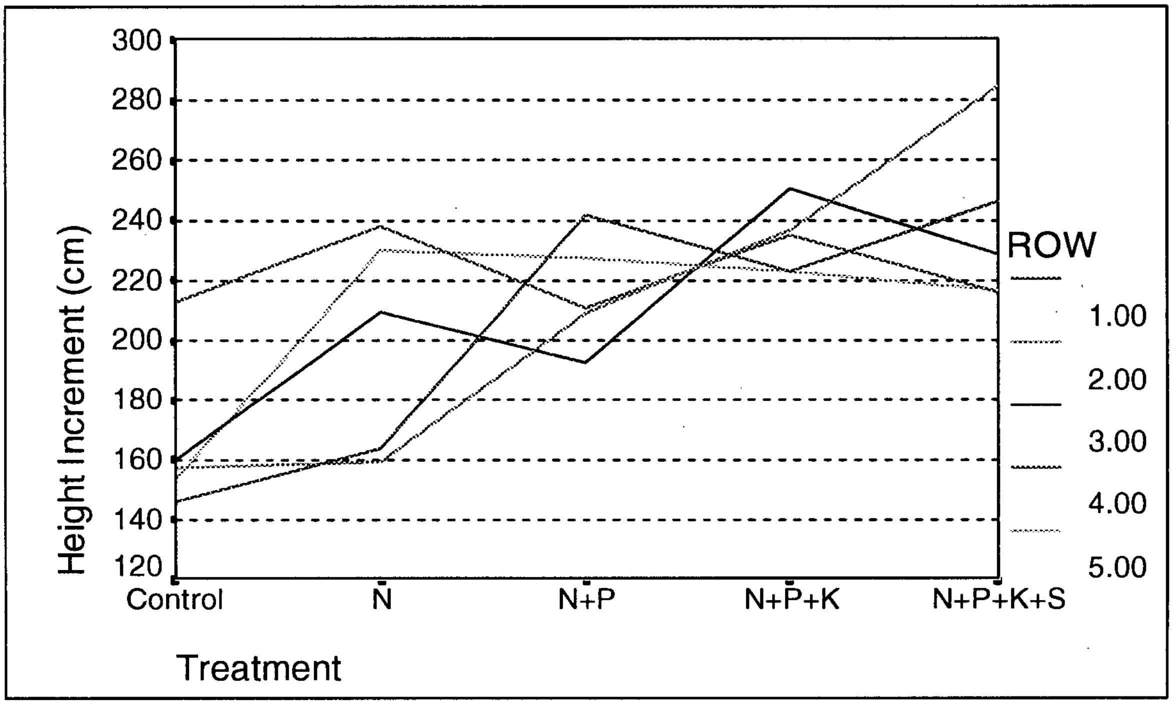

Figure 30: Height growth of hybrid poplar fertilized with 4 nutrient combinations and an untreated control -block x treatment interactions. Values on the graph are adjusted for initial height. (Trial 2)