THE EFFECT OF SEWAGE SLUDGE AND CHEMICAL FERTILIZER APPLICATIONS ON SOILS AND ON THE GROWTH AND YIELD OF HYBRID POPLAR

by

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ABSTRACT

M.Sc. T.D. Schwan Renewable Resources

THE EFFECT OF SEWAGE SLUDGE AND CHEMICAL FERTILIZER APPLICATIONS ON SOILS AND ON THE GROWTH AND YIELD OF HYBRID POPLAR

Aerobically-digested municipal sewage sludge was applied at 0, 200, and 400 Mg/ha (wet basis) for two years to a Grande Ligne gravelly sand and a Bearbrook clay that were planted with hybrid poplar (*Populus deltoides* cv. `angulata' X *Populus trichocarpa*). A fertilizer treatment of 30-60-30 Mg/ha N-P-K was also tested but caused few changes to measured variables. All variables were measured annually for three years. Soil N, P, and Mg were significantly increased at the Grande Ligne site, while most nutrients showed no change at the Bearbrook site. Soil Ca, K, pH, org. C and bulk density were the other measured variables. Foliage N and P responded dramatically to sludge treatment at Grande Ligne while K, Ca, and Mg were considered either non-limiting or diluted by growth. Bearbrook foliage did not change significantly due to sludge treatment. Biomass after three years increased by 246% in the highest sludge treatment at Grande Ligne, but only by 35% at Bearbrook. Heights and stump diameters showed similar results.

RESUME

M.Sc. T.D. Schwan Renewable Resources

EFFET PRODUIT PAR DES APPLICATIONS DE BOUES D'EPURATION ET D'ENGRAIS CHIMIQUES SUR DES SOLS AINSI QUE SUR LA CROISSANCE ET LE RENDEMENT DU PEUPLIER HYBRIDE

Des boues d'épuration municipales digérées à l'air ont été appliquées à un taux de 0, 200 et 400 Mg/ha (état de base humide) sur un sable graveleux de Grande Ligne et une argile de Bearbrook pendant une période de deux ans. Ces deux sols étaient plantés de peupliers hybrides (Populus deltoides cv. 'angulata' X Populus trichocarpa). Un traitement d'addition d'engrais de 30-60-30 Mg/ha de N-P-K a aussi été testé mais n'a enregistré que peu de changement sur les variables mesurées. Toutes les variables ont été mesurées annuellement durant trois ans. On notait au site de Grande Ligne que les concentrations de N, P et Mg du sol avaient augmenté d'une manière significative alors qu'au site de Bearbrook la plupart des éléments nutritifs n'avaient subi aucun changement. Les autres variables mesurées sur le sol comprenaient: Ca, K, C organique, pH et densité apparente. Le N et P du feuillage répondaient très fortement au traitement de boues à Grande Ligne, cependant les concentrations de K, Ca et Mg étaient considérées soit non limitantes ou diluées par la croissance. Du site de Bearbrook, le traitement de boues n'avaient pas changé le feuillage de façon significative. Après trois ans, la biomasse au site de Grande Ligne avait augmenté de 246% avec le traitement de boues le plus élevé, mais seulement de 35% à Bearbrook. La hauteur et les diamètres des souches montraient des résultats similaires.

Suggested short title -

EFFECT OF SEWAGE SLUDGE ON SOILS AND HYBRID POPLAR YIELD

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Chapter 1. Introduction

The need for intensive forest management has been demonstrated in recent years (Reed 1977). Fertilization is one aspect of forest management that also includes using genetically superior growing stock, proper site selection, and vegetation management to produce fibre or other wood products for societal needs.

Most forest fertilization has used chemical fertilizers to increase growth. Other available sources of nutrients are domestic and industrial wastes. In particular, municipal sewage sludge is one type of waste that could be applied to the land both as a fertilizer to enhance tree growth, and as a means of disposal. The use of municipal sludges (and effluents) to help shorten wood production cycles, by increasing productivity shows some potential especially on marginally productive sites (Kerr and Sopper 1982).

In 1980 the United States produced 4.24 million dry tons of treated sludge. One million dry tons or 24% was applied to the land as a soil amendment/fertilizer (Bastian et al. 1982). Most of this sewage sludge was applied to agricultural land. Forest land application is rare although research has shown the advantages to be gained from forest land application (Sopper and Kerr 1979a; Riekirk 1982; Harris et al. 1984).

To be safely applied to the land sludge must be digested to remove most of the pathogens. In Quebec there are a number of small municipalities that produce this type of sludge. Although present laws prohibit land application of sludge - it is usually landfilled - a guide to good practice has been recently developed to allow land application of sewage sludges (St-Yves 1985). Guidelines for utilization on agricultural lands have been published for Ontario (1978) and Alberta McCoy et al. 1981).

The application of sewage sludge to hybrid poplar has great potential. Intensive management of hybrid poplar requires a high level of nutrients (Hansen and Baker 1979). Sludge contains large amounts of available nutrients although some hazards exist in its use.

Since the early 1970's hybrid poplar has been managed on an intensive basis in Ontario (Zsuffa et al. 1977) and Quebec (Vallée 1979). Chemical fertilizers have been shown to increase poplar growth (Vallée 1979). But the idea of disposing of sewage wastes and providing a required nutrient supply for fast growing tree species at the same time only seems both logical and desirable in that it converts a liability into an asset.

1.1 Objectives

The objective of this study was to determine the increase in biomass productivity resulting from the use of aerobically digested sewage sludge and chemical fertilizer on planted hybrid poplar on two different soils.

This was accomplished by the following secondary objectives;

1) to analyze the chemical properties of the soils to determine the effect of a chemical fertilizer and different rates of sewage sludge

applications to the soils;

2) to analyze the foliage nutrient levelsin order to quantify the nutrients transferred to the leaves;

3) to measure rates of height growth and biomass of hybrid poplars that were treated with a chemical fertilizer and different rates of sewage sludge;

4) to compare biomass productivity on two different soil types using sewage sludge and a chemical fertilizer;

5) to correlate soil chemical properties with foliage analyses and height growth data;

6) based on these findings to propose other research activity essential to the effective land application of sewage sludge in Quebec.

Chapter 2. Literature Review

2.1 Intensive Management of Hybrid Poplar

Intensive management of hybrid poplar involves using genetically superior stock, matching clone to site, intensive site preparation including use of herbicides, fertilization, shorter rotations, and whole tree harvesting. The latter two should contribute to a substantial nutrient loss from the site (Hansen and Baker 1979). Therefore if the objective of management is intensive cropping of high nutrient demanding species on short rotations the only currently feasible method of maintaining adequate fertility levels will be addition of fertilizer.

The following examples show the effect of intensive management on yield. Alban et al. (1978) reported mean annual production(MAP) of 4170 kg/ha for a 30-year-old natural stand of Populus. MAP of wood plus bark in short rotation plantations ranges up to 20000 kg/ha, three to five times that reported for natural stands (Hansen and Baker 1979). Anderson (1979) reported yields of 15000 kg/ha/yr on two-year rotations for the best poplar clones (leafless). Yield increases of this stature would require added nutrients over the years to maintain productivity.

Ontario has been a leader in developing intensive management techniques in hybrid poplar. The Fast Growing Hardwoods Program is a major technology development aimed at developing the techniques necessary for the successful establishment of intensively managed high yielding plantations (Barkley 1982). In 1970-71 a large program of short rotation intensively managed poplar plantations was initiated in southeastern Ontario (Zsuffa et al. 1977). The area was selected because there was a good land base and close markets. Plantations have been established mainly on abandoned marginal farmland. Management systems have been developed for growing poplar in a variety of cultures and for a number of end products (Raitanen 1978). The key elements in plantation establishment are intensive soil surveying, matching clone to site, and complete weed control. Very little work has been done on nutrition and fertilization. According to Barkley (1983) fertilization studies have just begun.

Most poplar clones are not suited to extremes in soil properties. (Barkley (1983) outlined soil requirements for hybrid poplar. Good growth is achieved on moderately-well to imperfectly drained soil with well developed structure, and textures ranging from sandy loam to clay loam with a pH of 7. Soils considered not acceptable are excessively and poorly drained soils, lacking structure, with coarse sands or massive clays, and with a pH less than 5.5.

Research programs in poplar culture were started in Quebec in 1970. Research has focused on clonal selection, plantation establishment and maintenance, economic feasibilities, and fertilizer trials (Vallée 1979). In contrast to Ontario, poplar plantations have been established on forest land.

In 1971 poplar research was begun by the North Central Experiment Station(NCES) and has expanded over the years (USDA 1980).

Specific experiments were initiated to study the interaction of irrigation and fertilization as they affect plant growth. Studies also beganusing mill effluent spread by an irrigation system. Guidelines (Hansen et al. 1983) for hybrid poplar fertilization have been developed by the NCES. Present recommendations are for application of 100 lb N/ac (110 kg N/ha) applied annually for several years.

2.2 The Effect of Fertilization on Hybrid Poplar Growth

In Quebec the first reported poplar fertilization study was carried out by Aird (1962). He treated Raverdeau poplar (Populus nigra X P. deltoides) with a 10-10-10 fertilizer in one experiment and P. eugenei with N fertilizer in another. Nitrogen fertilizer significantly increased leaf weight and, concentration and content of N in the leaves. Leader growth showed no significant response to N fertilizer because nitrogen probably was not limiting in the soil. This was due to the low availability of P and possibly K. The second year, growth of the leader indicated highly significant response to N fertilizer.

The Quebec program resulted in many chemical fertilizer trials as reported by Sheedy and Vallée (1976), Ménétrier (1979), Ménétrier and Vallée (1980), Sheedy and Vallée (1981), and Sheedy (1982). Results of these studies showed that fertilizer was helpful in establishing plantations of poplar cuttings, and increased biomass by more than 200% in many cases. But weed control was necessary to obtain these results.

Phosphorus was best applied in a band along the planting line at a rate of 28 kg/ha of P three weeks after planting. Nitrogen (urea) applied at a rate of 100 kg/ha in the second year gave significantly better growth (Ménétrier and Vallée 1980). Some tests showed increased frost damage and mortality with fertilizer treatments (Sheedy and Vallée 1981). Using one-year-old rooted cuttings, Sheedy (1982) found that fertilizer, especially N, strongly stimulated the growth of cuttings. Contrary to other research, fertilized trees were generally less affected by frost than control trees.

In Ontario, Ogar (1981) examined the interaction of hybrid poplar clone, site, spacing, and fertilizer treatment. He found clone I45/51 responded more to high dosage NK fertilizer (N600-K300 kg/ha) than clone DN17. The latter clone seemed to indicate maximum growth response with an application of N200-K100 kg/ha.

In greenhouse experiments, Leech and Kim (1979) established standards of nutrient requirements for poplar. They have used the Diagnostic and Recommended Integrated System (DRIS) to help with selection of limiting nutrients and the order in which fertilizer amendments should be applied.

In Tennessee, Curlin (1967) demonstrated large increases in the growth of clones of *Populus deltoides* with application of N fertilizer. The study demonstrated a strong clone-fertilizer interaction for diameter, height, and volume growth.

Heilman et al. (1972) found increased growth due to fertilization of black cottonwood after the first year. Blackman (1977) applied N fertilizer, at rates up to 672 kg/ha, to eastern cottonwood plantations that were seven- and ten-years-old. Fertilization caused marked increases in height, diameter, and volume growth. The highest rates of fertilizer produced the maximum response but lower rates (84 and 168 kg/ha) produced more tree growth per unit of applied nitrogen. Three years after treatment, the growth advantage of the fertilized plots was declining.

McLaughlin et al. (1985) found that N fertilization did not affect tree height growth during the first growing season but significantly increased total height growth in the second and third years. Laing et al.(1985) fertilized hybrid poplar planted on marginal abandoned farmland. Fertilization had significant effect on height, diameter and stem weight.

Ogar (1981), in his literature review, noted that many authors found poplar produced a more vigorous growth response to fertilizer when established on poor infertile soils or on soils impoverished by agronomic cropping. Nutrient-poor soils caused poplar yield to decline.

2.3 Land Application of Sewage Sludge

2.3.1 Introduction

Many symposia and seminars in the past few years have been published on the topic of recycling wastes, both solid and liquid, on the land. They have dealt mostly with applications to agricultural land with a small reference to forest land (Ontario 1974; Loehr 1976; Sanks and Asano 1976; Elliott and Stephenson 1977; Loehr 1977; Loehr et al. 1979). Three symposia in particular have dealt with the application of sewage sludges and effluent to forest and strip-mined land. (Sopper and Kardos 1973; Sopper and Kerr 1979a; Sopper et al. 1982). Other reviews on land application of sewage sludge are found in Bates (1972), Smith and Peterson (1982), with emphasis on recycling N and, Sommers and Sutton (1980) and Kirkham (1982), who reviewed P in waste recycling.

The main conclusion from these studies was that sewage sludges and effluents must be recycled as a means of disposal. The soil is a natural place to dispose of them. Sewage wastes are full of nutrients that aid in plant growth. Large quantities of N, P, and K in treated sewage sludges can be recycled through harvested crops with benefits in both yield and quality. Sewage sludges should be stabilized or digested by secondary treatment in order to be biologically safe. Close monitoring of land application can avoid problems with nitrates, salts, and heavy metals.

Bates' (1972) review quoted references that municipal sewage has been applied to land in the 1500's. He also noted that a literature review was done in 1894. There was much research on land application of sewage between 1940 and 1955. In the late 1960's and early 1970's interest in land sewage disposal was based on a search for the least expensive means of waste disposal which would not harm the environment. Improved crop production was considered to be an unexpected bonus. In the past ten years the amount of research produced has been voluminous. A quick search of the Journal of Environmental Quality showed 78 papers in the years between 1978 and 1983 on the land application of sewage sludges alone. Only a few are mentioned here.

Effects on soil physical properties have been studied by Epstein et al. (1976) and Harding (1985). Soil chemical properties have been studied by King and Morris (1973); Soon et al. (1978); and Robertson et al. (1982). Particular studies on the effect of nitrogen in sludge and its effect on the soil have been reported by Sabey (1977), Magdoff and Amadon (1980), Parker and Sommers (1983) and King (1985). Aspects of heavy metal contamination on soil properties and plant growth have been reported by Soon et al. (1980), Emmerich et al. (1982) and Chang et al. (1984).

2.3.2 Constraints in the Use of Sewage Sludges

The problems encountered during waste application vary according to waste type, rate of application, and region. The two main areas of concern are 1) nitrate-N leaching to the ground water and, 2) metal accumulation. Other problems include presence of pathogens and pesticides, accumulation of phosphorus, and salt accumulation (only in arid or semiarid regions).

Contamination of ground water with nitrate-N is a potential problem in soils treated with rates of sludges supplying nitrogen in excess of crop needs. The potential for NO_3-N leaching in forest soils receiving sewage sludge has been demonstrated (Brockway and Urie 1983; Riekerk 1981). Forest sites are generally poorer nitrogen renovators than crops, leading to a potential increase in NO_3-N in the ground water (Sidle 1977). Nitrate-N leached below the rooting zone will likely contaminate subsurface waters and possibly pose a threat to human and animal health. The leaching of NO_3-N can be overcome by applying an amount of waste that will supply a level of available nitrogen equivalent to the N demand of the crop being grown (Sommers and Sutton 1980).

Metal accumulation is a long-term problem and may result in decreased crop yields for significant periods of time after waste application. Some metals such as Cu and Zn are essential for crop growth and if applied in low amounts in wastes, they may help increase plant yields. However, high levels of these metals are toxic to plants, resulting in lower yields. Metal accumulation problems are encountered with industrial sludges. Domestic municipal wastes are generally low in metals but may be a problem if combined with industrial wastes. Wastes also contain other metals, particularily Ni and Cd, as well as Cr, Hg, Pb which are not essential for plant growth and are toxic at low concentrations. As well as causing yield reductions, certain metals such as Cd are assimilated by the plants.

2.4 Application of Sewage Sludges and Effluents on Forest Land

2.4.1. Introduction

Application of sewage sludges and effluents to forest land poses many similar questions to that of agricultural land. But with forest applications there are new benefits as well as different constraints (Sidle 1977; Smith and Evans 1977). Sludge disposal in forested areas seems to be a viable alternative since the vegetation is generally not harvested as an edible crop. Forests have a long cycling period. Decomposition and nutrient release from wastes may occur over a long time period. Odor in waste disposal areas would provoke little adverse public reaction or pose health problems because of low human population densities in forested areas.

On the other hand, public acceptance may not be easy to overcome. The pristine image of the forest may be marred. Sludge application may not be accepted with other forest uses. The effect of sewage on wildlife is not well understood and may pose health problems. Roads and access to the forest must be available at low cost for transport of sewages.

Spreading of wastes will be a problem. Many lands are steep and rugged, thus denying easy access. In natural forest settings large vehicles have problems manoeuvering through the forest. With effluent disposal, irrigation systems must be set-up. Urie (1979) concluded that sludge application will probably be confined to establishment and thinning periods due to difficulty of access to forest lands.

2.4.2 Effect on Forest Soils and Tree Growth

Forest land application of wastes are not common. In a 1974 search (Smith and Evans 1977) of organizations in the United States conducting research in evaluating forests for waste recycling, there were only eleven groups studying waste application to the forest. Four of these groups dealt with municipal sludge. Since then there have been a few other projects started.

Application of sewage to forest land in Canada is rare. The earliest documented study is by Gagnon (1973). He applied 500 lb/A (550 kg/ha) of dried anaerobically digested sewage sludge which is equivalent to 2.0-1.1-0.4 N-P-K fertilizer, to ten-year-old white spruce growing on marine sand deposits at Grand-Mère, Québec. After one year, average height of sludge-treated trees exceeded that of control trees by 7%. Subsequently this difference increased to 30%. At another site (Gagnon 1974), jack pine was treated with the same type of sludge. After two growing seasons sludge-fertilized trees showed a greater growth increase than unfertilized trees.

Ogden et al. (1979) reported on the possibilities of applying digested sewage sludge to regenerating forest land in Nova Scotia. Guidelines for sludge disposalwere suggested for Nova Scotian conditions.

Industrial sludge high in N was applied to a hybrid poplar plantation near Brockville, Ontario (Barkley et al. 1983b). One year results showed no changes in growth. Rates of application were too low to cause significant impact on growth in the first year.

A wastewater irrigation study was conducted over a five-year period in a lodgepole pine forest in the Kananaskis Valley near Calgary (Graveland, 1980). Soil and groundwater chemistry showed no major changes due to irrigation. Tree growth was 38% greater on the irrigated plot.

A textile factory sludge was applied to fir and maple stands near Sherbrooke, Quebec (Morin et al. 1985). One of the objectives was to test the effect on forest land of sludge dewatered by the freeze-thaw technique. Sludge was applied at rates up to 800 kg N/ha for one year. There were no major changes to groundwater chemistry. No measurements of forest growth were taken.

In the United States sewage application has been more common and has developed into long term studies. One of the earliest and most successful projects of sewage disposal involves the "living filter" systems (Sopper 1968; Sopper and Kerr 1979b). Sewage effluent was applied to forest land in order to utilize the soil as a filter and to take advantage of the entire biosystem to renovate the effluent for ground water recharge. Aerobic conditions were maintained so that mineral nutrient and detergent residues might be removed and degraded within the biologically active soil surface horizons. Also mineral nutrients could be removed by absorption through the root system of the vegetative cover.

In Washington, Riekerk (1982) showed that utilization of sewage sludge as a forest soil amendment was feasible with certain limitations. Problems arose with the actual spreading of sludges in forest areas. Because sludge decomposition was slower in forest areas due to more humid environments, there was less dramatic impact on the forest system. From these studies (Cole 1982), it appeared that neither heavy metals nor pathogens will be of lasting concern when sludge is applied to forest areas. But nitrate-N leaching below the rooting surface can be excessive especially when sludge has been applied to newly cleared areas. Weed control was important to maintain tree growth in areas receiving sludge applications (Cole 1982). Established forests that received sludge also demonstrated a remarkable growth response. Fifty-year-old Douglas fir on a (low) site index IV increased basal area growth by 60% over a two-year period.

On a gravelly soil in Washington, Stednick and Wooldridge (1979) found low leaching rates for P, Ca, K, and Mg. These were retained in large measure in the upper soil profile. Results of N leaching were variable.

In a Georgia sandy loam, Nutter et al. (1979) found that all nutrients, except N, increased in the forest floor with addition of sludge. In the mineral soil, P increased in the upper 15 cm. while K and Ca increased in concentration with soil depth. Mg and N were not changed in the soil. Brister and Schultz (1981) found that overstory white pine showed increased stem diameter growth within the canopy. This was detected by stem analysis. Overstory trees failed to show any growth responses in height or diameter breast height.

Brockway et al. (1979) identified increases in soil pH as Ca and Mg concentrations increased but only in the surface layers. Phosphorus showed the same effects while K increased at all depths. Nitrate-N accumulated throughout the profile and NH_4-N showed an overall decline.

Brockway (1983) found that municipal sludges produced significant forest floor increases in total salts, pH, concentrations of N and P and, trace elements and heavy metals. Very small fluctuations in nutrient levels occurred in the soil below 15 cm. Movement of nutrients from the forest floor into the soil was generally limited to NH_4-N and total P leaching into the upper soil layers. Accelerated humification developed along the interface between the sludge layer and the accumulated forest litter.

The concern of nitrate-N leaching into the ground water due to sludge or effluent application was expressed by many of the above authors. Brockway and Urie (1983) studied a number of ecosystems in northern Michigan expressly to determine the safest sludge level at which to maintain ground water quality. Recommended sludge fertilization rates for forest land depended on sludge characteristics, soil properties, water table depth, hydrologic conditions, vegetation type, and age of stand. They recommended a digested sludge application rate of 19 Mg/ha for an aspen stand. This high (for them) rate was suitable due to the ability of this ecosystem to assimilate the sludge.

2.5 Application of Sewage Sludge and Effluents to Natural and Hybrid Poplar

As was mentioned earlier, hybrid poplar increased growth by addition of chemical fertilizers. Sewage sludges and effluents have been applied successfully to hybrid poplar plantations also.

In Maryland (McIntosh et al. 1984), a field study was conducted to determine the benefit of land application of composted municipal sewage sludge on growth of white pine and hybrid poplar. White pine was not affected by compost treatment, but the effect on poplar was dramatic. After 3 years the average hybrid poplar heights were 233, 443, and 483 cm for the 0, 150, and 300 Mg/ha (dry weight basis) treatments, respectively. The poplars were one-year-old cuttings when the sludge was applied and the height differential was seen in the first year of compost treatment. There was no difference in poplar height between the two compost levels.

In Pennsylvania (Kerr and Sopper 1982), hybrid poplar planted in an abandoned field, was irrigated with municipal waste water at a rate of 5 cm/week throughout the growing season. Waste water irrigation significantly increased the diameter and the total height growth of the poplar. Total woody biomass production was more than doubled. In another project by the same authors, dewatered and heat-dried municipal sludge was applied at rates up to 150 t/ha to an anthracite coal-refuse bank. After five years, poplar on the high sludge rate site had grown 4.5 m in five years compared to poplar growth of 2.5 m on the no-sludge site. Potential woody biomass was increased more than tenfold with the largest application of sludge.

In Michigan, Brockway et al. (1979) showed that cottonwood exhibited superior growth characteristics under irrigation with municipal waste water. Cottonwood also accumulated large amounts of nutrients. Harris (1979) also in Michigan, applied sludge and effluent to sandy forested soils. Sludge applied to a coppice aspen (*Populus grandidentata* Michx.) stand resulted in increased biomass productivity of 30 - 150% on the plots that received the sludge. In another experiment in Michigan, (Cooley 1979), two different hybrid poplar clones (*Populus canescens* X *grandidentata* and *P. deltoides* X *nigra*-Raverdeaux) were planted on a Boyer gravelly loamy sand as unrooted cuttings and irrigated with municipal effluent. After four years the irrigated Raverdeaux poplar was 169% taller, and the average dry weight was 1200% greater than those not irrigated.

Chapter 3. Materials and Methods

3.1 Site Description

Cuttings of hybrid poplar (Populus deltoides cv.'angulata' x Populus trichocarpa) were planted on two sites in southwestern Quebec in May 1980.One site was an excessively drained Grande Ligne gravelly sand developed on fluvio-glacial deposits at Macdonald College's Blair Farm near Rockburn, Quebec. It is classified as an Orthic humo-ferric podzol. The other site was an imperfectly drained Bearbrook clay, developed from marine sediments, near Rigaud Quebec. It is an Humic gleysol. Soil properties for both sites are found in Table 3.1. Precipitation data for both sites is found in Appendix A.

3.2. Field Procedures

3.2.1 1980

Poplar cuttings 25 cm long were obtained from the Ministère de l'Energie et des Ressources, Quebec. Cuttings were planted at 2 m spacing. Each main-plot unit had 20 cuttings with 4 rows and 5 cuttings per row (Fig. 3.1).

At the Grande Ligne site sewage sludge was applied at 0, 200, and 400 wet Mg/ha, and fertilizer applications were made of urea, triple superphosphate, and muriate of potash to give an application rate of 30, 60, and 30 kg/ha of N, P, and K respectively. Each treatment was replicated three times in a randomized complete block design.

The Bearbrook site was arranged as a completely randomized design with the same treatments and three replications as above.

Table 3.1. Soil properties of Grande Ligne and Bearbrook sites.

	Grande Ligne		
Depth (cm)	0-15	15-30	30+
Characteristic			
pH	5.1[1]	4.6	4.8
Org. C(% dw)	2.3	1.7	1.2
P (mg/l)	26	25	27
K (mg/l)	33	21	15
Ca (mg/l)	755	365	279
Mg (mg/l)	54	27	24
clay (%)	8	9	8
silt (%)	14	9	11
sand (%)	78	82	81
	loamy-sand	loamy-sand	loamy-sand

Note: All materials greater than 2 mm have been removed.

	Bearbrook		
Depth (cm)	0-15	15-30	30+
Characteristic			
pH	5.0	5.1	5.4
Org. C(% dw)	3.4	2.0	0.7
P (mg/l)	42	36	48
K (mg/l)	251	184	239
Ca (mg/l)	2038	1875	1858
Mg (mg/l)	620	640	940
clay (%)	45	48	61
silt (%)	40	36	28
sand (%)	15	16	11
	silty-clay	clay	heavy clay

[1] All chemical properties are an average of 12 values; one from each main-plot unit.

Both sites had been plowed the autumn of 1979 and disked in the spring of 1980. No herbicides were applied before planting.

Sludge and fertilizer were spread in a one square metre area around each planted cutting. This amounted to 20 kg per tree for the 200 Mg/ha sludge treatment and 40 kg per tree for the 400 Mg/ha treatment. At the Grande Ligne site sludge treatments were applied two to three weeks after planting, and fertilizer was applied four weeks after planting. At the Bearbrook site all treatments were applied four weeks after planting. At the Grande Ligne site two loads of sludge were required to cover all the plots. The first load was applied to the 200 Mg/ha treatment and the second load was applied to the 400 Mg/ha treatment. This resulted in different elemental concentrations in the two treatments (Table 3.4).

Soil samples were taken from each main-plot unit at 0-15, 15-30, and 30+ cm at the time the cuttings were planted in mid-May 1980.

Weeds were controlled by one application of Round-up (Monsanto) in mid-June and by hand weeding as required throughout the season. The Grande Ligne site was mechanically cultivated in mid-July.

Leaf samples were collected at the Grande Ligne site in mid-September. Tree heights were measured in October.

Fig 3.1 Tree arrangements on main-plot units in 1980.

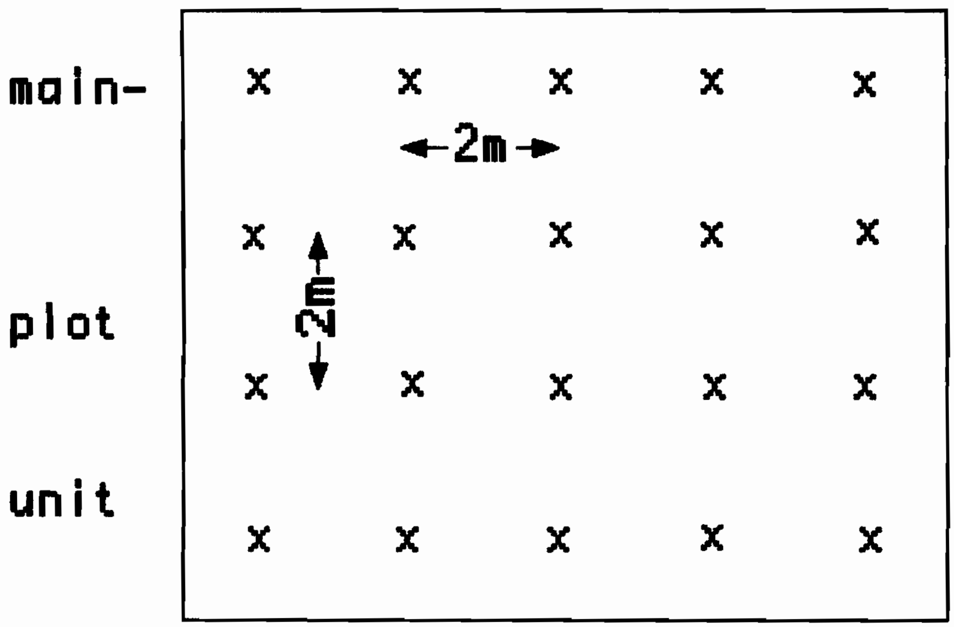
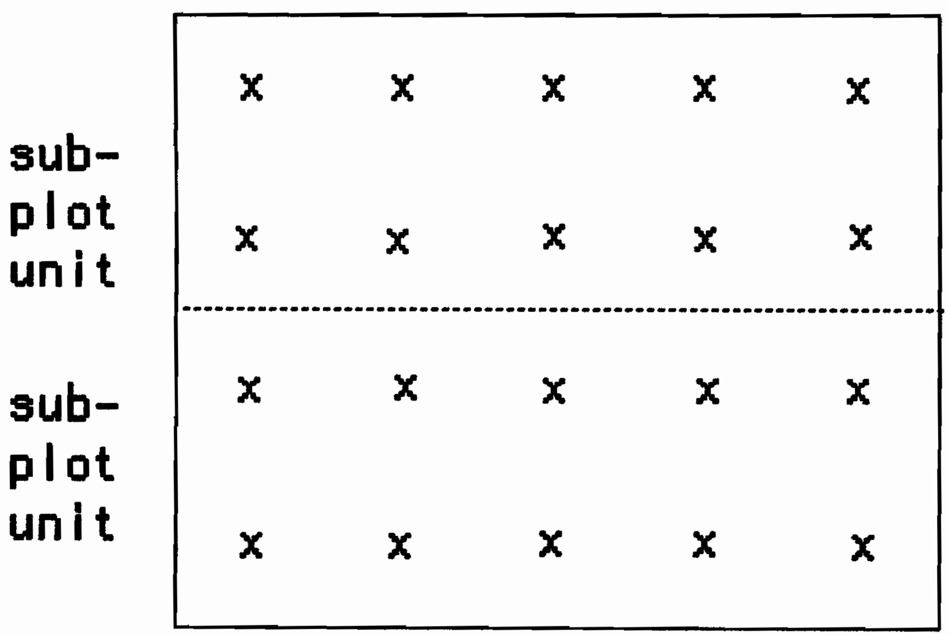


Fig 3.2 Tree arrangements on sub-plot units in 1981 and 1982.



3.2.2. 1981.

Soils were sampled in May before the second sludge and fertilizer application. Sampling was the same as the previous year except that samples were taken for NH_4-N and NO_3-N on the Bearbrook site only. Samples were taken only in the m^2 area around the tree where the treatments were applied.

The main-plot units were split in half leaving 10 trees (2 rows by 5 trees) to each sub-plot unit (Figure 3.2). Sewage sludge and fertilizer were applied at the same rates as the 1980 season to one-half of the 1980 main plot unit. The other half of each main-plot unit received no further treatment. Sub-plot units were randomized. A summary of all treatments, with codes, is found in Table 3.2.

At the Grande Ligne site weeds were controlled by two applications of Round-up,while at Bearbrook, Paraquat (Chevron) was applied first followed two months later by Round-up. Weeding by hand was done as required.

Leaf samples were collected at both sites at the end of August. Sampling was done for each treatment sub-plot unit except for the control in which the main-plot unit only was sampled. Annual and cumulative tree heights were measured in October on all trees.

Table 3.2 Summary of treatments and codes

Year of application	Code	Treatment
--	0	Control - no sludge
1980	200[1]	200 Mg/ha wet sludge on main-plot units
1981	200-1	No sludge on sub-plot unit (1/2 area of 1980 treatment)
	200-2	200 Mg/ha wet sludge on sub-plot unit (1/2 area of 1980 treatment)
1980	400	400 Mg/ha wet sludge on main-plot unit
1981	400-1	No sludge on sub-plot unit (1/2 area of 1980 treatment)
	400-2	400 Mg/ha wet sludge on sub-plot unit (1/2 area of 1980 treatment)
1980	F	Fertilizer 30-60-30(N-P-K) on main-plot unit
1981	F-1	No fertilizer on sub-plot unit (1/2 area of 1980 treatment)
	F-2	Fertilizer 30-60-30(N-P-K) on sub-plot unit (1/2 area of 1980 treatment)

[1] 200, 400, and F refer to treatment in 1980 or combined sub-plot treatments in subsequent years.

- No treatments in 1982.

3.2.3. 1982.

No further treatments were applied to the plots.

In May, soils samples were collected from each sub-plot unit except for the control which was collected as one main-plot unit. In September all sub-plot units were sampled. Bulk-density measurements were made by radiation scattering using a surface moisture density gauge (Troxler Model 3401). The instrument determined wet density which was corrected to an oven-dry basis from a gravimetric-moisture determination.

Leaf samples were taken at the end of August on both sites following the same procedure as in 1981 except that the control plot was split for sampling purposes.

Annual and cumulative tree heights were measured in October for all trees. Tree diameter at 15 cm above ground was also measured for all trees.

At each site, 20 representative (21 at Bearbrook) trees were cut and weighed for the biomass study. These trees were taken only from the inside of the plots. Green mass was measured. Subsamples were taken from each component and these were used to determine moisture content. From this data oven-dry weight was obtained for each of the sample trees (Table 3.3).

Table 3.3 Characteristics of trees used in regression to estimate yield.

Tree No.	Treatment	Diameter at 15 cm	Height	Oven-dry Mass	Green Mass
		cm		g	
		Grande Ligne			
1.5[1]	200-2	5.7	332	1487	3068
2.6	C-1	4.3	345	968	2059
3.1	C-1	3.5	248	542	1152
3.0	C-1	2.7	203	212	456
3.5	C-2	3.2	235	341	783
3.6	C-2	4.3	325	803	1762
4.4	200-1	6.0	311	1516	3222
4.6	200-1	5.0	307	978	1858
5.4	C-1	6.2	321	1397	2922
6.2	400-2	8.1	483	2950	6706
6.5	400-1	8.5	385	2192	4718
7.6	F-1	5.0	295	1130	2463
8.6	400-1	4.5	278	919	1999
9.2	F-2	4.3	270	710	1561
9.6	F-1	3.0	171	213	451
10.1	400-1	9.2	432	3988	8498
10.4	400-2	8.7	445	3563	6578
11.2	200-1	5.5	286	1578	3531
11.5	200-2	6.5	305	1668	3689
12.6	F-2	7.2	361	2553	5615
		Bearbrook			
1.1	200-2	5.7	388	1688	3629
1.2	200-2	6.2	420	2040	4444
2.6	C-1	4.3	329	839	1889
3.3	400-1	4.4	300	843	1733
4.6	400-2	5.3	362	1333	3002
5.1	F-2	4.1	282	610	1320
5.4	F-1	5.5	318	1522	3325
6.1	C-2	3.9	284	682	1317
6.6	C-1	5.9	375	1686	3682
7.3	400-1	5.1	345	1188	2235
8.3	F-2	4.1	271	707	1503
8.4	F-1	4.0	273	717	1536
9.0	F-2	2.5	177	179	383
9.1	F-2	3.7	260	576	1249
9.3	F-2	3.2	229	392	845
9.4	F-1	3.3	243	404	881
10.5	200-1	5.2	323	1204	2559
10.6	200-1	4.5	298	889	1757
11.4	C-1	2.8	220	293	640
12.2	200-1	5.5	345	1443	3054
12.6	200-2	5.0	317	1111	2344

[1] Tree no. for identification purpose only. 1.5---1 refers to main-plot unit number, 5 is tree number on main-plot unit.

3.3 Laboratory Procedures

3.3.1. Soil Analysis

Soil samples were oven-dried, and sieved to pass a 2 mm sieve before analyses. Soils for NH_4-N and NO_3-N analysis were frozen after collection and extractions were made on thawed samples in a moist condition.

Ammonium-N and NO_3-N were extracted from the soil samples by shaking a sub-sample of 15 g of moist soil with 100 ml of 1 M KCl for one hour. The filtrate was analyzed for NH_4-N and NO_3-N using colorimetric methods on a Technicon Auto Analyzer (O'Brien and Fiore 1962, and Kamphake et al. 1967). Gravimetric moisture content was determined by drying, at 110^0C, of an additional sub-sample. Therefafter all results were expressed on a dry weight basis.

Extractable P was determined by the Bray 2 method (Bray and Kurtz 1945). This consisted of shaking 2.5 cm^3 of soil in 25 ml of 0.03 M NH_4F-0.1 M HCl solution for one minute. The filtrate was analyzed by the ascorbic acid-reduced ammonium molybdophosphate method (Watanabe and Olsen 1965) using a Technicon Auto Analyzer.

Available K, Ca, and Mg were determined by shaking 2.5 cm^3 of soil with 25 ml of 1 M ammonium acetate at pH 7 for 15 minutes (Jackson, 1958). K and Ca were determined by flame emission. Mg was determined by atomic absorption spectro-photometry.

Organic carbon was determined by the Walkley-Black wet oxidation method (Allison 1965). Soil pH was determined using a glass electrode assembly and a 1:1 soil:water ratio.

Particle-size distribution was measured by the hydrometer method described by Day (1965) and classified to texture class according to the Canadian system of soil classification (CSSC, 1978).

3.3.2. Tissue Analysis and Presentation

Leaf samples were collected in 1980 from the Grande Ligne site only and in 1981 and 1982 from both sites. One leaf was taken from every tree in each of the main- and sub-plot units. The second leaf from the leader bud was taken in every case, except if the leaf was damaged or badly diseased. In this case the third or fourth leaf was taken. Leaves were put in a plastic bag for transport to the laboratory. A composite sample was made of all leaves from each main- or sub-plot unit as the case may be.

In the laboratory, leaves were rinsed with distilled water, blotted dry and the petioles were removed. Samples were dried at $70^{0}C$, weighed, and ground to pass a 40-mesh sieve. Leaf material was digested using concentrated H_2SO_4 and 30% H_2O_2 (Miller and Miller 1948). Total P, K, Ca, and Mg determination was by the methods described for the soils. Total N was determined colorimetrically as NH_4-N (O'Brien and Fiore 1962).

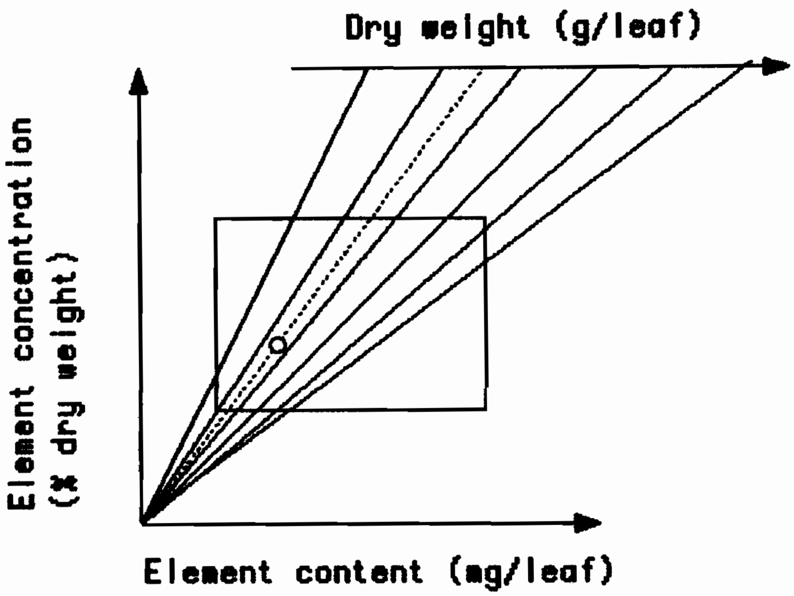
Nutrient composition of the leaves was expressed both as a percentage of oven-dry weight (concentration) and milligrams per leaf (content or uptake). Foliage analysis results are displayed in a single graph for each element. This technique was first used by Krauss (1965, cited by Timmer and Stone 1978). Interpretations were refined by Timmer and Stone (1978) (Fig. 3.3).

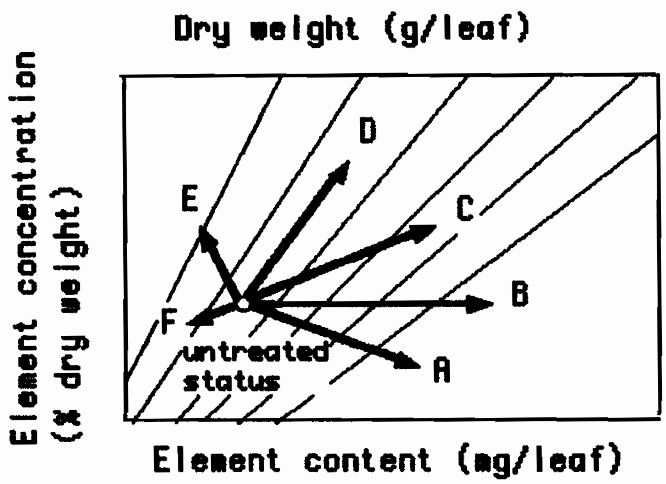
3.3.3. Sewage Sludge Analysis

Grab samples were taken from each sludge pile just before field application. Sludge was frozen immediately for later analysis of total N, NH_4-N, and NO_3-N. Total N was determined using the standard semi-micro-Kjeldahl procedure. Inorganic N (NH_4-N and NO_3-N) was determined by steam distillation techniques after 2 M KCl extraction (Bremner 1965).

Sludge samples for other elemental analysis were dried at 105^0C and ground to pass a 40-mesh sieve. Sludge samples were digested using nitric-perchloric acids and were analyzed for total Ca, Mg, Fe, Cu, Mn, Zn (Atomic absorption spectrophotometry) and K and Na (flame emission). Total P was analyzed by the ascorbic acid-reduced ammonium molybdophosphate method on a Technican Auto Analyzer (Watanabe and Olsen 1965).

For B, dry sludge was digested by dry ashing for 4 hours with CaO at 475^0C. The ash was dissolved in 2 M HCl and B determined by the azomethine-H colorimetric method (Basson et al. 1969) on a Technicon Auto Analyzer. pH was determined using a glass electrode assembly using the normal sludge water solution as it was obtained. Organic carbon was determined by the Walkley-Black wet oxidation method using 0.1 gm of dried sludge (Allison 1965). Mineral matter was defined as the





Direction of shift	Response in			Interpretation	Possible Diagnosis
	Leaf Weight	Nutrient			
		Conc.	Content		
A	+	−	+	Dilution	Non-limiting
B	+	0	+	Sufficiency	Non-limiting
C	+	+	+	Deficiency	Limiting
D	0	+	+	Luxury consumption	Non-toxic
E	−	++	+	Excess	Toxic
F	−	−	−	Excess	Antagonistic

Fig 3.3 Schematic relationship between foliar nutrient dry weight, nutrient concentration, and nutrient content following application of sewage sludge (from Timmer and Stone, 1978)

insoluble white crystalline material remaining after nitric-perchloric digestion and was calculated as a percentage by weight of the dry sludge sample. Loss-on-ignition is calculated as the percentage of the dried sludge lost after ignition in a muffle-furnace.

Table 3.4 contains results of these analysis on sewage sludge for all applications on both sites. The values obtained in this study fall in the range of values of research done by Sommers (1977). The Grande Ligne site received two different loads in 1980. This resulted in two different elemental concentrations. In all other cases the elemental concentration for the 200 Mg/ha application is one-half of the 400 Mg/ha application.

3.4 Statistical Methods and Biomass Calculations

Analysis of variance using General Linear Models procedure (GLM) of SAS (SAS Institute Inc. 1982) was conducted on all soil, foliage and tree height data. Group comparison of the means was performed by partitioning the treatment sums of squares into components. A within-treatment comparison using the single degree-freedom contrast method was carried out (Gomez and Gomez 1983).

A comparison of

- control versus other treatments,
- fertilizer versus sewage sludge, and
- low sludge level versus high sludge level

provided an orthogonal contrast. Other tests were carried out to compare control against each fertilizer and sludge level. These comparisons were not orthogonal. In 1981 and 1982, the data was analyzed as a split-plot

Table 3.4 Characteristics of sewage sludge applied to hybrid poplar sites.

	Grande Ligne			Bearbrook	
	Year and Treatment (Mg/ha)				
	1980		1981	1980	1981
	200	400			
Solid (as % of wet weight)	28.5	17.4	14.6	14.3	11.9
pH	7.1	7.4	7.1	7.0	7.5
Org. C. (g/kg)	197	184	234	179	225
Mineral Matter (g/kg)	na	238	259	241	230
Loss on Ign. (g/kg)	424	534	602	471	596
Total N (g/kg)	28.5	39.1	48.0	33.5	51.7
NH_4-N (mg/kg)	1910	3205	1433	na	na
NO_3-N (mg/kg)	42	140	na	na	na
C/N ratio	7:1	4.7:1	4.9:1	5.3:1	4.3:1
Total P (g/kg)	12.3	17.0	23.7	18.2	25.9
K (g/kg)	5.9	4.9	5.0	6.4	4.8
Ca (g/kg)	19.8	7.2	7.2	15.3	8.2
Mg (g/kg)	11.8	5.9	5.5	9.6	5.9
Fe (g/kg)	21.6	16.7	16.8	20.8	15.8
B (mg/kg)	183	208	238	165	240
Cu (mg/kg)	222	330	337	316	338
Mn (mg/kg)	506	626	742	677	890
Na (mg/kg)	1430	1368	1687	1646	1734
Zn (mg/kg)	383	447	637	459	685

design with the sub-plots nested in the main-plot treatments (no cross classification).

From the biomass sample, GLM was applied to see if there was an effect due to block, treatment and level. Since there was no treatment effect (due to the small size of the sample), regression was performed without adjusting for blocks, treatments or levels. Therefore the regression equation is based on the assumption of no effect.

Diameter at 15 cm and height from the forty-one trees sampled on both sites were used to develop the biomass predicting equations for each site. The sample tree data is found in Table 3.3.

Many different coefficients have been used as the independent variable. For trees of this size and age many authors have used D^2H as the variable where D=diameter (at stump or DBH) and H=tree height (Alemdag, 1981; and Williams and McClenahan, 1984).

Two models were considered for the regression:

Linear $\quad Y = a + b*(D^2H) \quad$ (1) and

Allometric $\quad Y = a*(D^2H)^b \quad$ (2)

A plot of sample values show log transformation provided the straightest line. When converted to logarithmic form equation (2) became linear in form:

$$\ln Y = a + b*\ln(D^2H) \quad (3)$$

where Y = dry weight in grams

D = diameter at 15 cm in cm

H = total height of tree in cm

ln = natural logarithm

Regression equations obtained were as follows:

$$\ln Y = -.74371 + .85845 \times \ln(D^2H) \qquad r^2 = .966$$

for the Grande Ligne site and,

$$\ln Y = -.99703 + .89259 \times \ln(D^2H) \qquad r^2 = .991$$

for the Bearbrook site.

Only trees that grew continuously over the three years were subjected to the regression and GLM that was performed on the lnY. The data was transformed back to obtain yield in arithmetic units and was adjusted for bias inherent in the log transformation (Baskerville 1972). Yield which had been determined on a per tree basis was converted to Mg/ha. Potential yield was calculated assuming there was 100% survival on plots and actual yield was calculated considering only trees present on the site.

Treatment means of soil, foliage, and tree height were subjected to correlation analysis.

Chapter 4. Results.

4.1 Sludge

The GLM procedure was carried out according to total sludge applied in wet form but the calculation of concentrations (Table 3.2) and dry weight resulted in varying nutrients loads which are not equivalent across treatments (Table 4.1).

Five different batches of sludges were applied. In 1980 at Bearbrook, and 1981 at both sites, only one sludge was applied and therefore nutrient loads of the sludge applied at the rate of 200 Mg/ha (referred hereafter as treatment 200) were one half of those of the sludge applied at the rate of 400 Mg/ha (400). In 1980, at the Grande Ligne site, the 200 sludge was a different batch from the 400 sludge. This resulted in different nutrient concentrations between the batches, and therefore different loading rates.

To illustrate this, at the Grande Ligne site in 1980, the 200 treatment received as much K and Fe as the 400 treatment, twice as much Ca, and one and a half times more Mg (Table 4.1). All other nutrients in the 200 treatment, including N and P, were less than the 400 treatment, but not one-half the amount.

Generally speaking, sludge in 1980 contained a greater percentage of dry matter than in 1981 with a resulting higher nutrient load.

Table 4.1 Sludge loading rates by site, year, and application--dry weight basis

	Grande Ligne				Bearbrook			
Sludge applied (Mg/ha)	1980		1981		1980		1981	
Wet basis	200[1]	400	200	400	200	400	200	400
Dry basis	57	70	25	51	29	57	22	44
Org C (kg/ha)	11229	12880	5850	11934	5191	10203	4950	9900
N (kg/ha)	1625	2723	1219	2438	958	1916	1127	2254
P (kg/ha)	703	1188	604	1207	519	1039	564	1129
K (kg/ha)	336	340	127	254	184	369	105	210
Ca (kg/ha)	1131	504	183	367	437	875	179	358
Mg (kg/ha)	673	414	139	278	279	559	129	257
Fe (kg/ha)	1229	1160	426	852	594	1188	344	689
B (kg/ha)	10	15	7	14	5	9	6	11
Cu (kg/ha)	13	22	9	17	9	18	7	15
Mn (kg/ha)	29	44	19	38	19	39	19	39
Na (kg/ha)	82	95	43	86	47	94	38	76
Zn (kg/ha)	22	31	16	32	13	26	15	30

[1] See Table 3.2 for explanation of treatments.

4.2 Soil

4.2.1 Ammonium-N

At the Grande Ligne site, soil samples were collected only in May and September of 1982 (Table 4.2). In the spring sampling no significant ($p > .05$) differences were found, but treatments with the highest sludge application had higher NH_4-N level than the control from 0-30+cm. Plots treated with two applications of fertilizer (F-2) showed the highest NH_4-N levels.

By September of 1982, all sludge treatments, except the 200 Mg/ha 1980-sludge-treated plots (200-1), had significantly ($p < .05$) higher NH_4-N than the control at the 0-15 cm depth. Significantly higher levels of NH_4-N were found at 15-30 and 30+ cm depths in the plots treated with two applications of 400 Mg/ha sludge (400-2) where 5160 Kg/ha of sludge N was applied over two years (Table 4.1).

At the Bearbrook site, NH_4-N was analysed in May 1981 before the second sludge treatments. Throughout the profile, NH_4-N levels from all sludge treatments were generally higher than the control. By May of 1982, at the 0-15 cm depth, plots receiving the second application of sludge (treatment 200-2 and 400-2) had significantly higher levels of NH_4-N than plots receiving only one application (200-1, 400-1). Plots receiving the 400 treatment of sludge had significantly higher NH_4-N values than the control below 15 cm. In contrast to Grande Ligne, fertilizer treatments had NH_4-N levels similar to the control.

4.2.2 Nitrate-N

At Grande Ligne, sampling was the same as for NH_4-N. In May of 1982, soil in all sludge treatments, except the 200-1 treatment, contained more NO_3-N than the control throughout the profile (Table 4.3). Results were only significant at depths below 15 cm. Results in September 1982 were similar to the previous sampling, but absolute values were much lower.

At Bearbrook, NO_3-N was not sampled until May 1982. Nitrate-N levels throughout the profile in treatment 400-2 were higher than levels in other treatments. By September 1982, overall values were two to five times lower than in May. Treatment 400-2 continued to have higher levels of NO_3-N than all other treatments, throughout the profile.

4.2.3 Phosphorus

Sludge application had a highly significant ($p < .01$) effect on soil P, on the Grande Ligne site. (Table 4.4). In May 1981, treatment 400 had over twice as much extractable P as the control. At Bearbrook, results were not significant after the first year, although sludge treatments had higher P levels (avg. 64 mg/l) than the control (43 mg/l) at the 0-15 cm depth.

At Grande Ligne site in May 1982, P in the control was significantly ($p < .01$) lower than P in sludge treatments at 0-15 cm depth. By September 1982, all depths were significantly ($p < .01$) affected by sludge treatments.

Table 4.2 Results of NH_4-N analysis.

			Treatment						
			Sewage Sludge(Mg/ha)					Fertilizer	
Sampling Date	Depth - cm -	Application	0	200		400			
				1	2	1	2	1	2
			mg/l						
			Grande Ligne						
May 1982	0-15		5.8	6.6	9.3	6.0	9.7	7.3	13.5
	15-30		1.5	1.5	2.3	2.2	7.9	5.8	2.8
	30+		0.8	0.9	2.0	1.6	1.8	2.2	1.2
Sept 1982	0-15		5.8 ad	6.5 g	11.3 c	12.3	14.5 ff	5.3	6.3 b
	15-30		3.3	2.6	4.0 cc	5.3	6.0 ff	2.5	3.1 b
	30+	*	1.6	1.6	2.1	2.8	3.0 f	1.4	2.0 i
			Bearbrook						
May 1981	0-15		10.9	11.7		14.1		8.6	
	15-30		6.1	5.9		8.2		5.6	
	30+		4.1	4.7		5.5		6.4 j	
May 1982	0-15		5.6	5.3 g	7.1	5.9 h	8.3	4.8	5.2 b
	15-30		3.8 d	8.6	7.5	7.3	11.2 f	2.0	4.2 b
	30+		4.3	3.7	6.4	8.0	8.9 f	4.4	2.4 b
Sept 1982	0-15		5.7	7.6	6.3	6.9	5.6	7.0	6.8
	15-30		4.1	4.2	4.3	3.8	5.4	3.9	3.5
	30+		2.5	3.3	3.6	2.9 h	5.2	3.1	3.2

a(aa) control is significantly different from all other treatments at .05(.01) level of significance.
b(bb) fertilizer is significantly different from sewage-sludge treatments at .05(.01) level of significance.
c(cc) 200 Mg/ha treatment is significantly different from 400 Mg/ha treatment at .05(.01) level of significance.
NOTE-the above three treatments are orthogonal.
d(dd) control is significantly different from sewage-sludge treatments at .05(.01) level of significance.
e(ee) control is significantly different from 200 Mg/ha treatments at .05(.01) level of significance.
f(ff) control is significantly different from 400 Mg/ha treatments at .05 (.01) level of significance.
g(gg) 200-1 Mg/ha treatment is significantly different from 200-2 Mg/ha treatment at .05(.01) level of significance.
h(hh) 400-1 Mg/ha treatment is significantly different from 400-2 Mg/ha treatment at .05(.01) level of significance.
i(ii) 200-1 Mg/ha treatment is significantly different from 200-2 Mg/ha treatment at .05(.01) level of significance.
j(jj) control is significantly different from fertilizer treatments at .05(.01) level of significance.
*(**) effect of block at .05(.01) level of significance.

Table 4.3 Results of NO_3-N analysis.

Sampling Date	Depth - cm -	Sewage Sludge (Mg/ha) 0	200		400		Fertilizer	
	Application		1	2	1	2	1	2
		mg/l						
Grande Ligne								
May 1982	0-15	3.4	2.2	6.8	7.5	12.4	1.4	1.8
	15-30	0.4	0.8	1.7 c	3.6 hh	9.1 f	1.7	1.1
	30+	0.5 ad[1]	0.4	2.1 c	2.6 h	4.7 ff	1.9	1.0
Sept 1982	0-15	0.5	0.4	0.5 c	1.7	1.8	0.2	0.4
	15-30	0.2	0.2	0.3 c	1.1	1.1 f	0.2	0.2
	30+	0.2	0.1	0.2	0.7	0.4	0.7	0.1
Bearbrook								
May 1981	0-15	2.1	1.0 g	2.2	1.6 hh	4.5	1.0	.4
	15-30	1.2	.6	1.0	1.0 hh	4.4	.5	.4
	30+	.2	.0	.5	.2 hh	1.3	.5	.4
Sept 1982	0-15	.4	.2	.9	0	1.6	.1	0
	15-30	.1	0	.3	0	1.0	0	0
	30+	.1	0	.1	0	.5	0	0

[1] See inside back cover for contrast statement codes.

By May 1982 at Bearbrook, all sludge treatments, except 200-1, had higher P levels than in the control throughout the profile. At 0-15 cm depth, the 400-2 treatment had significantly higher P than the 400-1 treatment. At 15-30 cm depth, the same effect was observed, as well as a significantly higher level of P in the 400 treatment compared with the 200 treatment. In September 1982 at 0-15 cm level, the control was significantly lower in P than sludge treatments.

4.2.4 Potassium

At Grande Ligne, there were very few significant changes in available K due to sludge treatments (Table 4.5). By May 1981, application of fertilizer resulted in significantly higher K levels compared with other treatments. There were significant differences between replicates at 0-15 cm and 15-30 cm depths in 1981.

No changes in available K due to treatments were discerned at Bearbrook.

4.2.5 Calcium

There were no significant differences in available Ca as a result of sludge treatments (Table 4.6) at Grande Ligne. Generally values on the control were higher than those on the treatments before sludge was applied. This trend continued through three years of analysis except for the 200-1 treatment, where at the 0-15 depth soil Ca was higher than in the control in both 1982 samplings.

Table 4.4 Results of extractable P analysis.

Sampling Date	Depth - cm - Application	Sewage Sludge (Mg/ha) 0	200 1	200 2	400 1	400 2	Fertilizer 1	Fertilizer 2
		mg/l						
Grande Ligne								
May 1980	0-15	33	27		22		22	
	15-30	28	26		21		25	
	30+	39	21		24		24	
May 1981	0-15	26	34		71 f[1]		35	
	15-30	22	16 c		30		23	
	30+	49 ad	19		23		21	
May 1982	0-15	24 aadd	90	82 ee	44 hh	129 ff	20	27 bb
	15-30	22 d	19 gg	58 e	26	40	16	26 b
	30+	23	29	33	14	40	14	26
Sept 1982	0-15	15 add	61	85 e	72	133 ff	21	30 bb
	15-30	15 aadd	35	43 ce	39 hh	82 ff	17	24 bb
	30+	23 d	18	22 cc	45	47 ff	12	26 b
Bearbrook								
May 1980	0-15	47	45		42		34	
	15-30	37	30		42		34	
	30+	53	50		44		46	
May 1981	0-15	43	68		60		34	
	15-30	43	40		44		40	
	30+	59	45		40		39	
May 1982	0-15	57	56	75	76 h	105	37	44 b
	15-30	47 d	52	72 c	82 h	144 ff	39	36 b
	30+	49	50	57	64	66	58	38
Sept 1982	0-15	54 d	101	97 e	81	91	42	46 bb
	15-30	49	61	71	68 h	92	47	39 b
	30+	82	110	104	73 h	84	70	69

[1] See inside back cover for contrast statement codes.

Table 4.5 Results of available K analysis.

Sampling Date	Depth - cm -	Application	Sewage Sludge (Mg/ha) 0	200 1	200 2	400 1	400 2	Fertilizer 1	Fertilizer 2
			mg/l						
Grande Ligne									
May 1980	0-15		32	30		42		29	
	15-30		23	19		24		16	
	30+		10	15		19		16	
May 1981	0-15	*	29 a[1]	32		37		54 bbjj	
	15-30	*	14 a	16		22 f		26 bjj	
	30+		12	15		14		14	
May 1982	0-15		50	54	51	41 h	72	29	43 bb
	15-30		23	19	29	24	33	21	28
	30+	*	15	14	18	17	16	14	17
Sept 1982	0-15		27	28	29	32	40	26	31
	15-30		18	17	21	22	23	15	18
	30+		14	12	11	19	14	11	14
Bearbrook									
May 1980	0-15		266	259		237		241	
	15-30		199	166		193		177	
	30+		225	211		264		255	
May 1981	0-15		225	274		227		195	
	15-30		187	194		174		188	
	30+		241	246		240		253	
May 1982	0-15		210	205	203	211	220	175	181
	15-30		168	183	183	181	198	190	181
	30+		237	288	275	281	227 h	264	242
Sept 1982	0-15		200	188	192	155	154	171	159
	15-30		167	157	153	154	139	145	141
	30+		200	234	203	210	177	177	219

[1] See inside back cover for contrast statement codes.

At Bearbrook, there were few changes in available Ca as a result of treatments. By May 1981, at the 15-30 cm depth the 200 treatment had significantly higher Ca levels than other treatments. By September 1982, at the 0-15 cm depth the 200 treatment contained significantly more Ca than other treatments.

4.2.6 Magnesium

Analyses of soils sampled in May 1980 before sludge treatment revealed available Mg in future-control plots (66 mg/l) was significantly higher than Mg in future-sludge-treated plots (avg 54 mg/l) and future-fertilizer-treated plots (41 mg/l) at 0-15 and 15-30 cm depths (Table 4.7). There was also a highly significant ($p < .01$) replicate effect.

By May 1981, after the first treatment, the significant differences in the May 1980 sampling disappeared and, at the 0-15 cm depth, Mg in the 400 treatment was 25% higher than Mg in the control. By May 1982, most sludge treatments had higher Mg levels than the control. The 400-2 treatment had 177% more Mg than the control at 0-15 cm depth. By September 1982, the control Mg levels were significantly ($p < .01$) lower than the sludge treatments. At the 15-30 cm depth in the control, Mg was significantly higher than all other treatments. Sludge Mg had not moved through the soil profile.

Table 4.6 Results of available Ca analysis.

		Treatment						
		Sewage Sludge(Mg/ha)					Fertilizer	
Sampling Date	Depth - cm -	0	200		400			
	Application		1	2	1	2	1	2
		mg/1						
		Grande Ligne						
May 1980	0-15	987	893		657		483	
	15-30	540 a[1]	343		313		263 j	
	30+	304	327		283		327	
May 1981	0-15	930	740		633		717	
	15-30	457	337		387		337	
	30+	337	330		293		277	
May 1982	0-15	1040	1227	997 c	577	850	600	510 bj
	15-31	563	477	570	407	480	323	340
	30+	390	320	403	267	340	257	300
Sept 1982	0-15	893	1080	893	747	773	630	847
	15-30	645	543	560	497	537	380	470
	30+	468	327	360	400	430	270	410
		Bearbrook						
May 1980	0-15	2000	2167		1950		2033	
	15-30	1917	2083		1700		1800	
	30+	1867	2033		1867		1667	
May 1981	0-15	2433	2550		2267		2167	
	15-30	1967	2300 ce		2000		1950	
	30+	1933	2267		2050		2283	
May 1982	0-15	2200	2283	2267	2317	2250	2283	2216
	15-30	2033	2200	2433	2100	2250	2200 i	1850
	30+	2267	2700	2650	2183	2233	2400	2133
Sept 1982	0-15	2375	2833	2667ce	2367	2383	2350	2333
	15-30	2267	2600	2550 c	2067	2233	2283	2233
	30+	2117	2533	2483	2250	2150	2083	2367

[1] See inside back cover for contrast statement codes.

Table 4.7 Results of available Mg analysis.

Sampling Date	Depth - cm -	Application	Sewage Sludge (Mg/ha) 0	200: 1	200: 2	400: 1	400: 2	Fertilizer 1	Fertilizer 2
			mg/l						
Grange Ligne									
May 1980	0-15	**	66 aad[1]	53 e		55 f		41 bjj	
	15-30		46 ad	25		21 f		18 bj	
	30+		25	24		21		25	
May 1981	0-15		61	51		74		48	
	15-30		41	27		32		22	
	30+		36	23		28		17	
May 1982	0-15		65	83	77	59 hh	115	35	41 bb
	15-30		51	40	45	38	47	23	26 j
	30+		38	27	32	25	31	20	22 j
Sept 1982	0-15		62 dd	82	83 ee	70	84 f	39	46 bbjj
	15-30		60 a	46	49	41	50	24	25 bj
	30+		45	28	29	33	32	20	28 j
Bearbrook									
May 1980	0-15		620	613		577		667 b	
	15-30		620	603		677		670	
	30+		840	837		1010		1053	
May 1981	0-15		583	617		623		563	
	15-30		567	583		567		583	
	30+		777	853		900		877	
May 1982	0-15		537	553	557	580	560	567	537
	15-30		487 a	587	590 e	537	543	627	537 j
	30+		693	1060	907	790	767	910	827
Sept 1982	0-15		632	683	660	680	667	633	647
	15-30		630	687	643	637	670	667	687
	30+		850	1003	913	1033	950	937	1140

[1] See inside back cover for contrast statement codes.

There were few changes in available Mg due to treatments at Bearbrook. In May 1982, at the 15-30 cm depth, the 200 treatment contained significantly more Mg than the control.

4.2.7 pH

At Grande Ligne, pH levels in the control were generally higher than in the treatment throughout the profile in each year, except for treatment 200-1 (Table 4.8). At 0-15 cm depth, on treatment 200-1, pH values increased following sludge application. Table 4.1 shows a higher amount of Ca in the sludge for this treatment and Table 4.6 (May, 1982) reflects the increased amount of soil Ca on the 200-1 treatment.

There appeared to be little change in soil pH due to treatment at Bearbrook.

4.2.8 Organic Carbon

At Grande Ligne, treatment 400 had significantly higher organic carbon than the control and 200 treatment in the May 1980 and May 1981 sampling (Table 4.9). Nevertheless, treatment 400-2 increased from 2.6% organic carbon in May 1980 to 3.1% in September 1982. The first three sampling periods showed significant replicate effect at the 0-15 cm depth.

At Bearbrook, treatment 400 had a significantly ($p < .01$) higher percentage of organic carbon by May 1982 than the control or treatment 200. Treatment 200-2 contained significantly higher amounts of organic carbon compared with treatment 200-1.

Table 4.8 Results of soil pH analysis.

Sampling Date	Depth - cm -	Treatment						
		Sewage Sludge(Mg/ha)					Fertilizer	
		0	200		400			
	Application		1	2	1	2	1	2
		Grande Ligne						
May 1980	0-15	5.5 a[1]	5.1		4.9		4.4 j	
	15-30	5.0	4.7		4.5		4.2	
	30+	5.3	4.8		4.4		4.7	
May 1981	0-15	5.5	5.4		5.0		5.1	
	15-30	5.2	4.9		4.4		4.6 j	
	30+	5.4	4.9		4.7 f		4.8	
May 1982	0-15	5.8 a	5.9	5.8 c	4.9	5.6 f	4.9	4.7bbjj
	15-30	5.0	4.9	5.0	4.6	4.6	4.5	4.5
	30+	5.2	5.0	5.0	4.7	4.8	4.6	4.7
Sept 1982	0-15	5.3	5.7	5.6 c	5.0	5.0	4.8	5.2
	15-30	5.0	4.8	4.8	4.6	4.7	4.6	4.7
	30+	5.2	4.8	4.7	4.7	4.8	4.6	4.9
		Bearbrook						
May 1980	0-15	5.2	5.0		4.9		5.0	
	15-30	5.2	5.1		5.0		5.1	
	30+	5.4	5.4		5.3		5.4	
May 1981	0-15	5.4	5.2		5.2		5.1	
	15-30	5.3	5.1		5.1		5.1	
	30+	5.2	5.3		5.2		5.2	
May 1982	0-15	4.9	5.1	5.2	4.9	4.9	5.1	4.8
	15-30	5.0	5.1	5.0	4.9	4.9	5.0	4.8
	30+	4.9	5.5	5.3 e	4.8	5.2	5.2	5.2
Sept 1982	0-15	5.3	5.3	5.3	5.3	5.3	5.1	5.1
	15-30	5.3	5.3	5.2	5.2	5.2	5.2	5.3
	30+	5.4	5.5	5.4	5.5	5.4	5.4	5.5

1 See inside back cover for contrast statement codes.

Table 4.9 Results of organic carbon analysis.

Sampling Date	Depth - cm - Application	Treatment: Sewage Sludge (Mg/ha) 0	200		400		Fertilizer	
			1	2	1	2	1	2
		(%)						
Grande Ligne								
May 1980	0-15	** 2.3	2.2 c[1]		2.6 f		2.3	
	15-30	1.4	1.3		2.3		1.7	
	30+	0.9	1.3		1.3		1.2	
May 1981	0-15	** 2.4	2.3 c		2.9 f		2.7	
May 1982	0-15	* 2.4	2.7	2.5	2.7	3.2 f	2.2	2.7
Sept 1982	0-15	2.5	2.4	2.8	2.7	3.1	2.2	2.4 b
	15-30	1.9	1.9	2.1	2.4	2.7	1.7	2.0
	30+	** 1.2 d	1.0	1.1 cc	1.9	1.7 ff	0.9	1.1 bb
Bearbrook								
May 1980	0-15	3.2	3.3		3.4		3.9	
	15-30	2.2	2.2		1.6		2.2	
	30+	.9	.7		.6		.7	
May 1981	0-15	3.4	3.4		3.7		3.5	
May 1982	0-15	3.2 a	2.9 g	3.7 cc	4.0	3.9 ff	3.8 i	3.1
Sept 1982	0-15	3.3	3.2	3.1 c	3.6	4.8	3.6	3.3
	15-30	2.8	2.4	2.6	2.8	2.9	3.0 i	2.1
	30+	2.2	1.5	.8	.7	1.2	1.1	.8

[1] See inside back cover for contrast statement codes.

In September 1982 at the 0-15 cm level, differences between treatments 200 and 400 were still significant.

4.2.9 Bulk density

Bulk density was significantly reduced as a result of high sludge treatment at Grande Ligne. The control had a bulk density of 1.12 Mg/m^3 compared with 0.91 Mg/m^3 on the 400 treatment (Table 4.10). Bulk density was significantly ($p < .01$ level) reduced on sludge treatments at Bearbrook.

Table 4.10 Results of bulk density analysis after three years growth.

Treatment	Site: Grande Ligne (Mg/m^3)		Site: Bearbrook (Mg/m^3)	
C	1.12	d[1]	1.03	add
200-1	1.01		0.92	e
200-2	0.96		0.84	
400-1	0.93	f	0.90	f
400-2	0.89		0.76	h
F-1	1.07		1.03	
F-2	1.06		0.90	

[1] See inside back cover for contrast statement codes.

4.3 Foliage

4.3.1 General

In 1980, foliage was not sampled at Bearbrook, while at Grande Ligne foliage was collected but dry weight of leaf tissue was not measured. Therefore only foliar concentration values are presented. In 1981 and 1982, values for dry weight, foliar concentration and foliar content (uptake) are presented. A summary of significant contrasts is found in Table 4.11 for the Grande Ligne site, and in Table 4.12 for Bearbrook. Means for all foliage data are found in Appendix C.

At the Grande Ligne site, foliar relations for all nutrients were affected to some extent by sludge application, but P was the only element to show consistently significant effects in both concentration and content in 1981 and 1982. Generally the foliar concentration and content for N and P were higher in 1981 than in 1982. On the other hand K, Ca, and Mg were lower in leaves in 1981 than in 1982.

At the Bearbrook site, N, P and K foliar concentration and content were generally higher in 1981 compared with 1982. Foliar Ca and Mg were lower in 1981 compared with 1982. There were very few significant effects as a result of sludge treatment. Fertilizer treatments in 1981 produced significantly lower values for most nutrients.

4.3.2 Dry Weight

At Grande Ligne, foliar dry weight was not significantly effected by sludge treatments in 1981, but average foliar dry weight on sludge treatments was higher than on the control by 14% (Fig. 4.1).

Table 4.11 Selected[a] contrasts of foliar dry weight, nutrient concentration, and content at the Grande Ligne site.

Contrasts	1981										1982									
	C vs others	F vs sludge	200 vs 400	C vs F	C vs sludge	C vs 200	C vs 400	200-1 vs 200-2	400-1 vs 400-2	Block	C vs others	F vs sludge	200 vs 400	C vs F	C vs sludge	C vs 400	200-1 vs 200-2	400-1 vs 400-2	F1 vs F2	Block
Dry Weight	-	-	-	-	-	-	-	-	-	-	-	0.10	*	-	-	0.08	-	-	0.06	-
Nutrient Concentration																				
N	*	0.07	*	-	**	0.10	**	-	-	-	-	-	-	-	-	-	-	-	-	-
P	**	**	0.10	0.07	**	**	**	*	-	*	*	0.09	*	-	*	**	*	0.07	**	-
K	0.10	-	-	0.10	-	-	-	-	-	-	-	-	**	0.10	-	*	-	-	0.09	*
Ca	*	-	-	*	*	*	*	*	-	-	0.09	-	*	0.08	-	*	-	-	-	-
Mg	-	0.07	-	0.07	-	-	-	*	-	-	-	-	*	-	-	-	-	-	-	-
Nutrient Content																				
N	-	-	-	-	0.10	-	-	-	-	-	-	-	*	-	-	0.09	-	-	-	-
P	*	*	-	-	**	*	*	**	**	-	-	0.07	**	-	-	*	-	*	*	-
K	0.10	-	-	-	0.08		0.10	*	0.07	-	-	-	**	-	-	**	-	-	0.06	*

**,* Significant at 0.05 and 0.01 levels, respectively or by indicated values.

(a) Colums or rows with no significant effects to 0.10 level are removed. Degrees of freedom is one in each case except block df=2.

Table 4.12 Selected [a] contrasts of foliar dry weight, nutrient concentration, and content at the Bearbrook site.

	1981							1982					
Contrast	C vs F	F vs sludge	C vs sludge	200 vs 400	200-1 vs 200-2	400-1 vs 400-2	F1 vs F2	F vs sludge	C vs 200	200 vs 400	200-1 vs 200-2	400-1 vs 400-2	F1 vs F2
Dry weight	-	*	-	-	-	-	-	-	-	0.07	-	*	-
Nutrient Concentration													
N	-	0.08	-	-	0.10	-	-	*	-	-	-	-	-
P	-	*	-	-	*	-	-	-	0.10	*	-	-	-
K	0.08	-	-	0.10	-	-	-	-	0.07	-	-	-	-
Ca	-	-	-	-	-	**	*	-	-	-	-	-	0.09
Mg	-	-	-	-	-	-	-	-	0.09	0.08	-	-	-
Nutrient Content													
N	-	*	-	-	0.08	-	-	-	-	0.07	-	-	-
P	-	**	-	-	0.07	-	-	-	-	0.06	-	0.08	-
K	0.08	*	-	-	-	-	-	-	0.08	0.07	-	-	-
Ca	-	0.06	-	-	-	-	-	-	-	-	-	0.09	-
Mg	-	0.06	-	-	-	-	-	-	-	-	-	0.07	-

**,* Significant at 0.05 and 0.01 levels, respectively, or by indicated values.
(a) Columns with no significant effects to 0.10 level are removed.
Degrees of freedom is one in each case.

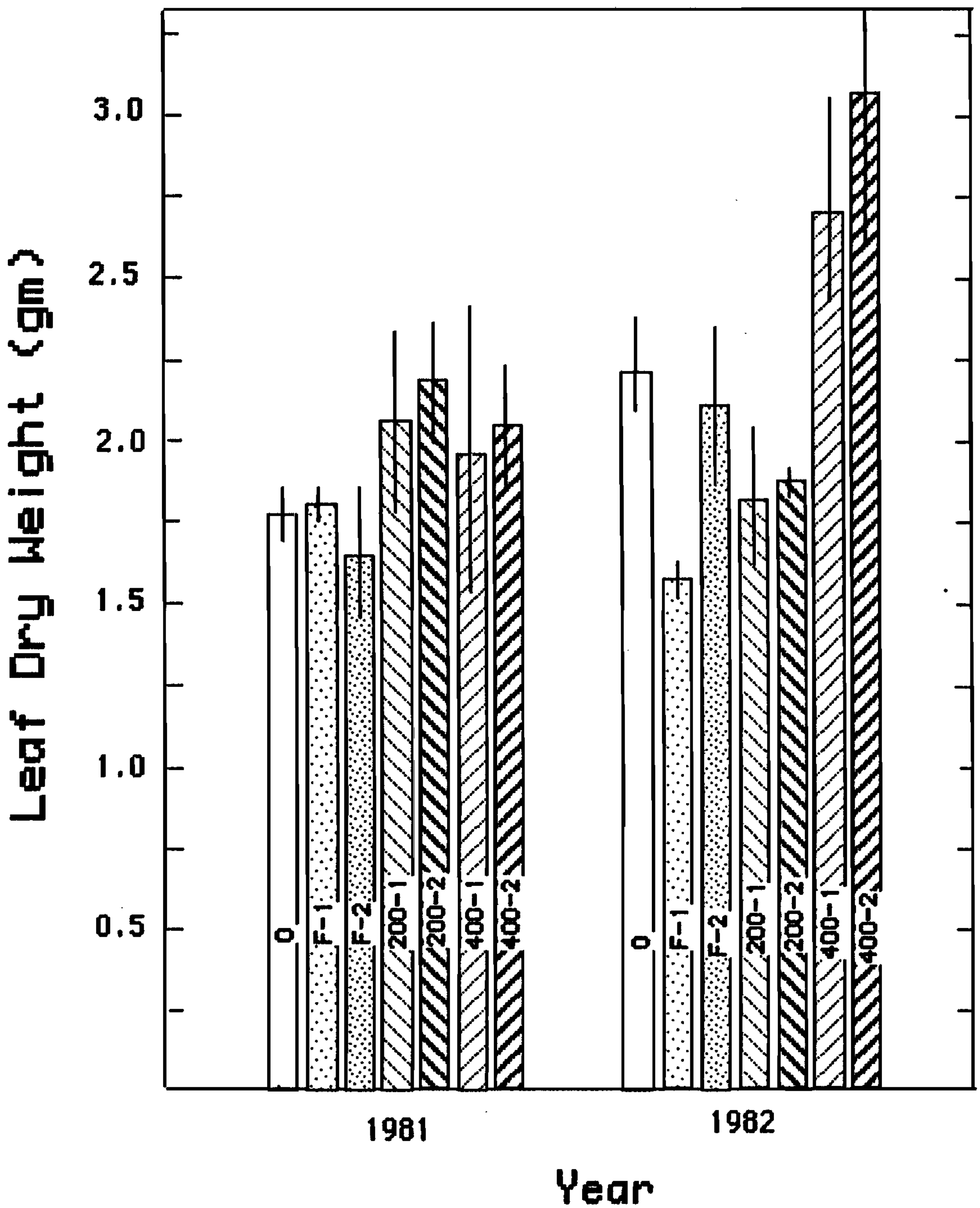


Fig 4.1 Leaf dry weight in the second and third year after planting at the Grande Ligne site. (I - std error of mean)

In 1982, dry weight of foliage in treatment 400 was higher ($p < .08$) than in the control and 200 treatment. The control had dry weight values falling between the two sludge rates.

At Bearbrook in 1981, foliar dry weight in the control was lower than dry weight on all sludge treatments at Bearbrook (Fig. 4.2). The 200-2 and 400-2 treatments had higher leaf weights than the 200-1 and 400-1 treatments respectively. Foliar dry weight in fertilizer treatments was significantly lower than in sludge treatments.

In 1982, foliar dry weight in treatment 400 was higher ($p < .07$) than in treatment 200. The control had dry weight values falling between the two sludge application rates. Leaves in treatment 400-1 weighed significantly more than leaves in treatment 400-2.

4.3.3 Nitrogen

In 1980, N foliar concentration increased ($p < .06$) from 2.21% in the control to 2.39% and 2.44% in the 200 and 400 sludge treatments, respectively at Grande Ligne (Fig. 4.3). In 1981, sludge additions resulted in highly significant ($p < .01$) foliar N concentrations in sludge treatments compared with the control (Fig.4.4). As well, the leaves in treatment 400 had significantly higher N concentrations than those in treatment 200. Nitrogen content was increased ($p < .10$ level) by sludge treatment and was 34% higher in sludge treatments compared with the control. Fig. 4.4 shows increased N concentration and content with an increased foliar dry weight in 1981 after sludge additions. This shift in "C" direction (see Fig. 3.3 for explanations) indicated a deficiency and N was diagnosed as limiting.

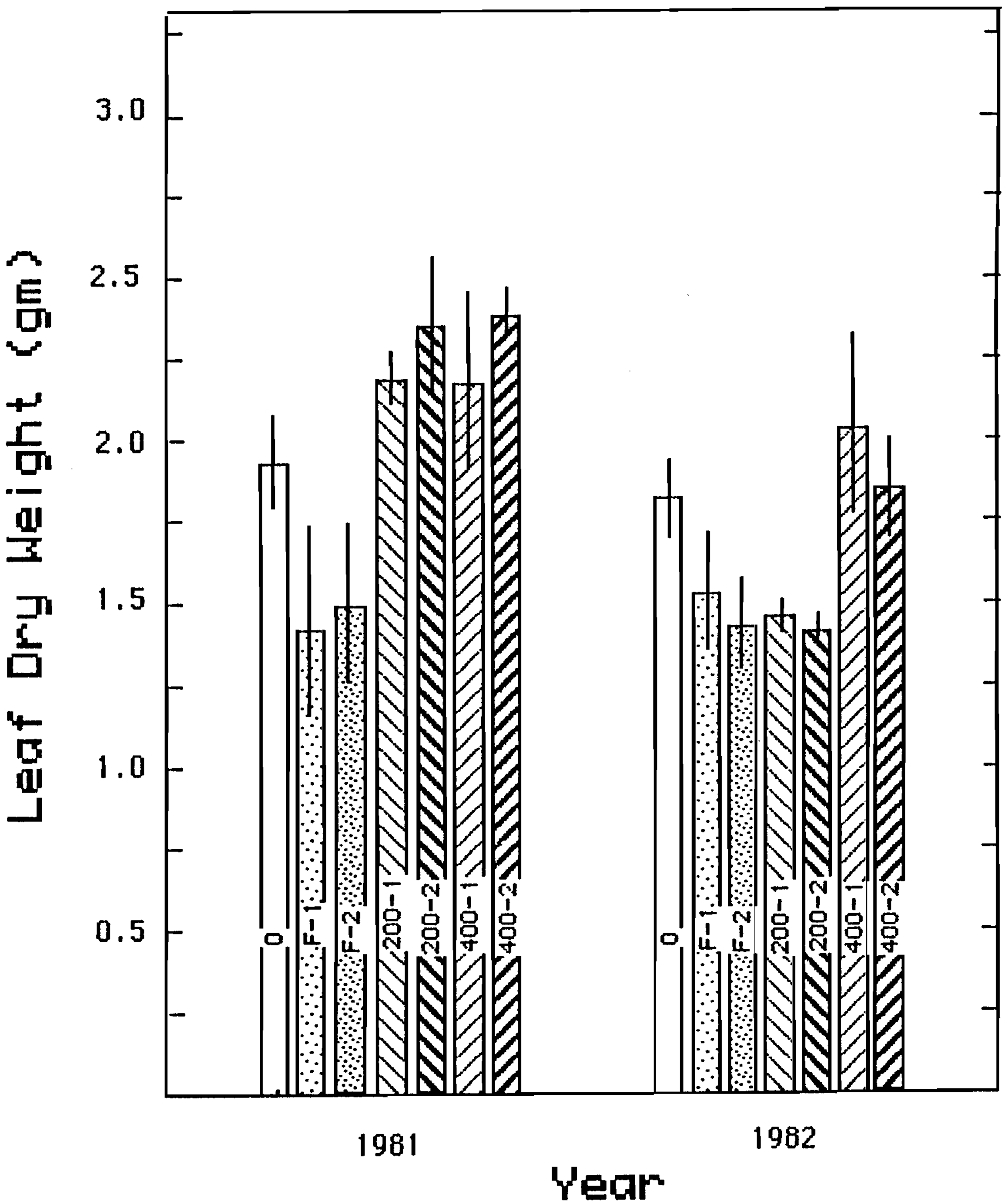


Fig 4.2 Leaf dry weight in the second and third year after planting at the Bearbrook site. (I - std error of mean)

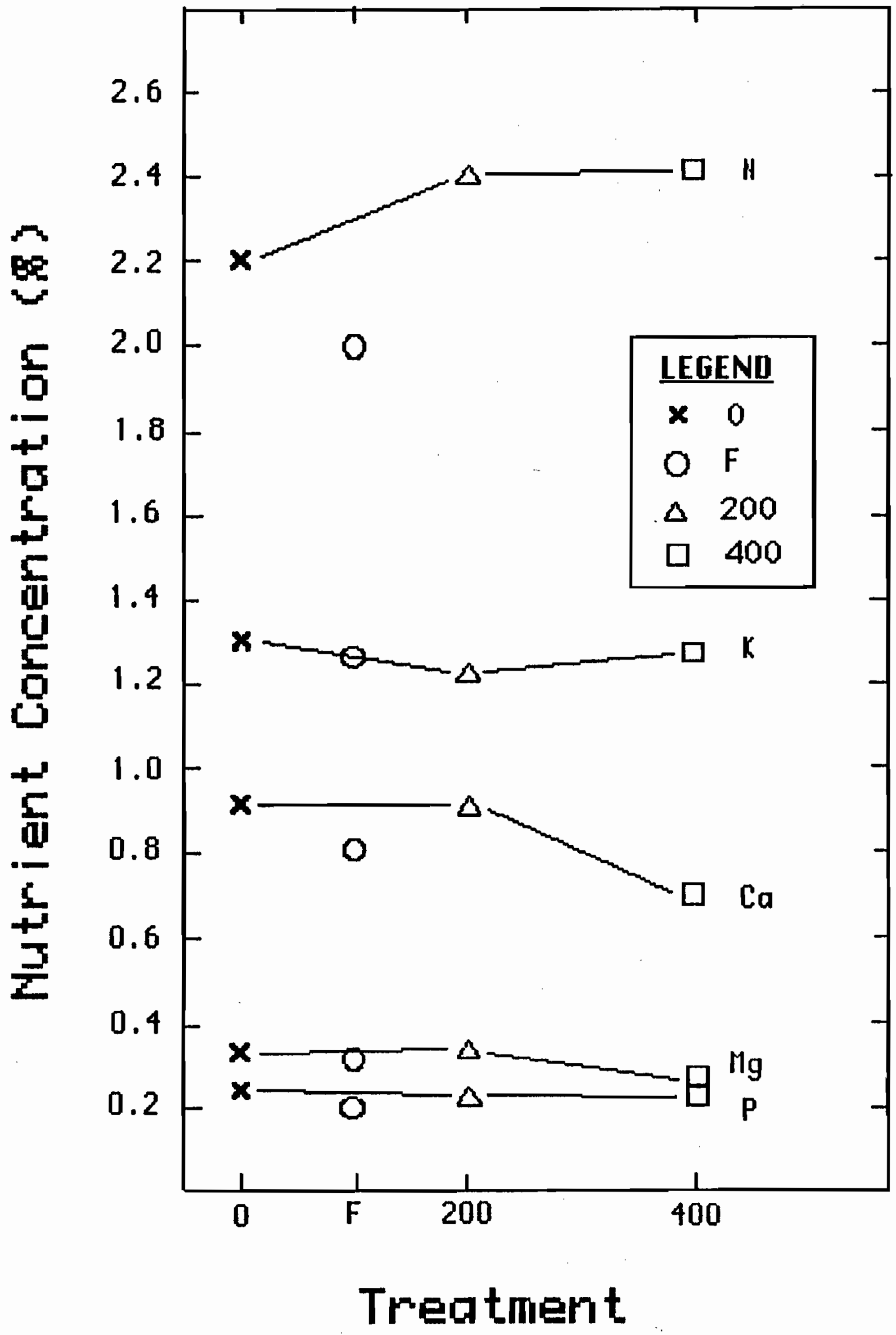


Fig 4.3 Effect of sludge and fertilizer treatments on foliar concentration of N, P, K, Ca, and Mg at the Grande Ligne site in 1980. (Value for fertilizer placed at position between 0 and 200 Mg/ha for convenience only.)

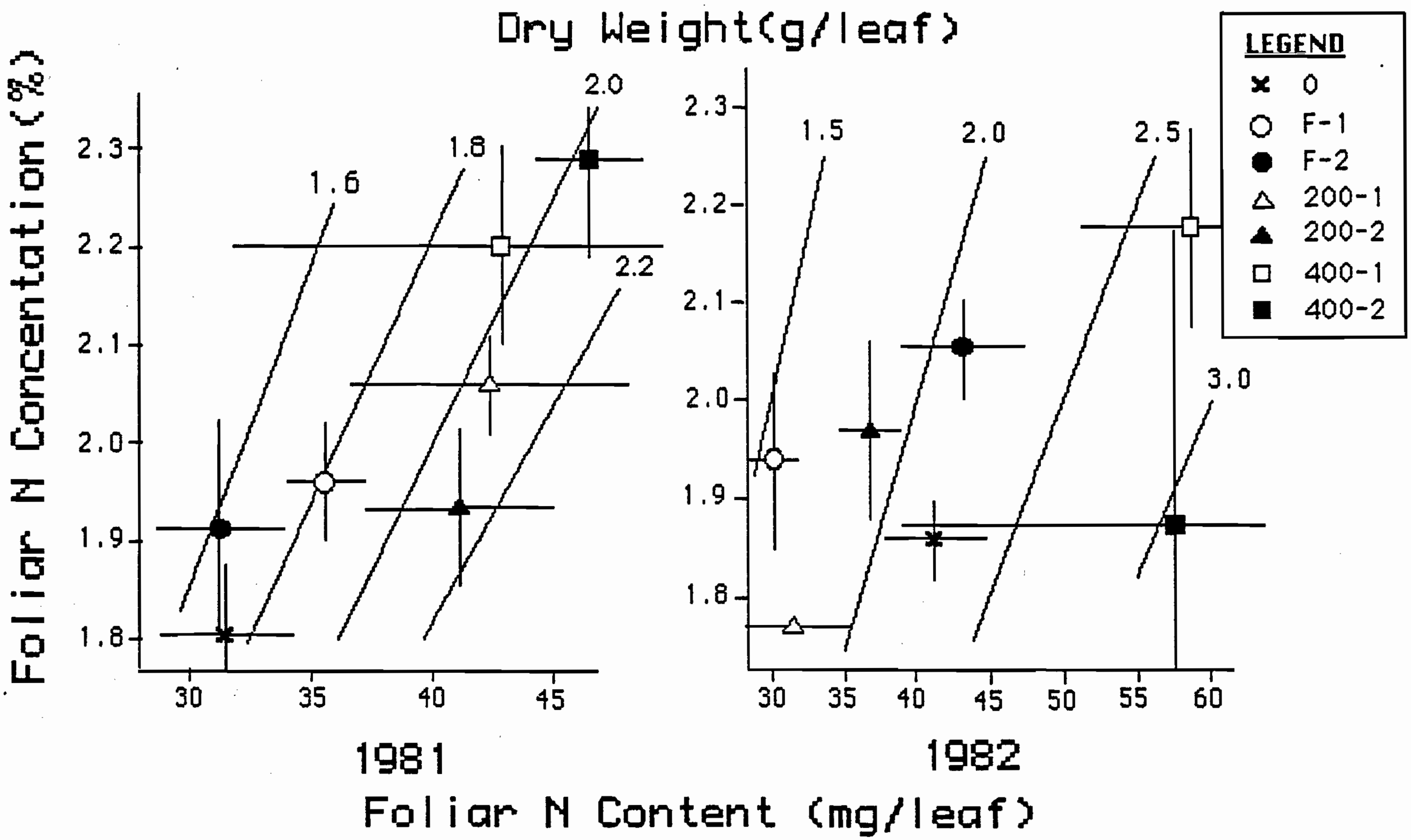


Fig 4.4 The relationship between foliar N concentration, N content, and unit dry weight of leaves at the Grand Ligne site. (note changes in scale). (+ = std error of mean)

In 1982, foliar N concentration in the control was lower than in treatments 200-2 and 400-1. Foliar N content in treatment 400 was significantly higher than treatment 200. The 400-1 and 400-2 treatments continued to show the same trend, in the "C" direction, as the previous year. The 200-1 treatment shifted to "F" which indicates a deficiency caused by treatment -a true antagonism (Cain, 1959), or another growth factor (Timmer, 1979).

At Bearbrook, there were no significant changes in N as a result of sludge treatments. Fig. 4.5 shows the same general trend as at Grande Ligne, that is, foliar N increased due to sludge treatments. Foliar N in 400-1 and 400-2 treatments maintained its position relative to the control in 1981 and 1982, but on 200-1 and 200-2 treatments foliar N decreased in 1982 relative to the control. Fertilizer treatments were significantly lower in N concentration and content compared with sludge treatments.

4.3.4 Phosphorus

At Grande Ligne in 1980, foliar P concentration was not changed by treatments (Fig. 4.3). In 1981, both P concentration and content were significantly affected ($p < .01$) by sludge treatments. Fig. 4.6 shows a shift in the "C-D" direction for all treatments indicating that P was limiting and the response was quite dramatic. Phosphorus concentration increased from 0.22% in the control, to an average 0.38% in the 400 treatment. Phosphorus content doubled from 3.90 mg/leaf in the control, to 8.08 and 7.92 mg/leaf on the 200-2 and 400-2 treatments, respectively.

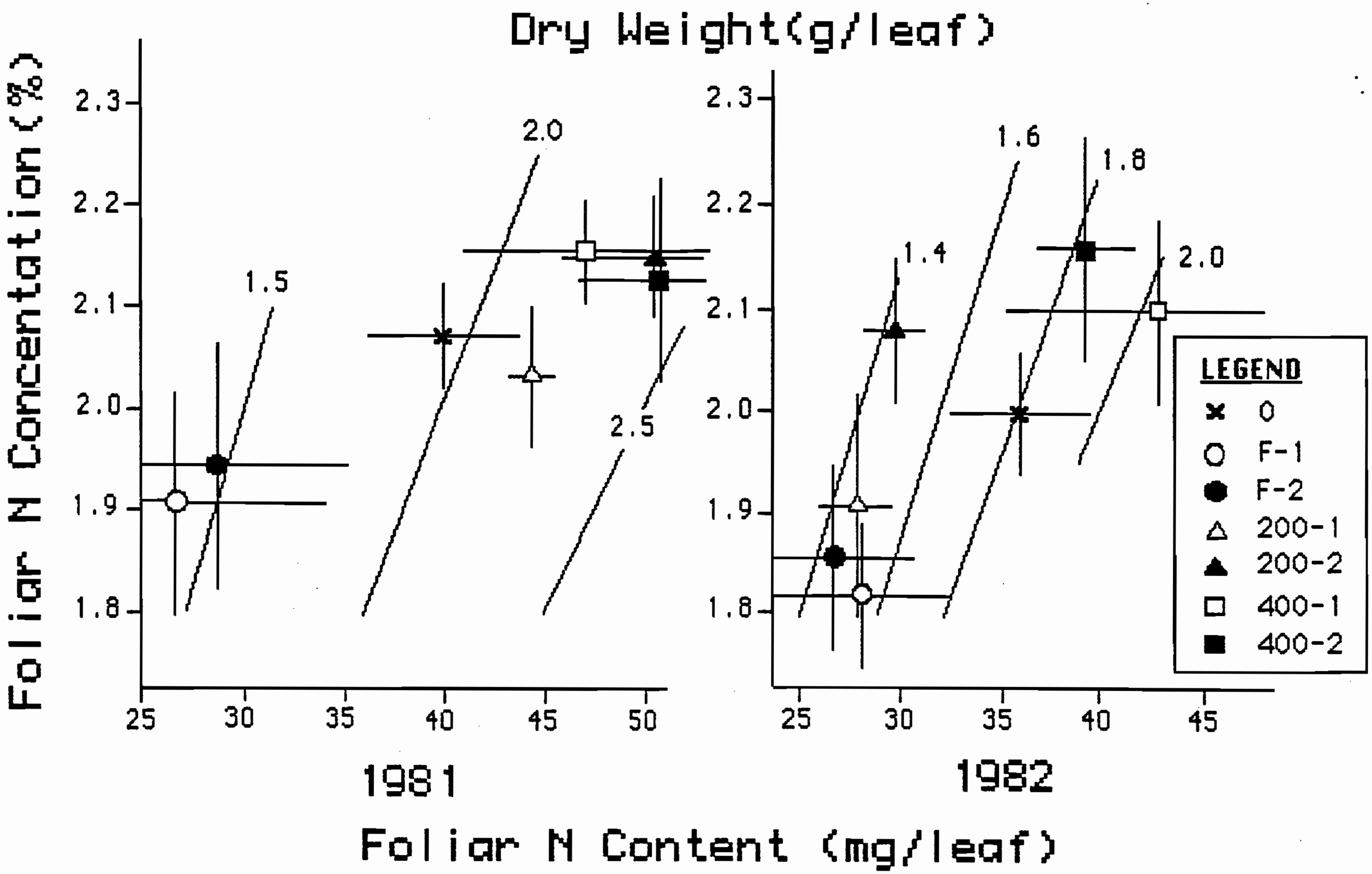


Fig 4.5 The relationship between foliar N concentration, N content, and unit dry weight of leaves at the Bearbrook site.

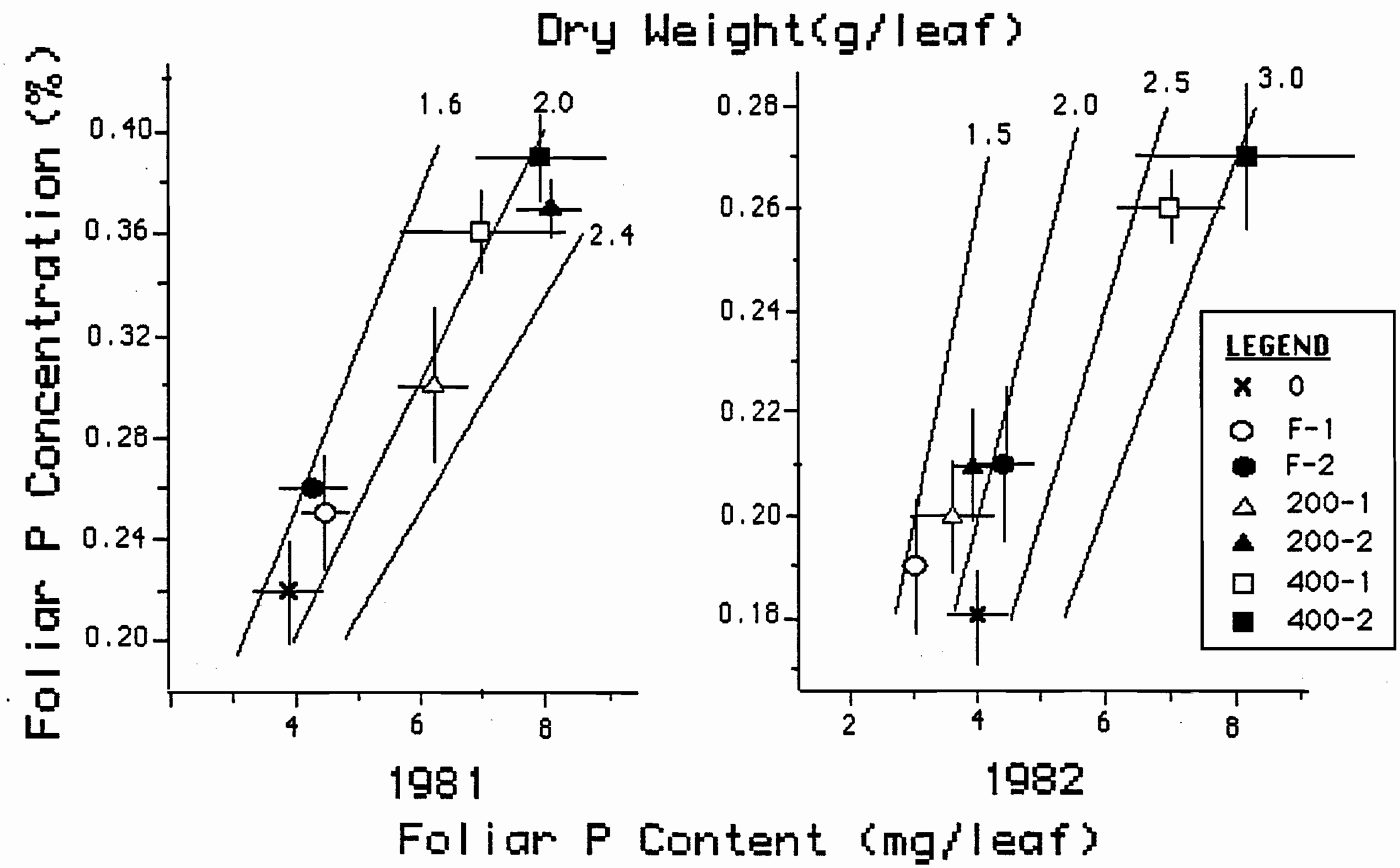


Fig 4.6 The relationship between foliar P concentration, P content, and unit dry weight of leaves at the Grand Ligne site. (note changes in scale). (+ = std. error of mean)

By 1982, overall foliar P concentration had declined compared with 1981. Nevertheless, treatment 400 had significantly ($p < .01$) higher foliar concentration and content than the control. The graph again shows this trend in the "C" direction.

Phosphorus was affected less by sludge treatment at Bearbrook (Fig 4.7). Fertilizer treatments had significantly lower P concentration and content than sludge treatments in 1981. The graph indicates a shift to "F" - a deficiency in P as a result of an antagonism. Phosphorus concentration ranged from 0.22% to 0.28% for fertilizer and sludge respectively. In 1982, overall P concentration ranged from 0.19% to 0.22%.

In 1982, P concentration ($p < .05$) and content ($p < .06$) in treatment 200 was lower than in treatment 400. Fig. 4.7 shows the same trend, as for foliar N, a shift in the "C" direction for sludge treatments (Fig. 4.5), but changes were not significant. Treatment 200 had a foliar content lower ($p < .06$) than treatment 400.

4.3.5 Potassium

After one growing season at Grande Ligne, foliar K concentration was not significantly affected by treatments (Fig. 4.3). There was a highly significant ($p < .01$) effect due to replication.

In 1981, foliar K concentration and content increased from control ($p < .10$) with increasing sludge rates (Fig 4.8). The graph shows the shift in the "C-D" direction. Soil K in sludge treatments was

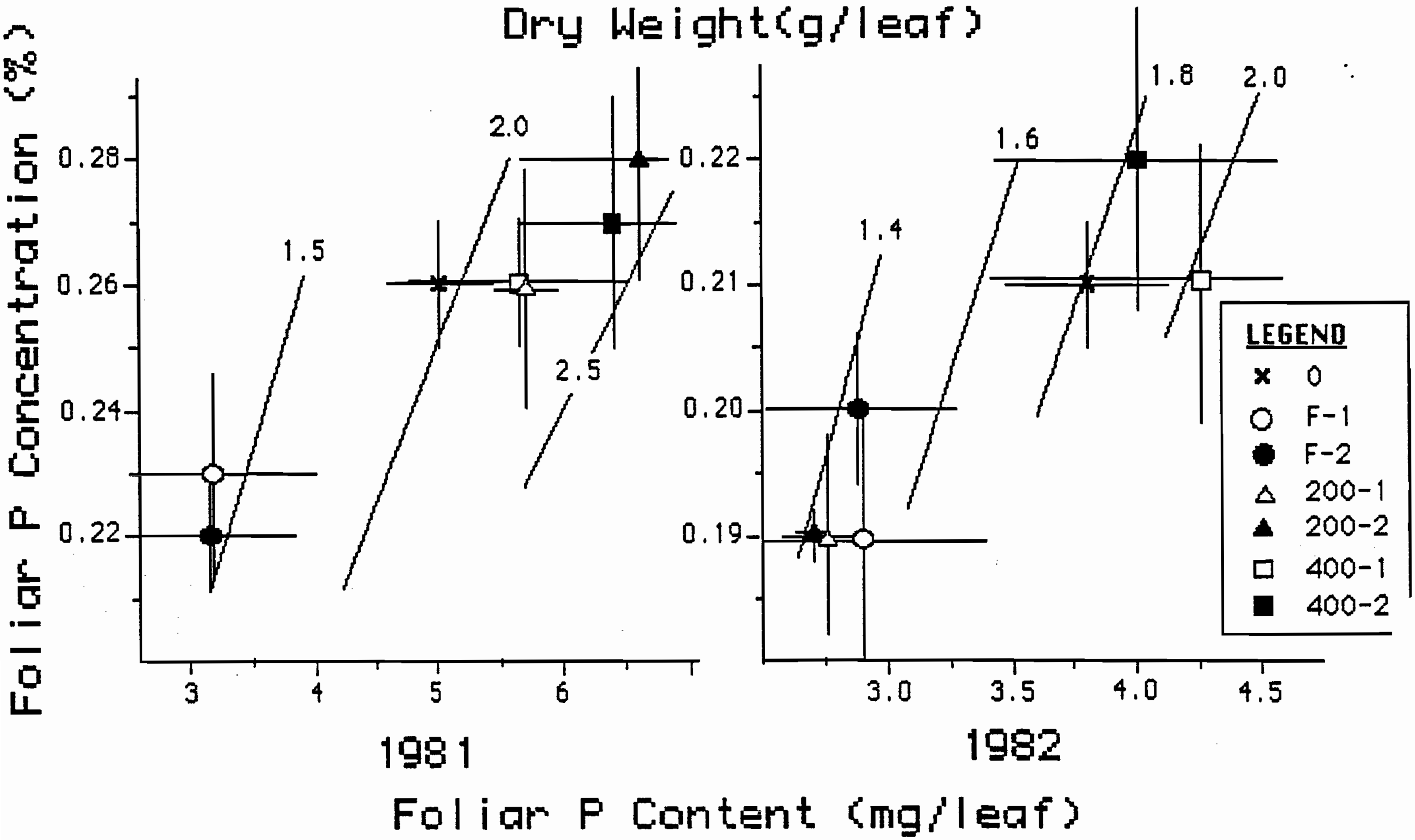


Fig 4.7 The relationship between foliar P concentration, P content, and unit dry weight of leaves at the Bearbrook site. (note changes in scale).

possibly not limiting but uptake of nutrient is obvious, implying luxury consumption. Foliar K on fertilizer treatments also showed evidence of luxury consumption.

In 1982, plots which received the 400 treatment had a foliar K concentration and content significantly ($p < .01$) higher than treatment 200 and the control. Fig. 4.8 shows that foliar K on treatment 400 moved in "C" direction and was limiting. Foliar K on treatment 200 shows deficiencies. F-2 treatment continues to exhibit luxury consumption of K.

At Bearbrook in 1981, foliar K in fertilizer treatments was lower ($p < .08$) than in the control (Fig. 4.9). The graph shows a trend in the "F" direction. This indicates a deficiency induced by treatment - a true antagonism. Foliar K concentration in treatment 400 was lower than in the control. This "A" shift indicates a dilution by additional growth, possibly due to increases in foliar N.

In 1982, foliar K concentration and content were lower ($p < .08$) in the 200 treatment. Fig. 4.9 indicates movement in the "F" direction - a deficiency caused by treatment. The trend of foliar K for other treatments is similar but not significant. Overall values at Bearbrook are lower than at Grande Ligne.

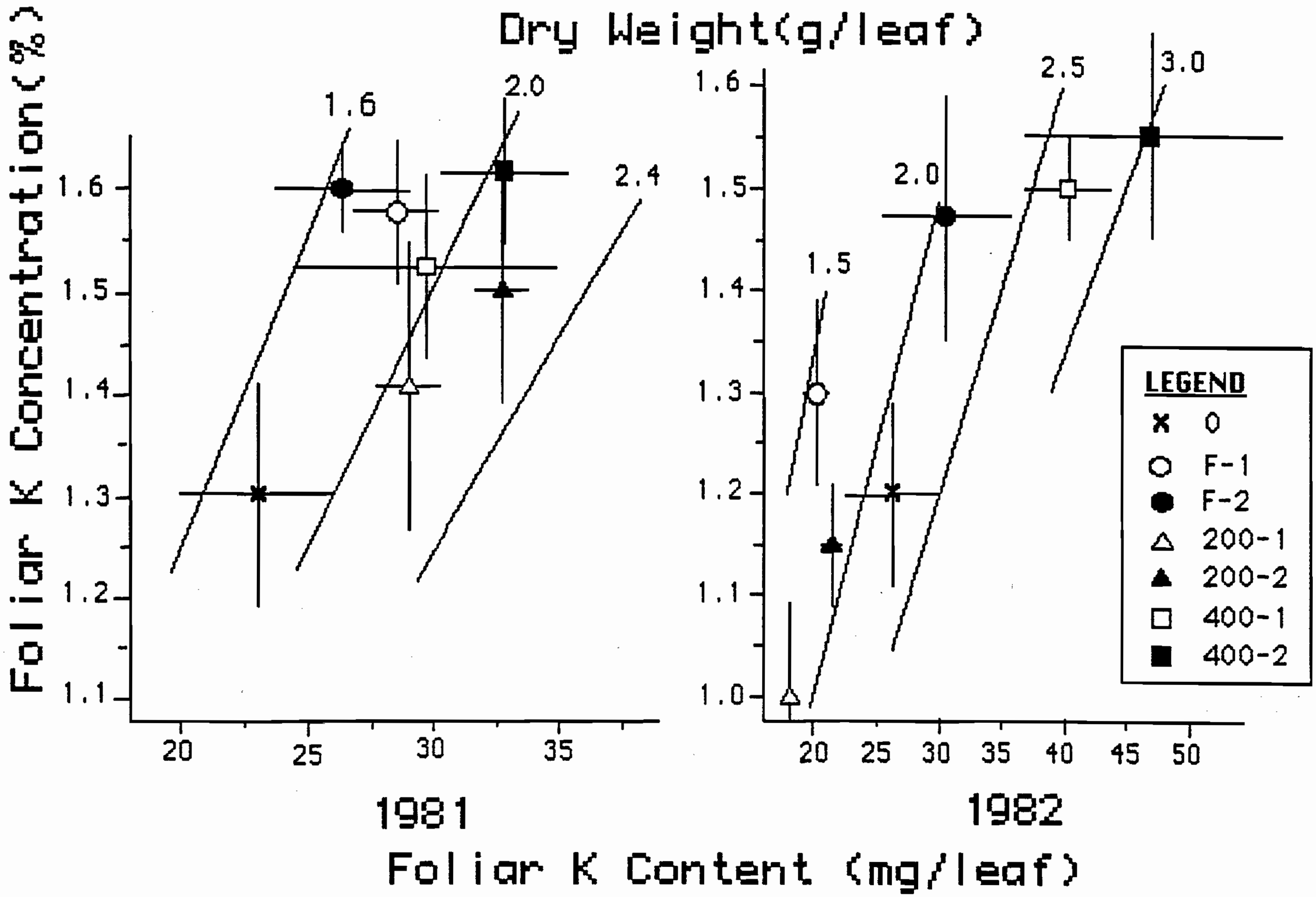


Fig 4.8 The relationship between foliar K concentration, K content, and unit dry weight of leaves at the Grande Ligne site. (note changes in scale).

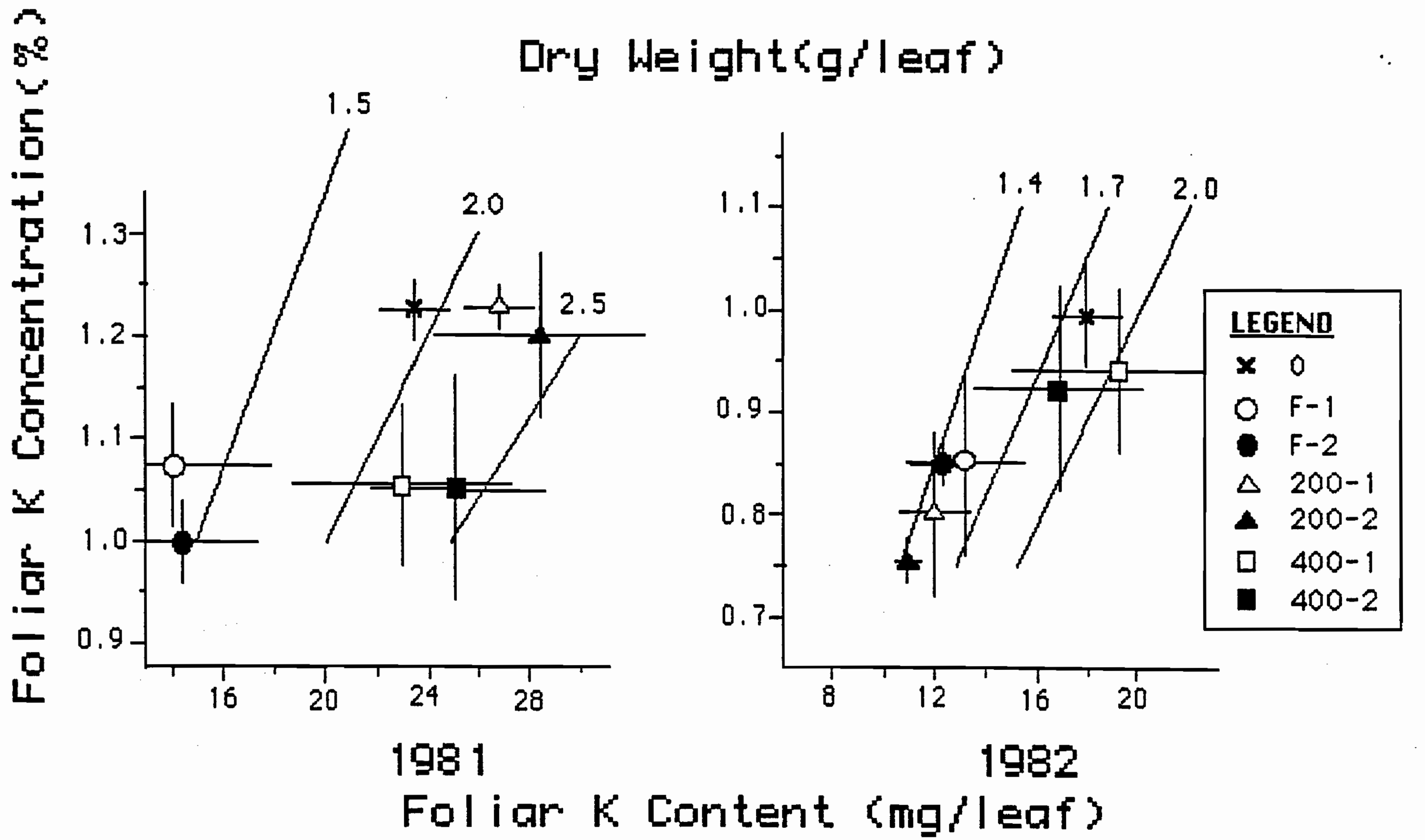


Fig 4.9 The relationship between foliar K concentration, K content, and unit dry weight of leaves at the Bearbrook site.

4.3.6 Calcium

At Grande Ligne in 1980, foliar Ca concentration in treatment 400 was significantly lower than in either the control or the 200 treatment (Fig. 4.3). In 1981, foliar Ca concentration decreased significantly from the control with increasing sludge application (but decreasing Ca in sludge - Table 4.1) and with fertilizer application. Leaf content of Ca decreased only slightly with treatments (Fig. 4.10). The graph shows a shift in "A" direction - a false antagonism causing a dilution of foliar Ca due to additional growth. Foliar Ca concentration in treatment 200-1 is very similar to foliar Ca in the control. This treatment received twice as much sludge Ca as the 400-1 treatment.

The following year overall foliar Ca concentration and content increased from 1981, especially in the control and 200 treatment. In the 400 treatment Ca concentration was significantly lower than in the control or the 200 treatment. Foliar Ca content was not significantly affected, but control levels were higher than all others. The reduction of foliar Ca concentration in the 400 treatments caused an "A" shift again - a dilution of foliar Ca.

At Bearbrook in 1981, the only significant ($p < .01$) result was a higher foliar Ca concentration in the 400-1 treatment compared with the 400-2 treatment. Foliar content was lower in the control than in sludge treatments (Fig. 4.11).

In 1982, the control had lower foliar Ca concentration than sludge treatments. However at Grande Ligne, foliar Ca concentration was

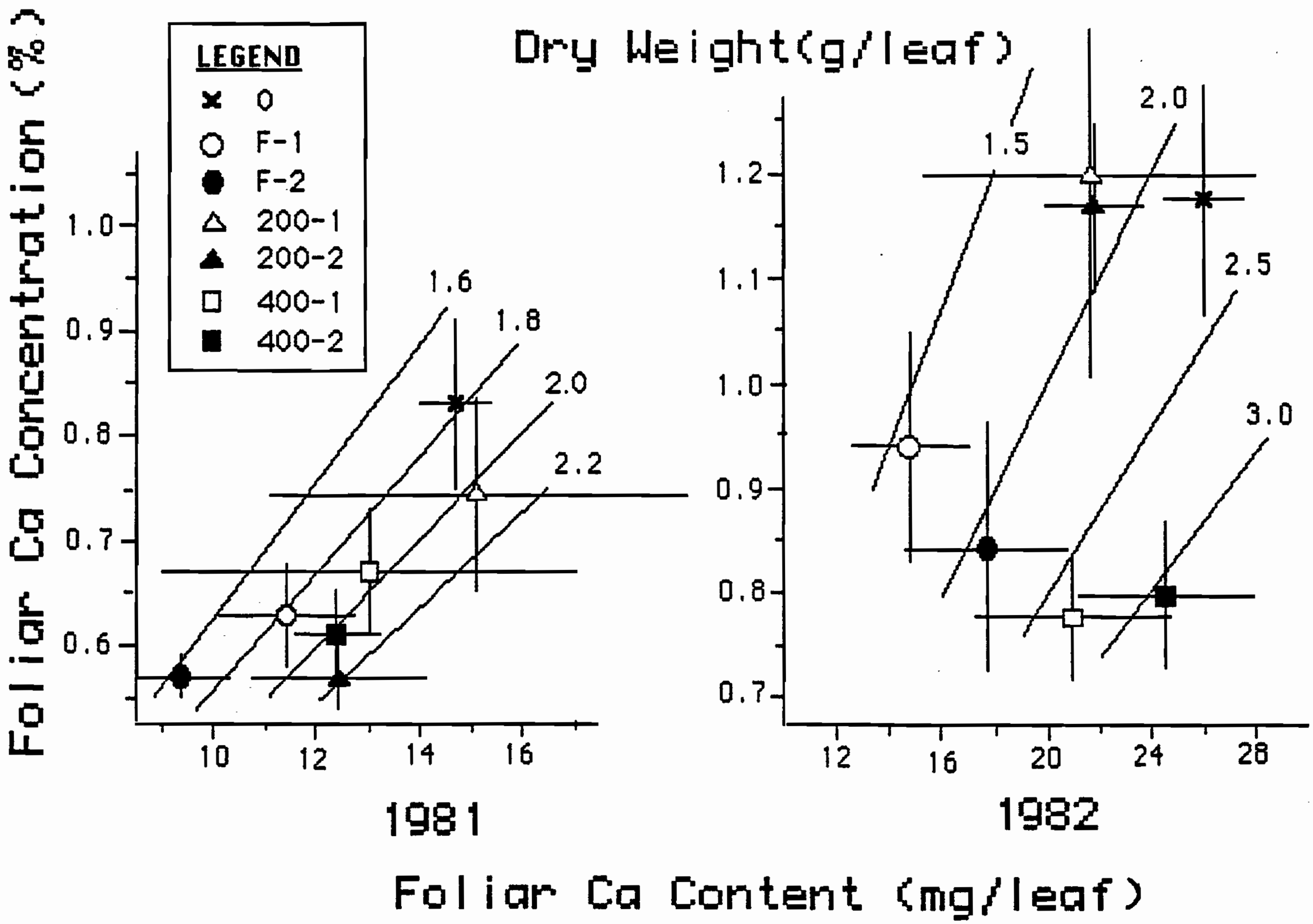


Fig 4.10 The relationship between foliar Ca concentration, Ca content, and unit dry weight of leaves at the Grande Ligne site.(note change in scale).

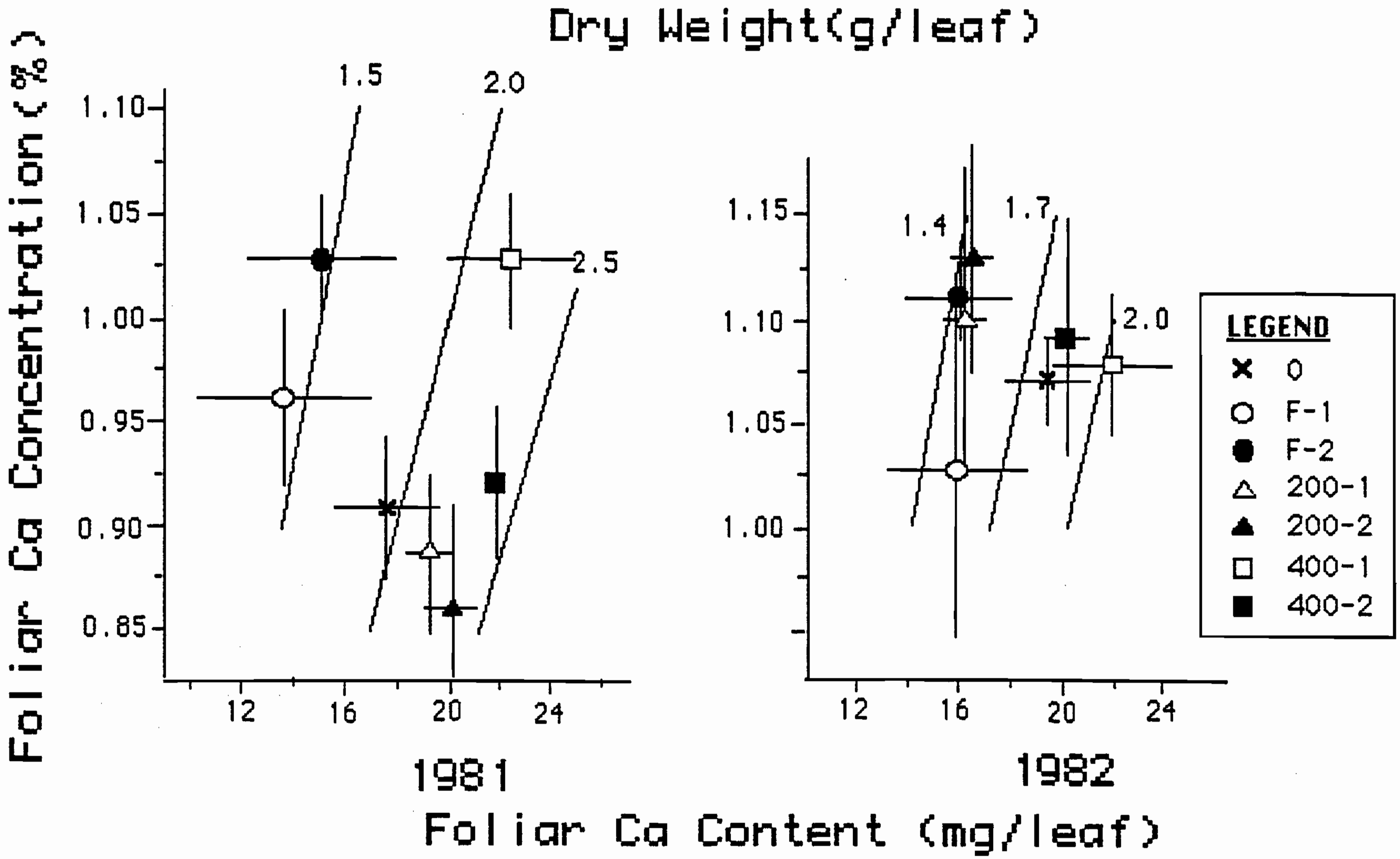


Fig 4.11 The relationship between foliar Ca concentration, Ca content, and unit dry weight of leaves at the Bearbrook site.

higher in the control than in sludge treatments. There was no dilution of foliar Ca due to growth. Average Ca concentration was higher than in 1981 on all treatments.

4.3.7 Magnesium

In 1980 at Grande Ligne, foliar Mg concentration results were similar to Ca. Treatment 400 had significantly lower Mg concentration than the control or treatment 200 (Fig. 4.3). There was a highly significant ($p < .01$) effect due to replication.

In 1981, foliar Mg concentrations between the 200-1 and 200-2 treatments were significantly different. Other treatments showed no significant differences. Magnesium content was lower in the control than all treatments (Fig. 4.12). Generally a shift in "B" direction is shown which indicates nutrient transport into foliage is just sufficient to keep pace with growth - a nonlimiting Mg status.

In 1982, Mg concentration in the 200 treatments was significantly higher than in the 400 treatments, while foliar Mg values in the control were between the two. Leaf content was higher in the 400 treatment than in the control. The overall trend from 1981 to 1982 was toward higher foliar Mg concentration and content.

At Bearbrook, foliar Mg was not significantly affected by sludge treatments. Magnesium concentration had increased on average from 1981 to 1982 (Fig. 4.13). Foliar Mg concentration and content in 1981 follows trends similar to Ca on this site.

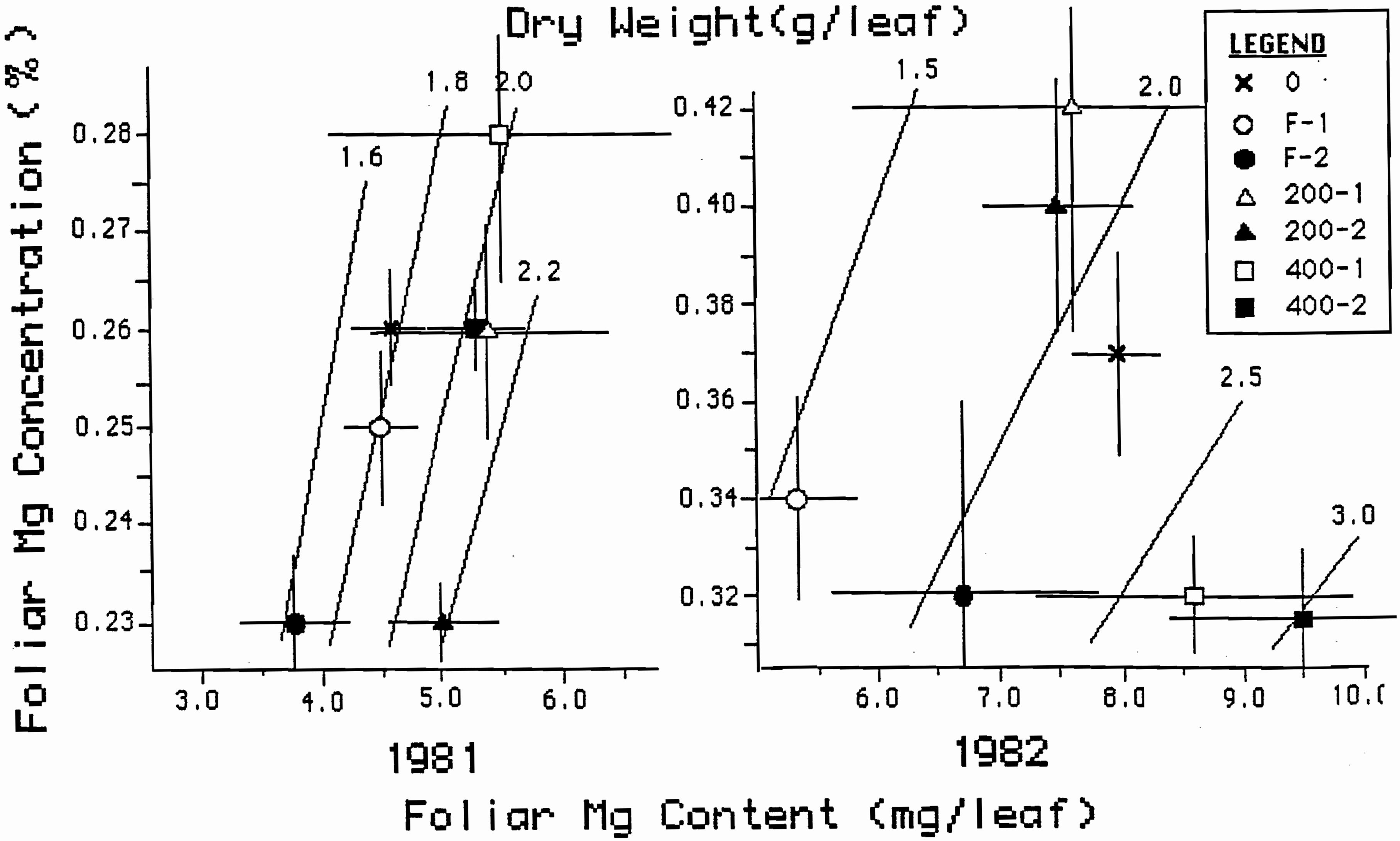


Fig 4.12 The relationship between foliar Mg concentration, Mg content, and unit dry weight of leaves at the Grande Ligne site.(note change in scale).

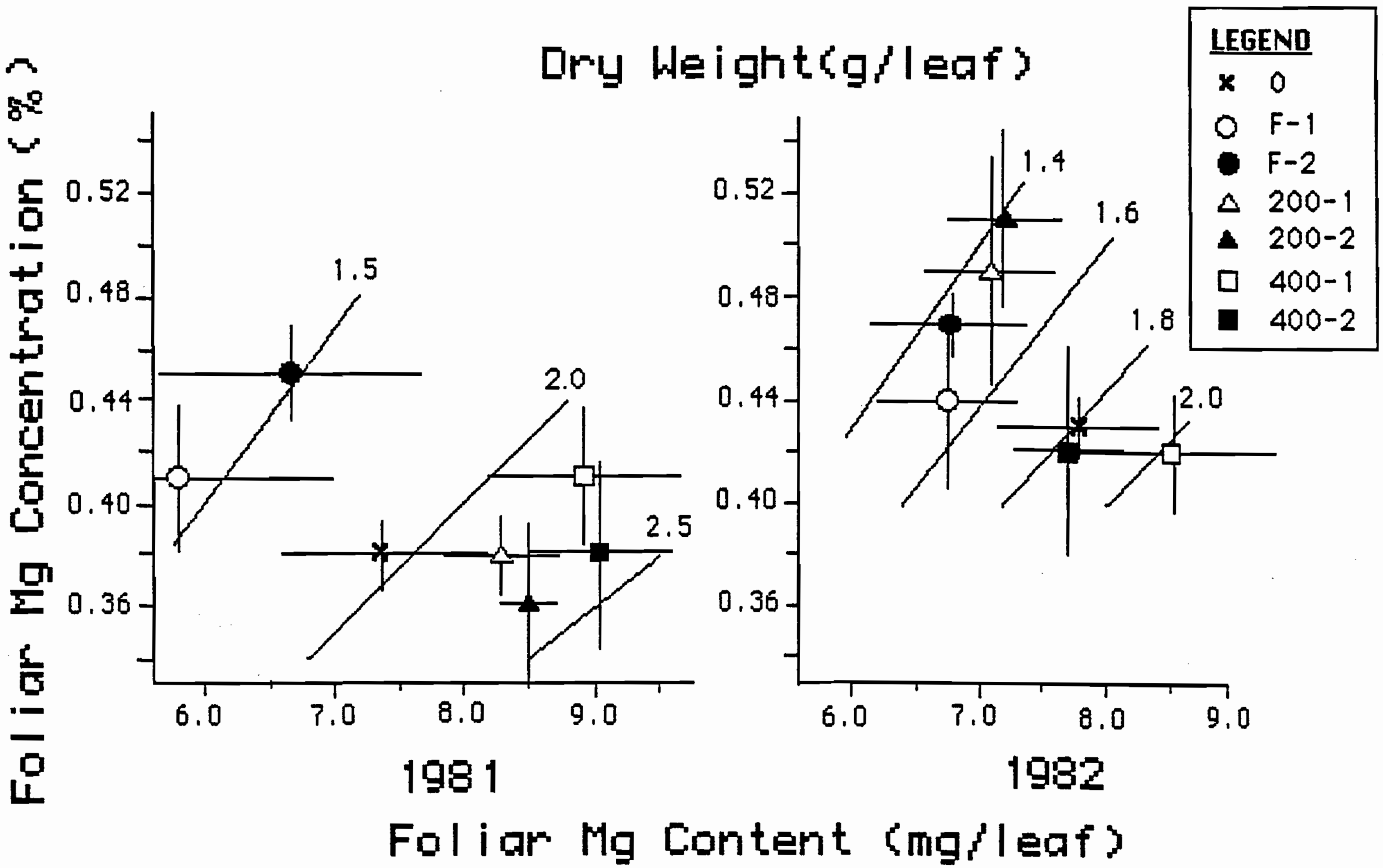


Fig 4.13 The relationship between foliar Mg concentration, Mg content, and unit dry weight of leaves at the Bearbrook site.

4.4 Tree Growth

4.4.1 General

Two hundred and forty cuttings were planted on each site. After the 1980 season survival on the Grande Ligne and Bearbrook sites was 88% and 94% respectively (Table 4-13).

All failures were noted as no-sprouting from the cuttings. Of the 30 failures on Grande Ligne site, 14 occurred on two adjacent plots. The Grande Ligne site lost three trees in 1981 and two more the following year due to frost and rodent damage.

On the Bearbrook site, 15 trees failed to sprout in 1980. But, in 1981, only 198 trees were used in the analysis. Most of the trees not included in 1981 analysis were lost due to frost. Some were girdled by mice or rabbits and some were knocked down by a vehicle.

Table 4.13 Number and percentage of trees used in analysis of variance at the Grande Ligne and Bearbrook sites (240 planted).

Year		Grande Ligne	Bearbrook
1980	No.	210	225
	%	88	94
1981	No.	207	198
	%	86	83
1982	No.	205	191
	%	85	80

Most of those that died back after one year resprouted and grew very well. But they were not used in the height calculations. In 1982, seven more trees were not included in calculations due to frost damage.

Application of sludge resulted in heavy grass cover. In some places chemical control was not sufficient and hand weeding was done. There appeared to be no insect problems. Rust appeared sporadically on leaves on both sites in late August. Because it was so late in the season it was not considered a problem.

Drainage was a problem on the Bearbrook site in late 1980, but ditching seemed to alleviate the problem for 1981 and 1982. In 1981 Arborguard was applied by brush to all trees on both sites to discourage girdling by rodents. There were no more losses following this treatment.

4.4.2 Height Growth

At Grande Ligne, there were no significant differences in height due to treatments in 1980. Trees growing in fertilizer treatments showed the highest growth (102 cm) while trees in the control grew the least (95 cm) (Fig. 4.14). Means for all tree height data are found in Appendix D.

In 1981, tree growth was significantly ($p < .01$) greater on sludge treatments. Trees on the control grew 105 cm during the year compared with the average of the sludge treatments at 152 cm, a 45% increase. Trees in treatments that received the second application of sludge (in 1981) showed significantly ($p < .01$) greater growth than trees that received only one application. Trees on the fertilizer

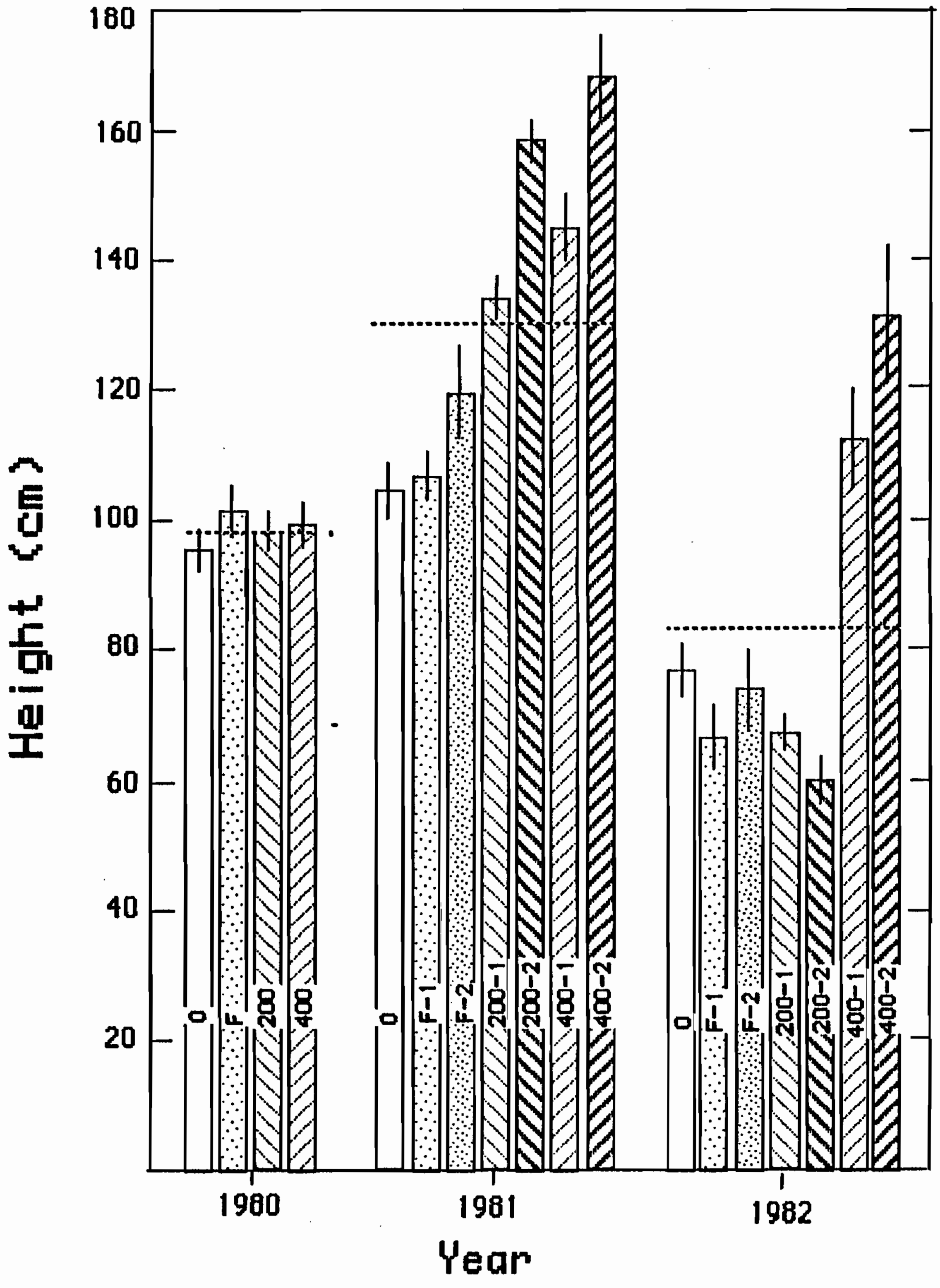


Fig 4.14. Mean annual height growth of hybrid poplar treated with sludge and fertilizer at the Grande Ligne site. (| std. err; ---- mean height of treatments)

treatment and the control had similar height growth. Cumulative growth after two years showed that trees in sludge treatments continued to have significantly more height growth than the control (Fig. 4.15).

In 1982 trees in treatment 400 continued to have significantly greater growth than trees in the control or in treatment 200. Mean height growth declined in all treatments, from an average in 1981 of 129 cm to 84 cm in 1982.

After three years only trees in treatment 400 showed significantly greater growth than trees in the control. Differences in height continued to be significant ($p < .01$) between trees in treatments 400-1 and 400-2. In the latter, trees were 404 cm in height after three years compared with 280 cm in the control, an increase of 44%. After three years, tree height growth in fertilizer treatments was similar to the control.

At Bearbrook in 1980, tree growth was greatest in treatment 400, second in treatment 200 and, least in the control. All differences were highly significant ($p < .01$). Trees in fertilizer treatments and the control had similar height growth (Fig. 4.16).

The following year trees in treatment 200-2 grew 140 cm while trees in the control grew 123 cm. Other sludge treatment values were intermediate. Tree growth in fertilizer treatments was significantly ($p < .01$) less than all other treatments.

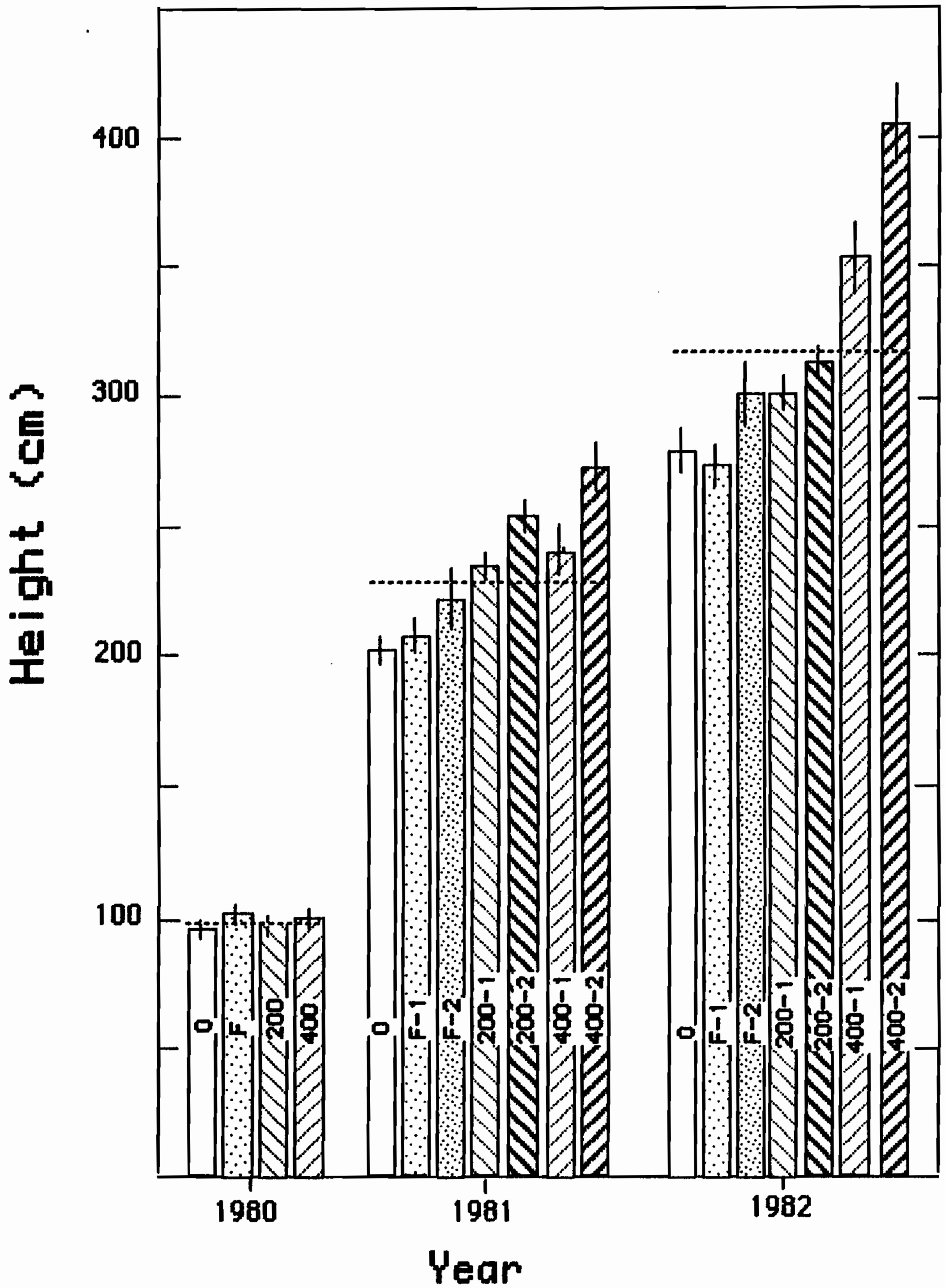


Fig 4.15. Mean cumulative height growth of hybrid poplar treated with sludge and fertilizer at the Grande Ligne site. (| std. error; ----- mean height of treatments)

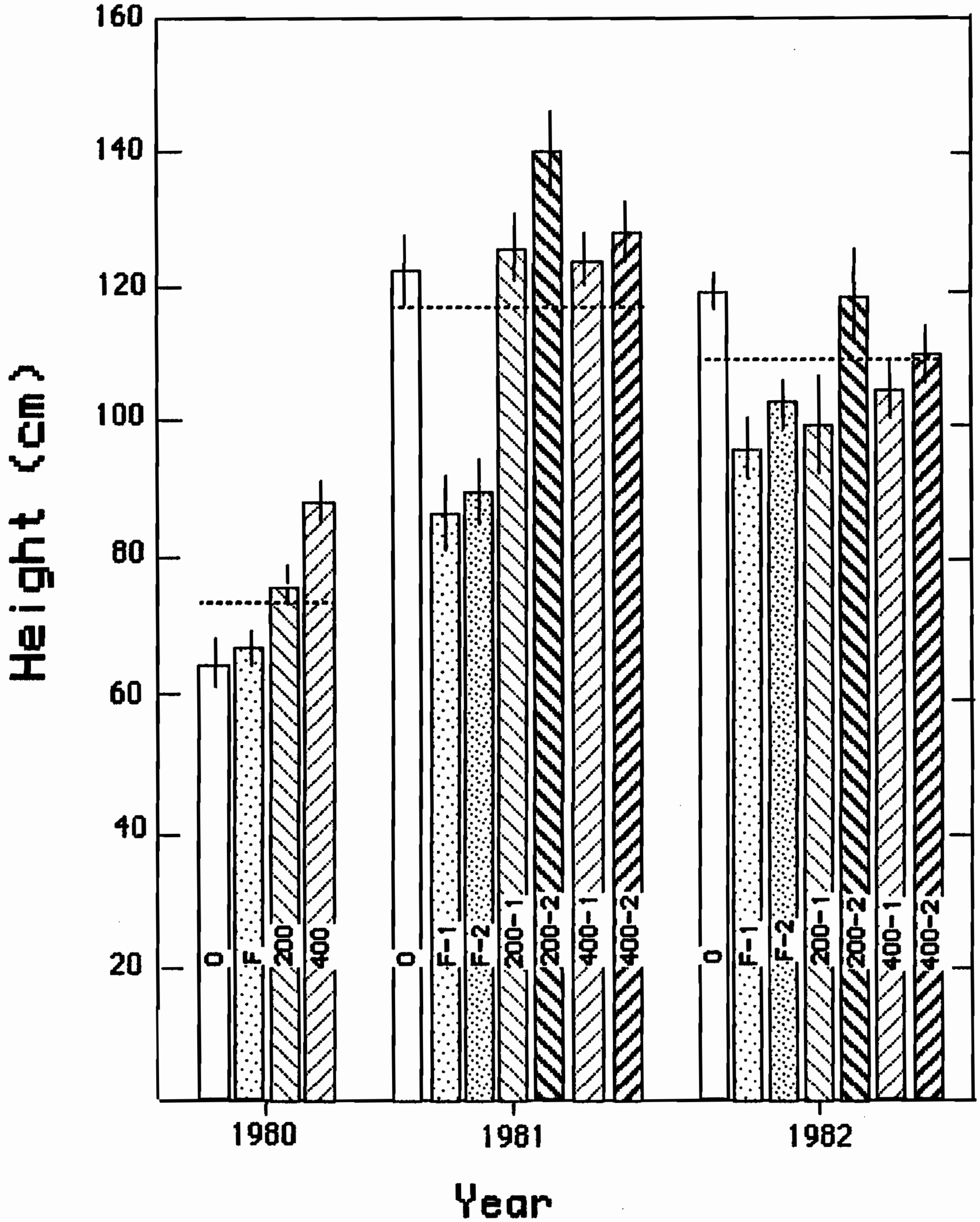


Fig 4.16. Mean annual height growth of hybrid poplar treated with sludge and fertilizer at the Bearbrook site. (| std. err; ----- mean height of treatments)

Cumulative growth after two years resulted in significantly ($p < .01$) less height growth in fertilizer treatments. Trees in treatment 200-2 were significantly taller than in treatment 200-1, a 15% increase (Fig. 4.17).

Mean tree growth on all treatments was less in 1982 compared with 1981. No significant differences due to treatments were observed, but trees in the control had the greatest growth.

Total height growth in sludge treatments after three years was not significantly different from control. Tree height growth in fertilizer treatments was significantly lower than in sludge treatments. Trees in treatment 200-2 (the greatest growth) were significantly taller (340 cm) than trees in treatment 200-1 (297 cm), but were only 10% taller than trees in the control (308 cm). A comparison of Figures 4.15 and 4.17 showed that height growth on sludge treatments at Grande Ligne far surpassed growth at Bearbrook. Only in 1982 was cumulative mean height growth similar on the two sites. Height growth in the Bearbrook control was higher than in the Grande Ligne control.

4.4.3 Stump Diameter

At Grande Ligne stump diameter at 15 cm, measured after three years of growth, showed a more dramatic difference due to treatments than height growth (Table 4.14). Almost all treatments differed significantly. Stump diameter ranged from 4.3 cm in the control plots to 7.8 cm in treatment 400-2, an 81% difference.

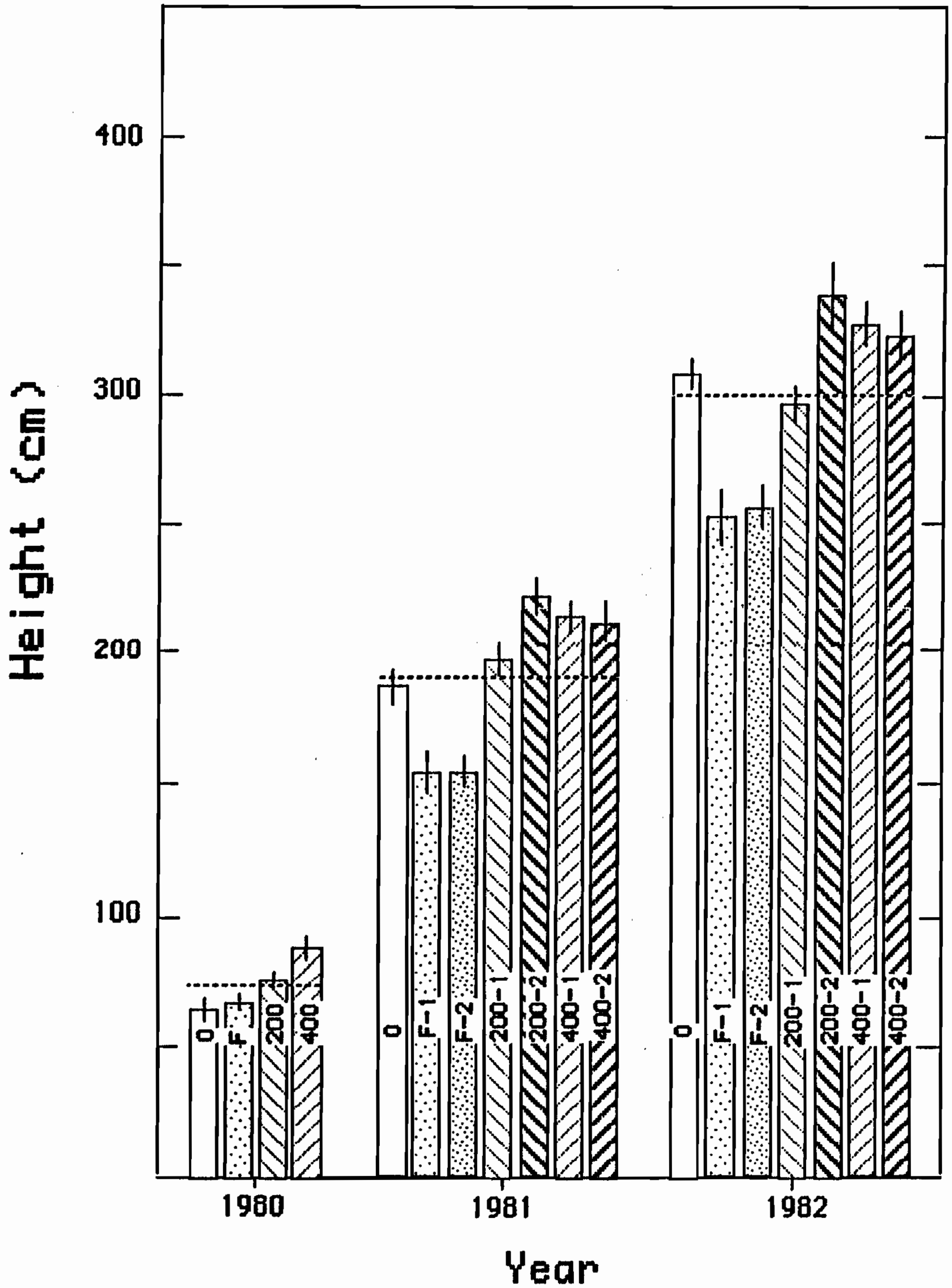


Fig 4.17. Mean cumulative height growth of hybrid poplar treated with sludge and fertilizer at the Bearbrook site. (| std. error; ----- mean height of treatments)

At Bearbrook statistical analysis showed that height and stump diameter growth trends were similar. Diameter ranged from 3.6 cm in F-1 plots to 5.2 cm in 200-2 plots, considerably less than at Grande Ligne (Table 4.14).

Table 4.14 Mean stump diameter (at 1.5 cm above ground) after three years.

	Grande Ligne	(205 trees)	Bearbrook	(191 trees)
Treatment	Stump diameter(cm)	No. of trees used for mean	Stump diameter(cm)	No. of trees used for mean
0	4.3 aadd[1]	55	4.5	49
200-1	5.2 e	28	4.4	24
200-2	6.2 gg	25	5.1 gg	22
400-1	6.5 ff	26	4.8	23
400-2	7.8 hh	26	4.9	25
F-1	5.0 i	21	3.7 bb	23
F-2	5.7	24	3.6	25

[1] See inside back cover for contrast statement codes.

4.4.4 Biomass

Estimates of potential yield (see explanation in Table 4.15) after three years produced highly significant ($p < .01$) results at Grande Ligne. In the control, potential yield was 2.13 Mg/ha and increased in treatments receiving progressively more sludge. Treatment 400-2 had a potential yield of 7.38 Mg/ha, 246% greater than the control. Fertilizer treatments which had the lowest survival rate in the field had greater potential yield than in the control. Although GLM was not performed on actual yield, the same trend as described above applies for sludge application. Significant differences in potential yield were very similar to those of stump diameter which proved to be a better yield estimator than tree height.

At Bearbrook estimates of potential and actual yield were much lower than at Grande Ligne. Treatment 200-2 had the highest potential yield at 3.24 Mg/ha while control had a potential yield of 2.40 Mg/ha, a difference of only 35%. Biomass on fertilizer treatments was significantly lower than all other treatments. Significant differences for yield were very similar to those of both stump diameter and tree height.

Table 4.15 Estimated leafless oven-dry yield of three-year-old hybrid poplar.

Treatment	Potential[1] Yield	MAI	Actual Yield	MAI
	Mg/ha			
Grande Ligne				
0	2.13 ad[2]	0.71	1.92	0.64
200-1	2.87 e(.07)[3]	0.96	2.68	0.89
200-2	4.00 gg	1.33	3.33	1.11
400-1	4.99 ff	1.67	4.33	1.44
400-2	7.38 hh	2.46	6.31	2.10
F-1	2.49	0.83	1.74	0.58
F-2	3.48	1.16	2.79	0.93
Bearbrook				
0	2.40	0.80	1.96	0.65
200-1	2.14 gg	0.71	1.71	0.57
200-2	3.24	1.08	2.37	0.79
400-1	2.81	0.94	2.15	0.72
400-2	2.94	0.98	2.45	0.82
F-1	1.45 bb	0.48	1.11	0.37
F-2	1.38 j	0.46	1.15	0.38

1 Potential yield assumed 100% survival on sample plots. Actual yield considered only trees that grew three years. While actual yield is a true appraisal of yield in the field, potential yield gives a better idea of overall treatment effect because it discounts the effect of lost trees.

2 GLM was performed on a "per tree" basis and therefore applies only to Potential Yield.

3 See inside back cover for contrast statement codes.

4.5 Correlations Between Soil, Foliage and Tree Characteristics

Correlation between soil properties, foliage data and, tree height are presented in Tables 4.16 to 4.23. Correlation coefficiants are quite variable and often hard to interpret. Some correlations were continuous through three years of sampling. For example soil Ca-Mg, Ca-pH, and Mg-pH were generally related to each other in each sampling period and at depth. But most soil properties changed from year to year as a result of sludge treatments and for unknown reasons. Most soil properties did not have a linear correlation.

Height growth did not have significant ($p > .05$) linear correlation with any soil or foliage properties on the Grande Ligne site. But at Bearbrook in 1981, height growth was linearly related to soil P ($r = .81$), foliar K concentration ($r = .84$) and negatively related to foliar Ca concentration ($r = .87$) at $p < .01$.

Correlations between foliage characteristics were more common and had greater statistical significance. Foliage dry weight usually accounted for (with few exceptions) 65% or more of the variation in foliage nutrient contents. This was not surprising since foliage content was calculated from the product of foliage dry weight and concentration (percent of dry weight). Foliar dry weight generally did not linearly correlate with foliar concentration. Correlations among foliage concentrations were not common.

Calcium and Mg concentrations had a strong linear relation ($p < .05$) on both sites in 1981 ($r = .95$ and $.89$) and 1982 ($r = .77$

and .74) at Grande Ligne and Bearbrook, respectively. Because they both had a strong linear relation with dry weight their respective nutrient content are closely related (r = .88 to .98). K concentration was often negatively correlated with Mg and Ca concentration although the relationship was not as close as above.

Highly significant linear correlations between foliage contents were common. All relationships were positive. Nitrogen content was most often linearly related with other nutrient contents. Much of this was related to dry weight, but with uptake of N, nutrient content varied. This was true at Bearbrook where N content was related to every other nutrient content. This suggested that other nutrients increased as a result of increases in N. It also suggests that only N was limiting. Correlations between nutrient concentration and content were also common but changes between years and sites did not show many trends.

Correlations between soil characteristics and foliage were common but difficult to interpret. For example at Grande Ligne in 1981 at the 0-15 cm level there were ten linear correlations between soil and foliage where $r > .57$. But in 1982 there were 28 linear correlations. Soil P was negatively related to N, P, and K content and concentration with r values between -.67 and -.91. At Bearbrook in 1981, there were 17 linear correlations while in 1982 there were only two minor correlations. Correlations at depths greater than 15 cm were variable and most had a coefficient $r < .70$.

Some particular correlation results will be discussed later.

Table 4.16 Correlation matrix for soil chemical properties at the Grande Ligne site before treatments in 1980. (df = 5)

d = 0-15 cm

	K	Ca	Mg	pH	OC
P		.94 ***		.87 **	
K					
Ca			.73 *	.91 ***	
Mg					
pH					

d = 15-30 cm

	K	Ca	Mg	pH	OC
P			-.69 *	-.67 *	
K		-.90 ***	-.87 ***	-.68 *	.77 **
Ca			.94 ***	.90 ***	-.95 ***
Mg				.87 **	-.83 **
pH					-.93 ***

d = 30+

	K	Ca	Mg	pH	OC
P					
K					
Ca			.97 ***	.87 **	
Mg				.86 **	
pH					

***,**,* significant at 0.01,0.05, and 0.10 levels respectively.
Correlation values included only for greater than r= .65 and significant at 0.10 level.

Table 4.17 Correlation matrix for soil chemical properties, foliar nutrient concentrations and tree height at the Grande Ligne site following the 1980 season. (df = 5)

d=0-15 cm

K	Ca	Mg	pH	NC	PC	KC	CC	MC	H	
							.67 *			P
				.85 **						K
		.89 ***	.83 **	.71 *				.85 **		Ca
			.71 *					.88 ***	.69 *	Mg
								.66 *		pH
										NC
							.83 **			PC
										KC
										CC
										MC

d=15-30 cm

K	Ca	Mg	pH	NC	PC	KC	CC	MC	H	
						-.81 **				P
			-.73 *				-.70 *	-.69 *	-.68 *	K
		.93 ***	.67 **					.73 *		Ca
										Mg
								.83 **	.69 *	pH

d=30+ cm

K	Ca	Mg	pH	NC	PC	KC	CC	MC	H	
-.67 *			.73 *							P
										K
		.87 **		.68 *				.81 **		Ca
			.76 **					.73 *		Mg
										pH

***,**,* significant at 0.01,0.05, and 0.10 levels respectively.
Correlation values included only for greater than r= .65 and significant at 0.10 level.
NC, PC, KC, CC, MC are foliar N, P, K, Ca, and Mg concentrations respectively, and H is average annual tree height.

Table 4.18 Correlation matrix for soil chemical properties, foliar dry weight, nutrient concentration and content, and tree height at the Grande Ligne site after the 1981 season. (df = 7)

d = 0-15 cm

	NO	P	K	Ca	Mg	pH	OC	DR	NC	PC	KC	CC	MC	NT	PT	KT	CT	MT	H
NH									-.59 *		-.72 **								
NC								-.63 *						-.63 *	-.60 *	-.88 ***			
P			.83 ***	.69 **	.82 ***	.79 **													
K					.66 *	.70 **					.83 **								
Ca					.64 *	.84 ***			.65 *						.62 *				
Mg																			
pH										.60 *									
OC																			
DR										-.86 ***	-.79 **			.87 ***		.88 ***	.80 **	.91 ***	
NC												.80 ***	.79 **	.69 **			.64 *		
PC											.63 *			-.70 **		-.79 **	-.74 **	-.83 ***	
KC																		-.65 *	
CC													.95 ***	.68 **			.84 ***	.71 **	
MC														.64 *			.78 **	.67 **	
NT																.77 **	.93 ***	.96 ***	
PT																			
KT																	.71 **	.77 **	
CT																		.97 ***	
MT																			

Table 4.18 (continued)

d = 15-30 cm

	NO	P	K	Ca	Mg	pH	DR	NC	PC	KC	CC	MC	NT	PT	KT	CT	MT	H
NH		-.82 ***																
NO							-.59 *							-.70 **	-.86 ***			
P			.67 **			.74 **												
K				.66 **	.68 **	.71 **												
Ca					.88 ***	.70 **								.63 *		.60 *		
Mg						.79 **										.60 *		
pH																		

d = 30+cm

	NO	P	K	Ca	Mg	pH	DR	NC	PC	KC	CC	MC	NT	PT	KT	CT	MT	H
NH							.59 *			-.82 ***								
NO															-.77 **			
P			.73 **	.78 **	.81 ***									.79 **				
K				.66 *	.74 **	.76 **												
Ca					.97 ***								.61 *	.69 **		.61 *		
Mg														.58 *		.61 *		
pH																		

***,**,* significant at 0.01,0.05, and 0.10 levels respectively.
Correlation values included only for greater than r= .57 and significant at 0.10 level.
DR is foliage dry weight, NC, PC, KC, CC, MC are foliar N, P, K, Ca, and Mg foliar concentrations, NT, PT, KT, CT, MT are foliar contents for the respective elements and H is average annual tree height.

Table 4.19 Correlation matrix for soil chemical properties, foliar dry weight, nutrient concentration and content, and tree height at the Grande Ligne site following the 1982 season. (df=7)

d=0-15 cm

	NO	P	K	Ca	Mg	pH	OC	DR	NC	PC	KC	CC	MC	NT	PT	KT	CT	MT	H
NH																			
NO									-.68**	-.75**									
P				.64*	.69**	.61*			-.73**	-.80***	-.91***			-.71**	-.67**	-.75**			-.65*
K									-.61*										
Ca					.59*	.93***				-.60*	-.80***	.78**	.82***						
Mg						.75**			-.58*		.60*		.61*				.64*	.66*	-.66*
pH											-.76**	.72**	.89***				.59*	.58*	
OC													.60*				.59*	.63*	
DR														.83***	.93***	.85***	.75**	.84***	
NC										.67**	.61*			.75**					.63*
PC											.76**			.75**	.73**	.70**			
KC												-.74**	-.66*	.67**	.67**	.81***			
CC													.77**				.64*		
MC																			
NT															.94***	.90***			
PT																.96***		.63*	
KT																			
CT																		.95***	
MT																			

Table 4.19 (continued)

d=15-30 cm

NO	P	K	Ca	Mg	pH	OC	DR	NC	PC	KC	CC	MC	NT	PT	KT	CT	MT	H	
.85 ***																			NH
		.65 *						-.73 **											NO
										-.65 *			-.60 *	-.66 *	-.74 **			-.76 **	P
								-.75 **					-.64 *						K
								-.65 *	-.76 **	-.91 ***	.77 **		-.58 *		-.65 *				Ca
					.74 **											.58 *	.66 *	-.73 **	Mg
							.69 **									.68 **	.74 **		pH
										-.78 **	.64 **	.81 ***			-.66 *				OC

d=30+ cm

NO	P	K	Ca	Mg	pH	OC	DR	NC	PC	KC	CC	MC	NT	PT	KT	CT	MT	H	
																			NH
		.65 *	.81 ***					-.60 *											NO
																			P
								-.66 *											K
																			Ca
					.73 **													-.65 *	Mg
						-.74 **	.62 *		.65 *					.67 **	.61 *				pH
									-.78 **				-.60 *	-.66 *					OC

***,**,* significant at 0.01,0.05, and 0.10 levels respectively.
Correlation values included only for greater than r= .57 and significant at 0.10 level.
DR is foliage dry weight, NC, PC, KC, CC, MC are foliar N, P, K, Ca, and Mg foliar concentrations, NT, PT, KT, CT, MT are foliar contents for the respective elements and H is average annual tree height.

Table 4.20 Correlation matrix for soil chemical properties at the Bearbrook site before treatment in 1980. (df=7)

d = 0-15 cm

	K	Ca	Mg	pH	OC
P			.66 *		
K				.58 *	
Ca				.60 *	
Mg				.76 **	.62 *
pH					

d = 15-30 cm

	K	Ca	Mg	pH	OC
P		-.71 **		-.72 **	
K					
Ca			.63 *	.71 **	
Mg					
pH					

d = 30+

	K	Ca	Mg	pH	OC
P		-.63 *			
K			.78 **		
Ca			.83 ***	.72 **	
Mg				.68 **	
pH					

***,**,* significant at 0.01, 0.05, 0.10 level respectively.
Correlation values included only for greater than r= .57 and significant at 0.10 level.

Table 4.21 Correlation matrix for soil chemical properties and tree height at the Bearbrook site following the 1980 season. (df=7)

d = 0-15 cm

	P	K	Ca	Mg	pH	OC	H
NH	.58 *	.64 *				.68 **	
P			.69 **	.74 **	.66 *	.61 *	
K							
Ca				.90 ***	.60 *	.75 **	.73 **
Mg					.66 *	.65 *	.72 **
pH							
OC							.62 *

d = 15-30 cm

	P	K	Ca	Mg	pH	H
NH						.64 *
P						
K						-.60 *
Ca						
Mg						
pH						
OC						

d = 30+

	P	K	Ca	Mg	pH	H
NH	.67 **	-.71 **				
P		-.59 *				
K				.78 **	-.66 *	
Ca						
Mg						
pH						
OC						

***,**,* significant at 0.01, 0.05, and 0.10 level respectively.
Correlation values included only for greater than r= .57 and significant at 0.10 level.
H is average annual tree height.

Table 4.22 Correlation matrix for soil chemical properties, foliar dry weight, nutrient concentration and content, and tree height at the Bearbrook site following the 1981 season. (df=7)

d=0-15 cm

	NO	P	K	Ca	Mg	pH	OC	DR	NC	PC	KC	CC	MC	NT	PT	KT	CT	MT	H
NH																		.63 *	
NO																			
P					-.58 *						.81 ***	-.84 ***	-.80 ***						.81 ***
K																			
Ca											-.77 **	.73 **	.79 **	-.75 **	-.71 **	-.74 **			-.66 *
Mg						.80 ***						.67 **	.70 **						
pH													.70 **						
OC								-.61 *						-.72 **	-.65 *	-.58 *	-.60 *		
DR											.58 *			.95 ***	.94 ***	.92 ***	.91 ***	.85 ***	
NC										.76 **								-.64 *	
PC											.61 *		-.70 **						
KC												-.92 ***	-.95 ***	.72 **	.81 ***	.84 ***			.84 ***
CC													.89 ***	-.59 *	-.69 **	-.78 **			-.87 ***
MC														-.64 *	-.71 **	-.73 **			-.72 **
NT															.98 ***	.95 ***	.81 ***	.70 **	.62 *
PT																.99 ***	.75 **	.63 *	.69 **
KT																	.68 **		.77 **
CT																		.98 ***	
MT																			

Table 4.22 (continued)

d=15-30

NO	P	K	Ca	Mg	pH	OC	DR	NC	PC	KC	CC	MC	NT	PT	KT	CT	MT	H	
.58*																-.68**	-.71**		NH
								.79**	.63*							-.75**	-.83***		NO
.65*		.61*						.74**											P
				.68**						-.60*				-.62*	-.60*			-.59*	K
				.62*					-.62*				-.64*	-.59*					Ca
									-.73**										Mg
							.63*			.73**	-.86***	-.73**	.62*	.71**	.77**			.62*	pH

d=30+ cm

NO	P	K	Ca	Mg	pH	OC	DR	NC	PC	KC	CC	MC	NT	PT	KT	CT	MT	H	
		-.63*	-.72**						-.68**	-.71**	.67**	.69**					.59*		NH
					-.60*								-.65*	-.60*	-.61*				NO
			-.59*				.68**	-.69**								.74**	.80***		P
			.89***	.73**	.60*						-.59*							.60*	K
				.61*	.60*						-.61*						-.61*		Ca
					.94***														Mg
																			pH

***,**,* significant at 0.01, 0.05, 0.10 level respectively.
Correlation values included only for greater than r= .57 and significant at 0.10 level.
DR is foliage dry weight, NC, PC, KC, CC, MC are foliar N, P, K, Ca, and Mg foliar concentrations, NT, PT, KT, CT, MT are foliar contents for the respective elements and H is average annual tree height.

Table 4.23 Correlation matrix for soil chemical properties, foliar dry weight, nutrient concentration and content, and tree height at the Bearbrook site following the 1982 season. (df=7)

d=0-15 cm

NO	P	K	Ca	Mg	pH	OC	DR	NC	PC	KC	CC	MC	NT	PT	KT	CT	MT	H	
																			NH
						.65 *													NO
					.72 **														P
					.81 ***														K
																			Ca
						-.59 *				-.66 *					-.59 *				Mg
																			pH
																			OC
								.83 ***					.95 ***	.90 ***	.65 *	.74 **	.70 **		DR
													.96 ***	.87 ***	.64 *	.58 *			NC
										.70 **		-.71 **			.63 *				PC
											-.72 **	-.81 ***			.87 ***				KC
												.74 **			.58 *	.61 *			CC
															-.60 *		.70 **		MC
														.91 ***	.64 *	.73 **	.70 **		NT
															.78 **	.61 *			PT
																			KT
																	.88 ***		CT
																			MT

Table 4.23 (continued)

d=15-30

	NO	P	K	Ca	Mg	pH	OC	DR	NC	PC	KC	CC	MC	NT	PT	KT	CT	MT	H
NH		.62*		-.67**				-.70**										-.59*	
NO						-.62*													
P			.83***																
K							.66*			.67**	.63*								
Ca												-.61*							
Mg							-.64*												
pH																			

d=30+ cm

	NO	P	K	Ca	Mg	pH	OC	DR	NC	PL	KC	CC	MC	NT	PT	KT	CT	MT	H
NH	-.65*							-.69**	-.71**					-.79**	-.67**		-.72**	-.76**	
NO																			
P																			
K				.92***	.84***	.92***													
Ca					.88***	.92***													
Mg						.89***	-.80***												
pH							-.60*												

***,**,* significant at 0.01, 0.05, 0.10 level respectively.
Correlation values included only for greater than r= .57 and significant at 0.10 level.
DR is foliage dry weight, NC, PC, KC, CC, MC are foliar N, P, K, Ca, and Mg foliar concentrations, NT, PT, KT, CT, MT are foliar contents for the respective elements and H is average annual tree height.

Chapter 5. Discussion

5.1 Sludge

Sludge concentration values for nutrients were generally within the bounds of other research (Sommers 1977). The effects of variation in sludge loads are discussed with each nutrient.

My analysis (Table 3.4) showed total NH_4-N to be < 10% of total sludge N. But other results from Vaudreuil found NH_4-N to be almost 50% of total N. (Appendix B). This means there is a slow mineralization or NH_3 volatilization from the sludges used in this experiment. Depending on the solid content of sludge, from 10-50% of total N in sludge may be in the form of NH_4-N (Beauchamp et al. 1979). The remainder (up to 90%) was in the organic form. In his review Sabey (1977), mentioned estimates of mineralization of organic N ranging from 2-50% in one year.

According to Sommers (1977) aerobic and anaerobic treated sludges have similar amounts of total N. Aerobic sludges may have more organic N and NO_3-N. Nitrogen content is highly dependent on sludge processing, and in particular water removal. Aerobic treatment processes are able to decompose residues more completely than anaerobic digestion resulting in lower C/N ratios (King 1985). The Vaudreuil sludges had C/N ratios ranging from 7:1 to 4:1 (Table 3.4). Therefore mineralization of these sludges should release N. Most of the research reported here used anaerobic sludge.

5.2 Soil

5.2.1 Nitrogen

On both sites there was probably a rapid mineralization of sludge to produce NH_4-N. Ammonium-N was being formed at Grande Ligne in 1981 and 1982 and the effect was cumulative with absolute values higher in the September 1982 sampling period. The Bearbrook site showed the reverse situation to Grande Ligne. Ammonium-N levels decreased over the sampling period. This may have been the result of NH_4-N fixation by clay minerals (C. Drury, personnal communication).

Volatilization of NH_4-N probably occurred following sludge treatment, particularly at the Grande Ligne site. At Bearbrook losses of NH_4-N due to volatilization would be less than at Grande Ligne because of higher clay content, increased moisture content, and CEC. Ryan et al. (1973) reported that losses due to volatilization decreased as clay content of soil increased. Volatilization rates increased with increasing rates and repeated sludge applications.

Measured levels of NO_3-N in the sludge were low (Table 4.1) and some sludges were not measured due to technical problems. On both sites, NO_3-N levels that were low in the control were significantly higher in the sludge treatments in May 1982. In September 1982 NO_3-N levels in treatments were much lower.

Levels of NO_3-N were higher in Grande Ligne than in Bearbrook due to better aeration in the coarse-textured soil and as a result of clay fixation of NH_4-N on the Bearbrook (clay) site. Leaching was noticeable due to the increased NO_3-N levels below 15 cm and the absence of NO_3-N in the last sampling period. This absence may also be due to denitrification.

5.2.2 Phosphorus

Sludge loadings of P were evenly distributed by application (Table 4.1). It appeared that the P in sludge was available for plant growth as the foliage results showed.

At Grande Ligne, P was made available to the plants by addition of sludge. By 1982 more P had moved down the profile on the sludge treatments as compared with the control. Phosphorus moved down at least to the 40 cm depth, indicating a surprising mobility of sludge P. The greater increase in soil P at Grande Ligne and the movement through the soil profile was the result of the coarse-textured soil.

At Bearbrook, the effect of sludge treatments on soil P was smaller then at Grande Ligne. This smaller increase in soil P may have been due to clay fixation of P. But the increase in soil P was a very small proportion of applied sludge P, meaning more fixation of P. Chang et al. (1983) concluded that Al- and Fe-bound P accounted for most of the P buildup in soils.

Bates (1972) reported that P in domestic sludges was up to one half as available as that in superphosphate. Sommers et al. (1976) found 64-84% of the P (1 N HCI extractable) in sludge was present in inorganic (plant-available) form. Organic forms of P are those likely to be leached.

Sommers and Sutton (1980) reported significant increases in soil P after typical rates of sludge application to soil but many reports showed that P was relatively immobile in the majority of soils, with P remaining near the soil surface. King and Morris (1973) found in the sludge crust, high amounts of P which was available for crop uptake. Although some P did move down the profile they assumed that most P was retained in an unavailable form in the soil.

5.2.3 Potassium

Potassium in sludges was normally low with respect to N and P when considering sludge as a fertilizer (Sommers et al. 1976). This can also be seen from Table 4.1 and was one of the reasons that there was little change in soil K at both sites.

The increase in exchangeable K due to sludge and fertilizer additions in the Grande Ligne soil was due to the low CEC of the soil. Conversely, at the Bearbrook site there was no increase in soil K due to the higher quantity of K-fixing minerals or because the higher CEC resulted in a fixation of added K. The same amount of K added to each site had a greater proportional effect at Grande Ligne.

Most K in sludges was in soluble inorganic form (Olsen and Barber, 1977). This resulted in either a quick uptake by plants, or a fixation of added K in the soil so that the exchangeable K balance of the soils was not changed. Soil has a large capacity to fix K and if large amounts of K in sludge are added K may be fixed (Olsen and Barber 1977). But uptake of K by plants increased as available soil concentration increased, therefore crops absorbed larger amounts (Sheedy 1978).

5.2.4 Calcium

Sludge Ca was not applied in proportion to treatment over the plots (Table 4.1). The 200-1 treatment at Grande Ligne in 1980 received 1130 kg/ha of Ca compared with 504 kg/ha and 183 kg/ha in the 400-1 treatment in 1980 and the 200-1 treatment in 1981, respectively. This accounted for the higher soil Ca during sampling in May 1982 and September 1982 on the 200-1 treatment. At Bearbrook soil Ca was high, masking increases in exchangeable sludge Ca. It was difficult, therefore, to draw conclusions about the effect of added sludge in soil Ca.

King and Morris (1973) found no significant effect due to treatment on exchangeable Ca to 45 cm in depth. They suggested a loss of Ca was a result of formation and subsequent leaching of $Ca(NO_3)_2$ and a result of low pH. Conservely, Soon et al. (1978) found higher Ca concentration in corn and bromegrass with higher amounts of N in sludge. The acidifying effect of nitrification of sludge N probably dissolved some of the $CaCO_3$ in the soil and increased plant absorption of Ca.

5.2.5 Magnesium

Like calcium, sludge Mg was not applied evenly over plots (Table 4.1). At the Grande Ligne site Mg accumulated at the 0-15 cm depth and showed no evidence of leaching. At Bearbrook, higher inherent soil Mg values probably masked any effect of sludge application.

5.2.6 pH

The application of the sludge to the Grande Ligne soil appeared to increase soil pH. Where the Ca sludge load was high (as illustrated earlier) the soil pH increased. At Bearbrook, with greater buffer capacity in the soil, the soil pH did not increase. Acidification through nitrification was masked by other processes (i.e. more nitrification in Grande Ligne means a lower pH). This is consistent with earlier data.

Soon et al. (1978) applied a sludge high in Ca and soil pH increased significantly as a result of a low N:base ratio. King and Morris (1972) observed a drop in pH which they said resulted from nitrification of applied NH_4-N. There were insufficient bases in their sludge to offset the acidity resulting from nitrification.

5.2.7 Organic Carbon

Although organic carbon was significantly increased on both sites the decrease in bulk density meant there was really no apparent change in organic carbon. The higher amount of organic carbon found in the Bearbrook soil was consistent with previous results. Organic carbon at Grande Ligne disappeared because of better soil aeration at this site compared with Bearbrook. Miller (1974) reported that decomposition of sludge was independent of soil texture and chemical properties but was affected by moisture relations. On a sandy soil moisture did not effect the rate of decomposition but, on a clay soil, decomposition stopped when the soil was saturated.

5.2.8 Bulk Density

The relative importance of decreasing bulk density and increasing organic matter remains to be determined. The fact that bulk density decreased is not surprising. The addition of large amounts of organic matter to any soil surface would cause a dilution to the soil mass. Harding et al. (1985) found decreased bulk density when comparing sludge- and non-sludge-treated plots. This was negatively correlated with organic carbon suggesting that the residual sludge-derived organic matter accounted for the lower bulk density.

This leads to an important discussion of the value of the sludge as a physical amendment to the soil. Harding et al. (1985) reported that, as a result of increased organic matter, twice as much water was available for uptake at low moisture tensions in high-rate-sludge plots as compared with control plots.

In studies of soil physical properties when high amounts of sludge were applied Epstein (1975) and Epstein et al. (1976) found that water content and water retention of a silt loam was increased and maintained over two years. They also reported that per cent stable aggregates increased along with the increased saturated hydraulic conductivity. It appears that the benefits of adding sludge would be the establishment of a more stable soil structure which would improve water relations.

5.3 Foliage

5.3.1 Considerations in using the graphical system

Results of foliar analysis are displayed in separate graphs for each element. This technique was first used by Krauss (1965, cited by Timmer and Stone 1978). Interpretations were defined by Timmer and Stone (1978) (Fig. 3.3). They contend that interpretation of the shift depends on 1) the assumption that needle weight (in conifers) is closely correlated with response to fertilization and 2) that needle number is fixed (determinate growth pattern) in the first season when fertilizer is applied. This means that addition of fertilizer will not change the number of needles, only their weight. Increased numbers of lateral and apical shoots do not occur until the second season after fertilization. Their development contributes to the overall dilution of foliar nutrients (Timmer & Stone 1978). They reported that changes in foliar nutrient composition were generally more pronounced and more consistent in the first season after fertilization as compared with the following season. Diagnosis of the changes are easier to detect and simpler to interpret.

Poplar has heterophyllous shoots, which are not fully formed in the winter bud and expand over the season (Kramer and Kozlowski 1979). I contend that these diagnostic interpretations can be made but that growth predictions should not be attempted. I have not used the graphs for predictive purposes. Results show significant responses in some nutrients with added sludge or fertilizer. This was accompanied by significant increases in tree volume. The sludge as a fertilizer increased total foliar biomass which probably diluted nutrient content. The dilution of nutrients is evident in 1982 but there may be reasons other than increasing foliar biomass for this.

5.3.2 Dry Weight

At the Grande Ligne site in 1982, the 400 treatments had significant increases in foliar dry weight. This means that one year after application the higher sludge treatments continued to supply nutrients for tree growth.

Visual estimates of the plots showed two to three times more foliage on larger trees compared with smaller trees. This was verified by estimates of woody biomass (Table 4.15). This extra foliage in sludge treatments was the reason why dry weight on a per-leaf basis was not significantly ($p > .05$) different.

At Bearbrook foliar dry weight in fertilizer treatments was always lower than the control. It was doubtful that the chemical fertilizers inhibited growth. Declines were probably due to some other environmental factor. The responses in dry weight were similar to that of height or biomass.

5.3.3 Nitrogen

Figures 4.3 and 4.4 indicate a very high response to sludge N at Grande Ligne. Apparently soil N was limiting to growth and foliar N showed a response in concentration and content. Foliar N was believed to be the main reason for foliar dry weight increases. By 1982 the 200-

1 treatment had less foliar N than the control. Perhaps sludge N applications on this treatment were insufficient to support increased growth.

At Bearbrook there was less response in foliar N to sludge treatment than at Grande Ligne. This was reflected in lower N concentration and content. Comparison of control plots showed foliar N at Bearbrook to be higher than at Grande Ligne. At Bearbrook in 1982, dry weight accounted for 69% of the total variation of N concentration.

5.3.4 Phosphorus

As indicated in Fig. 4.6 soil P was a limiting nutrient at Grande Ligne and foliar P responded dramatically to sludge application. This response continued in 1982 in the 400 treatments. Foliar P levels at Grande Ligne in 1980 did not change as a result of treatment because the root mass was not well developed in the first year. Sludge N was more mobile and roots were able to assimilate N which resulted in higher foliar N for both sludge treatments. As well sludge P did not immediately move down the profile.

The effect on foliar P in 1981 was indicated by its weak linear relation to dry weight (r^2 = 32%). This was an indication that the trees extracted P from the soil independently of their growth and it suggested a high mobility of the element in the plant, or luxury consumption. Dry weight accounted for 56% to 86% of the total variation in other nutrient contents in both years.

At Bearbrook there was lower response to sludge treatment than at Grande Ligne. The trend of foliar P was similar to that of foliar N at Bearbrook, indicating that foliar P was more dependent on foliar N or dry weight at this site. The overall decline of foliar P in 1982 from 1981 was due to overall dilution by a greater plant mass, and a fixation of soil P by the clay minerals.

According to Grunes (1959) the addition of N fertilizers had a marked effect in the absorption of soil and fertilizer P by plants. The potential of N fertilizer in increasing the uptake of P has been known for many years. Ballard (1980) described much research that showed strong interactions between N and P fertilizers when applied at planting on P-deficient sites. Where N was combined with P, N fertilization tends to enhance the response of P fertilizer. Stone (1981) on the other hand, found many studies that showed no effect due to P when N was applied.

5.3.5 Potassium

At Grande Ligne the most obvious effect of foliar K was luxury consumption in fertilizer treatments. This was because N and P were applied in smaller amounts in the fertilizer relative to sludge application. Fertilizer K was probably a more soluble source of K than in sludges. Foliar K was not masked to the same extent as in the sludge treatments. This also indicated that soil K was not limiting on this site. But, with higher amounts of sludge N and P added, more K may be required in the soil to maintain growth and nutritional balance.

At Bearbrook where there was higher amounts of soil K, and indications on the graph of antagonisms or dilutions, K was not considered a nutrient limiting to growth.

According to Stone (1981) K is efficiently recycled in forest stands. He showed that 23 years after application K continued to circulate in tissue. Leaf (1968) pointed out that although K may leach easily from agricultural soils, where trees are present, leaching of K beyond the effective tree rooting zone may be much less. In contrast to non-mobile Ca, fixed in the organic matter structure, K may be re-cycled several times to one such Ca cycle.

5.3.6 Calcium

At Grande Ligne in 1980 and 1981, the application of sludge resulted in a decrease in foliar Ca with increased levels of sludge. This means that there were higher levels of sludge and foliar N and, coincidently, decreasing levels of sludge Ca (Table 4.1). The higher amount of sludge Ca in treatment 200-1 offset the effect of sludge N so that it had the same N:Ca ratio as the control. The overall increase in foliar Ca, particularly in Ca content in 1982, resulted from the overall decline in foliar N. The explanation for this dilution of Ca is provided by Schomaker (1969). The dilution of foliar Ca was a common result of N additions to the soil. This was reported by Cain (1959) for fruit trees and by Sheedy (1978) in a similar clone of *P. deltoides* cv. 'angulata' X *P. trichocarpa*.

At Bearbrook there was no dilution of foliar Ca as a result of sludge or fertilizer additions. Foliar Ca in control plots was less than in treatment plots. Perhaps the higher inherent soil Ca was the reason for this. Lack of significant results made it difficult to draw further conclusions.

5.3.7 Magnesium

While there were differences in foliar Mg due to sludge treatments, generally Mg was sufficient to maintain growth. While foliar Mg did not show the same degree of dilution as Ca, there was strong linear correlation between Mg and Ca at both sites in both years. Correlation coefficients of Ca and Mg concentration ranged from r = .77 to .95. Coefficients of Ca and Mg content ranged from r = .88 to .98. Foliar Ca and Mg reacted similiarly in this experiment and it appeared that factors controlling foliar Ca have the same effect on foliar Mg. Sheedy (1976, 1978) found that increased N concentration caused decreases in concentration of Mg as well as Ca in hybrid poplars. Cain (1959) and Van den Driessche (1974) reported that the effect of K fertilizer in decreasing foliar Mg is widely recognized.

5.4 Tree Growth

The addition of large amounts of sewage sludge increased hybrid poplar yield at Grande Ligne by a difference of 246% over the control. The benefit from this high amount of nutrients added to the impoverished Grande Ligne site to increase yield can not be overemphasized. At the Bearbrook site, the addition of sludge did not significantly increase tree growth. The main reason for the different growth responses was due to soil reactions after sludge was applied.

The Grande Ligne soil had good aeration, coarse texture, and lack of nutrients and was able to retain the sludge nutrients in a form available for tree growth. Sludge supplied nutrients raised pH slightly and may have improved water relations and soil structure. At Bearbrook soil properties did not change enough as a result of sludge additions to significantly affect growth. This soil may have immobilized the sludge nutrients because of the high clay content. The imperfectly drained soil also did not allow much loss of sludge nutrients. Other cultural practices such as drainage or ditching might have increased growth. In his literature review Ogar (1981) quoted sources which concluded that NK fertilizers were beneficial only on poor soils which were impoverished by agronomic cropping.

Very few studies to test the effect of sewage sludge on hybrid poplar growth have been documented. MacIntosh et al. (1984) in Maryland found significant height increases in hybrid poplar treated with composted sludge. Cooley (1979) and, Kerr and Sopper (1982) also reported significant increases in growth of hybrid poplar following sludge applications.

Table 5.1 compares other hybrid poplar grown at similar spacings with this research. Yield on my control plots was slightly lower than others in the Table. According to Barkley's guidelines (1983) both Grande Ligne and Bearbrook would be considered not suitable soils for optimum poplar growth. Biomass data from Evers et al. (1983) were lower because of the wider tree spacing. Nevertheless the 400-2 treatment at Grande Ligne has provided much greater growth.

Correlation data showed no constant significant linear relations between height growth and soil or foliage characteristics. Studies of poplar nutrition at Queen's University, Kingston, showed very few linear correlations between foliage data and tree growth (J.S. Poland, 1986, personal communication). On the other hand, in conifers, Timmer and Morrow (1984) showed correlations between first-year-needle weight and growth variables such as basal area or volume.

Comparison of tree height and yield in control plots at both sites revealed that tree growth after three years was better at Bearbrook than at Grande Ligne. This was despite the fact that tree growth at Grande Ligne was better than at Bearbrook in the year of establishment (Tables 4.14 and 4.16). It seemed that trees at Bearbrook needed more time to establish a root system. Once established, they appeared better able to take advantage of the greater nutrient supply. Barkley et al. (1983a) showed that growth rates change over the years. On one site, trees may be quickly established and then may slow in their growth, while on a another site, trees may grow slower in the beginning and, as the roots become established, grow at a faster rate.

In 1982 at Grande Ligne there was an overall decline in tree height and a dilution of foliar nutrients. Factors that may have affected the decline include the weather, depletion of nutrients by uptake, or root growth beyond plots.

Table 5.1 Growth parameters of hybrid poplar after three years.

Location and Clone	Spacing (mxm)	Height cm	Biomass Mg/ha	Sources
E. Ontario[a] - I45/51	3.6x3.6	523	1.88	Evers et al. (1983)
E. Ontario[a] - I45/51	3.0x3.0	502	1.37	"
E. Ontario[a] - DN17	3.0x3.0	502	2.06	"
E. Ontario[a] - DN17	3.0x3.0	574	1.96	"
S. Ontario[b]	3.0x1.5	305	-	Von Althen (1981)
Wisconsin - Tristis-1	2.0x2.0	-	2.7	Zavitkowski (1983)
Montreal Region[c]				
3050[d]	1.2x3.0	300	-	Vallée (1984)
3053[e]	1.2x3.0	308	-	"
Bearbrook	2.0x2.0	308	2.4[f]	Control
"	"	340	3.2[f]	Best (200-2)
Grande Ligne	"	280	2.1[f]	Control
"	"	404	7.4[f]	Best (400-2)

[a] Weight OD of whole trees including leaves. Clones are on two different sites.
[b] Average of many clones.
[c] On clay soil; fertilized with P.
[d] Clone 3050 is clone used in this study.
[e] 3053 is a different clone from the same parents.
[f] Potential yield from this study.

Precipitation data from Grande Ligne showed a 60% reduction in rainfall in 1982 from 1981 (Appendix A). This lack of rain is particularly evident in June and August and probably contributed to the overall growth reduction in 1982. Another factor to consider in overall decline in growth and nutrient uptake in the third year was spacing. By the third year trees on sludge-treated plots (2.0x2.0 m spacing) were "rubbing shoulders" with much branch overlap. Ogar (1981) suggested that trees older than two years require a spacing of more than 1.8x1.8 m to achieve the greatest attainable dry weight. Three-year-old trees would, therefore, be competing for nutrients at 2.0x2.0 m spacing. A third factor was root spread. Hansen (1981) observed a maximum root length of 2.2 m for one-year-old trees and 5.2 m for three-year-old trees. For a 1.2 m spacing (on irrigated plots) he showed a border effect of at least two to three meters.

In this study there may have been a slight edge effect during the third year which could affect yield estimates. Observations of the five-year growth in 1984 at Grande Ligne showed border trees leaning out beyond the plots implying that they were crowded, and roots were probably extending to other plots.

In 1982 there was also a major decline in tree height growth on the 200 treatments at Grande Ligne. After three years the 200 treatments may have been running out of sludge-supplied nutrients. It can not be explained why tree growth on these treatments is less than the control. Ballard (1980) reported that hand-applied spot applications of chemical fertilizer rapidly decline in effectiveness. This is attributed to a decreasing proportion of the expanding root system in contact with the fertilizer-enriched zone and the "drying out" of the fertilizer-enriched zone due to intensive rooting activity.

Chapter 6. Summary and Conclusions

Municipal sewage sludge is a waste material rich in nutrients (although low in K). It has a proven ability to enhance soil properties and increase growth of tree crops. The nutrient content of sludge varies on a seasonal basis and must be monitored to determine the nutrient content before application.

At Grande Ligne soil properties were strongly affected by sludge application, but at Bearbrook, soil properties were not affected to the same extent. Soil nutrient values at Bearbrook were higher than at Grande Ligne before sludge additions and these did not cause much change to soil properties.

Mineralization, nitrification, and probably volatilization of sludge N were more pronounced on the coarse-textured, well-aerated Grande Ligne site. At Bearbrook there was probably less loss of N due to volatilization and nitrification because N was fixed in the clay minerals. Leaching of NO_3-N was noticeable below 15 cm at both sites. At Grande Ligne, soil P was increased by seven-fold in the 400-2 treatments. Phosphorus also leached down the profile. At Bearbrook soil P increased only two-fold after sludge applications and showed little evidence of leaching. Soil K did not change much after sludge addition, partly because of the small amount of K in sludge and, because of quick uptake by trees at Grande Ligne, or because of K fixing minerals at Bearbrook. Levels of Mg at Grande Ligne doubled in the soil at 0-15 cm but there was no leaching below 15 cm. No changes in Ca were detected at Grande Ligne and Bearbrook. Soil pH increased slightly at

Grande Ligne with higher amounts of sludge Ca. There were no changes in Ca, Mg, and pH at Bearbrook due to the buffering capacity of soil. Percent organic carbon increased at both sites but because of the decrease in bulk density there was no apparent change in organic carbon. There were very few changes in the soil due to fertilizer treatment.

The graphical technique of showing dry weight, concentration, and content on the same graph made diagnosis of nutrient status relatively simple. Foliage nutrients responded significantly to sludge additions at the Grande Ligne site and to a lesser extent at Bearbrook. Dry weight changes on a per-leaf basis were not obvious because overall tree growth caused a dilution of nutrients. At Grande Ligne both N and P were diagnosed as limiting to tree growth. The foliar response to sludge treatment was high, particularly to P. At Bearbrook increases in foliar N and P were not significant. Foliar K was not limiting on either site but at Grande Ligne large additions of N and P may cause a relative shortage of K. Fertilizer treatments showed luxury consumption of K at Grande Ligne. Foliar Ca was diluted by increased growth at Grande Ligne. There was no dilution of Ca at Bearbrook. Magnesium was considered to be non-limiting at both sites and seemed to be effected by the same factors that affected foliar Ca.

At Grande Ligne tree height was not significantly affected by sludge treatments in 1980, but produced significant height growth increases in the 200 and 400 treatments in 1981, and in the 400 treatments in 1982. After three years only trees in treatment 400 showed significantly more growth than trees in the control. Trees in treatment 400-2 were 44% taller than trees in the control. Stump diameter growth showed a more dramatic difference due to treatment than height growth. At Bearbrook height growth was significantly affected by sludge treatments in the first year. Thereafter, height of trees between sludge treatments and the control were not significantly different. Treatment 200-2 had the best growth but it was only 10% more than the control. Tree heights in fertilizer treatments were significantly less than in sludge treatments.

Potential yield at Grande Ligne in treatment 400-2 was 7.38 Mg/ha compared with 2.13 Mg/ha in the control, a difference of 246%. But at Bearbrook the 200-2 treatment, which had the best growth, had a potential yield of 3.24 Mg/ha a 35% increase over the control. These differences in height and yield are a result of the sludge-soil interactions. Mean height growth of each of the treatments declined at Grande Ligne in 1982. This was probably the result of lower rainfall in that year. Height growth in the 200 treatments was less than control in 1982 possibly because the trees had outgrown the nutrient source supply.

Chapter 7. Proposals for Future Research Activities

In order to provide for a coordinated effort a team of scientists from the Quebec Ministry of the Environment and the Ministry of Energy and Resources should be formed to set up a program of research to study forest land application of sewage sludges and effluents.

This team would set up pilot studies in many communities across the province to ensure there is a number of sewage treatment plants and, soil and forest types from which to obtain results. At least four different rates should be applied to determine the capacity of the site for waste disposal. Sewage applications should be monitored for at least ten years to determine long-term effects on the study sites.

At each location the team would;

a) study systems of applying effluents and sludges to forest land,

b) monitor soil reaction and properties,

c) monitor groundwater for NO_3-N and P movement,

d) study the effects on vegetation and particularily on tree growth,

e) monitor pathogens, and,

f) when industrial sludges are used, monitor heavy metal movements.

From a scientific viewpoint micronutrient reactions and pathways could be studied in the forest vegetation. Almost no research has been done on this topic.

Finally, public reaction should be studied and if necessary programs devised to educate the public about the range of benefits of sludge disposal on forest land.

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Appendix A. Precipitation data

Grande Ligne

Month	Year 1980	1981	1982
	cm		
May	nd	5.0	2.0
June	3.4(5)[1]	16.6	7.8
July	8.4	7.6	9.4
August	18.3	22.3	9.8
September	12.0	14.7(24)	9.8
October	4.9	nd	2.5(14)
Total	47.0	66.2	41.3

Bearbrook

Month	Year 1980	1981	1982[2]
	cm		
May	nd	9.7	5.9
June	2.8(5)	13.2	12.1
July	14.9	8.1	5.5
August	5.8	11.0	12.9
September	13.8	10.8(24)	7.1
October	7.5	nd	3.8
Total	44.8	52.8	47.3

[1] Number in brackets is the day of the month recording began or ended.
[2] Data from Ministére de l'Environnement du Québec.
nd Not determined.
(from MacRae, 1983).

Appendix B. Sewage sludge analysis from Vaudreuil treatment plant - 1983 (Source Ministère de l'Environnement du Québec).

STATION: VAUDREUIL (boues aérobies)

PARAMETRE / DATE	83-09-21	83-10-12			
Matière totale	61140	18590		mg/L	
Matière totale volatile	31900	9920		mg/L	
Matière dissoute	2040	1590		mg/L	
Matière dissoute volatile	1100	720		mg/L	
pH	7,6	7,9		---	
NTK (Azote total)	36068	---		mg/kg	N
$N-NH_4$ (Azote ammoniacal)	17799	---		mg/kg	N
$N-NO_3+NO_2$ (Nitrates + Nitrites)	38,4	366,3		mg/kg	N
Phosphore total inorganique	1695	---		mg/kg	P
Phosphore total	7460	69304		mg/kg	P
Aluminium	40599	40237		mg/kg	Al
Arsenic	3,86	4,2		mg/kg	As
Baryum	527	585		mg/kg	Ba
Bore (1)	51,6	153,3		mg/kg	Bo
Cadmium (2)	9,7	9,1		mg/kg	Cd
Mercure	5,7	2,9		mg/kg	Hg
Molybdène	29,0	23,8		mg/kg	Mo
Nickel	145,0	77,7		mg/kg	Ni
Plomb	193	219		mg/kg	Pb
Potassium	2588	4051		mg/kg	K
Sodium	9069	14266		mg/kg	Na
Calcium	15007	17214		mg/kg	Ca
Chrome	96,7	82,3		mg/kg	Cr
Cuivre	335	368		mg/kg	Cu
Fer	14575	12899		mg/kg	Fe
Magnésium	4839	6143		mg/kg	Mg
Manganèse	729	809		mg/kg	Mn
Zinc	623	503		mg/kg	Zn
Sélénium	1,9	4,0		mg/kg	Se

Appendix C. Means of foliar nutrient parameters

Appendix C1. Foliar nutrient concentrations for all treatments on Grande Ligne site in 1980.

Treatment Sewage sludge (Mg/ha)	N	P	K	Ca	Mg
	Concentration (%)				
			**		**
0	2.21	.23	1.32	.89	.33 d[1]
200	2.39	.23	1.22	.89 c	.34 cc
400	2.44	.23	1.31	.71 f	.26 ff
Fertilizer	1.99 bb	.21	1.27	.81	.32

[1] See inside back cover for contrast statement codes.

Appendix C2. Foliar dry weight, and nutrient concentration and content of hybrid poplar for all treatments on Grand Ligne site in 1981.

Treatment Sewage sludge (Mg/ha)	Dry Weight mg/leaf	N	P	K	Ca	Mg
		Concentration (%)				
			*			
0	1774	1.82 add[1]	.22aadd	1.30	.83 aad	.26
200-1	2056	2.06 c	.30 ee	1.41	.74 e	.26
200-2	2183	1.94	.37 g	1.50	.57 g	.23 g
400-1	1957	2.19 ff	.36 ff	1.52	.67 f	.28
400-2	2032	2.29	.39	1.62	.61	.26
Fertilizer						
1	1804	1.96	.25 bb	1.58	.63 j	.25
2	1646	1.91	.26	1.60	.57	.23

Treatment Sewage sludge (Mg/ha)	N	P	K	Ca	Mg
	Content mg/leaf				
0	32.29	3.90add	23.06	14.72	4.61
200-1	42.35	6.17 e	28.99	15.21	5.34
200-2	42.35	8.08 gg	32.75 g	12.44	5.02
400-1	42.86	7.04 f	29.75	13.11	5.48
400-2	46.53	7.92 hh	32.92	12.39	5.28
Fertilizer					
1	35.36	4.51 b	28.50	11.36	4.51
2	31.44	4.28	26.34	9.38	3.79

[1] See inside back cover for contrast statement codes.

Appendix C3. Foliar dry weight, and nutrient concentration and content of hybrid poplar for all treatments on Grande Ligne site in 1982.

Treatment Sewage sludge (Mg/ha)	Dry Weight (mg/leaf)	N	P	K	Ca	Mg
		Concentration (%)		*		
0	2210	1.86	.18 ad[1]	1.20	1.18	.37
200-1	1812 c	1.77	.20 c	1.00 cc	1.20 c	.42 c
200-2	1863	1.97	.21 g	1.15	1.17	.40
400-1	2689	2.18	.26 ff	1.51 f	.78 f	.32
400-2	3057	1.89	.27	1.56	.80	.31
Fertilizer						
1	1565	1.94	.19 ii	1.30	.94	.34
2	2097	2.05	.21	1.47	.84	.32

Treatment Sewage sludge (Mg/ha)	N	P	K	Ca	Mg
	Content (mg/leaf)		*		
0	41.10	3.98	26.52	26.08	7.96
200-1	32.07 c	3.62 cc	18.12 cc	21.74	7.61
200-2	36.70	3.91	21.42	21.80	7.45
400-1	58.62	6.99 f	40.60 ff	20.98	8.60
400-2	57.78	8.25 h	47.69	24.46	9.48
Fertilizer					
1	30.36	2.97 i	20.34	14.71	5.32
2	42.99	4.40	30.82	17.61	6.71

[1] See inside back cover for contrast statement codes.

Appendix C4. Foliar dry weight and nutrient concentration and content for all treatments on Bearbrook site in 1981.

Treatment		Concentration				
Sewage sludge (Mg/ha)	Dry Weight mg/leaf	N	P	K	Ca	Mg
		(%)				
0	1935	2.07	.26	1.22	.91	.38
200-1	2181	2.03	.26 g[1]	1.23	.88	.38
200-2	2352	2.15	.28	1.21	.86	.36
400-1	2176	2.16	.26	1.06	1.03	.41
400-2	2378	2.13	.27	1.06	.92 hh	.38
Fertilizer						
1	1415 bb	1.91	.23 b	1.07 i	.96	.41
2	1483	1.94	.22	1.00	1.03	.45

Treatment	Content				
Sewage sludge (Mg/ha)	N	P	K	Ca	Mg
	mg/leaf				
0	40.05	5.03	23.60	17.61	7.35
200-1	44.27	5.67	26.83	19.19	8.28
200-2	50.57	6.58	28.46	20.23	8.47
400-1	47.00	5.66	23.06	22.41	8.92
400-2	50.65	6.42	25.21	21.88	9.04
Fertilizer					
1	27.03 b	3.25 bb	15.14 b	13.58	5.80
2	28.77	3.26	14.83	15.27	6.67

[1] See inside back cover for contrast statement codes.

Appendix C5. Foliar dry weight and nutrient concentration and content for all treatments on Bearbrook site in 1982.

Treatment		Concentration				
Sewage sludge (Mg/ha)	Dry Weight mg/leaf	N	P	K	Ca	Mg
		(%)				
0	1816	1.99	.21	.99	1.07	.43
200-1	1450	1.91	.19 c[1]	.81	1.10	.49
200-2	1418	2.08	.19	.76	1.13	.51
400-1	2033	2.10	.21	.94	1.08	.42
400-2	1831 h	2.16	.22	.92	1.09	.42
Fertilizer						
1	1534	1.82 b	.19	.85	1.03	.44
2	1434	1.86	.20	.85	1.11	.47

Treatment	Content				
Sewage sludge (Mg/ha)	N	P	K	Ca	Mg
	mg/leaf				
0	36.14	3.81	17.98	19.43	7.81
200-1	27.70	2.76	11.75	15.95	7.11
200-2	29.49	2.69	10.78	16.02	7.23
400-1	42.69	4.27	19.11	21.96	8.54
400-2	39.55	4.03	16.85	19.96	7.69
Fertilizer					
1	27.92	2.91	13.04	15.80	6.75
2	26.67	2.87	12.19	15.92	6.74

[1] See inside back cover for contrast statement codes.

Appendix D. Mean of tree heights

Appendix D1. Mean height growth for three years and cumulative heights after two and three years at Grande Ligne site.

Treatment	1980	1981	1982	Sum[1] 1980 and 1981	Sum 1980, 81 and 82
Sewage sludge (Mg/ha)	(cm)				
0	95	104 add[2]	77	202 d	280
200-1	98	134 e	67 c	235	302
200-2		159 gg	60	254 g	314
400-1	100	146	113 f	241	354 f
400-2		169 hh	132	272 hh	404 hh
Fertilizer					
1	102	107 b	67	207	274
2		120	74	223	302

1 Sums do not total across the years due to missing values.
2 See inside back cover for contrast statement codes.

Appendix D2. Mean height growth for three years and cumulative heights after two and three seasons at Bearbrook site.

Treatment	1980	1981	1982	Sum[1] 1980 and 1981	Sum 1980, 81 and 82
Sewage sludge (Mg/ha)	(cm)				
0	65 aadd[2]	122	119	187	308
200-1	76 ccee	125	100	197	297
200-2		139	119	222 gg	340 gg
400-1	88 ff	124	107	214	327
400-2		128	110	213	323
Fertilizer					
1	67 bb	87 bbj	95	154 bbj	253 b
2		90	103	154	256

1 Sums do not total across the years due to missing values.
2 See inside back cover for contrast statement codes.