EFFECTS OF PAPER MILL SLUDGE ON TREE GROWTH AND COMPETITION IN YOUNG RED PINE PLANTATIONS

by

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(Abstract)

The disposal of pulp and paper industry sludge has become a significant problem in recent years. Increasing costs and regulatory constraints associated with landfilling and incineration have caused the industry to look for viable alternatives for the disposal of their wastes. In September of 1988, a nutrient-enriched, combined (primary/secondary) paper mill sludge was surface applied to a 4-year-old and a 6-year-old red pine (*Pinus resinosa* Ait.) plantation in central Wisconsin at rates of 10, 20 and 40 dry Mg ha $^{-1}$. Red pines measured 10 and 22 months following sludge application did not show a significant volume growth response to increasing sludge rates. Nonetheless, some biologically significant trends did occur following the first growing season, namely, diameter growth in the younger plantation decreased by 27%, 36% and 39% with increasing rates of sludge application. Reductions in height, crown width and volume growth were seen as well. Increased absorption of moisture among the heavier application rates coupled with already dry conditions is believed to be the cause of the growth reduction. Tree growth in the older plantation was more variable, possibly reflecting the greater degree of establishment and reduced susceptibility to moisture deficits. By the end of the second growing season, there was some indication that the trees were responding to sludge application in both plantations, with the greatest growth occurring among the 40 Mg ha $^{-1}$ treatment plots for all growth parameters. Red pine fascicles examined 12 months following sludge application showed significant increases in foliar concentrations of N, P, Ca, Mg and S with increasing rate of sludge application. This corresponded with

a significant increase in fascicle biomass relative to application rate in the younger plantation. Fascicle biomass was not affected by sludge application in the older plantation. Analysis of nutrient response, in general, indicated luxury consumption taking place among all nutrients with the exception of boron, which decreased in foliar concentration, to low or deficient levels, and content in sludge amended plots in both plantations. Analysis for nutrient concentrations and dry matter production of *Carex* spp. (sedge), the predominant herbaceous understory component, showed increasing foliar N levels with sludge application 21 months following treatment in above-ground tissue, with a corresponding increase in above-ground biomass relative to controls of 22%, 33% and 85% among the 10, 20 and 40 Mg/ha treatments, respectively. An assessment of woody vegetation using a competing vegetation assessment system (CVAS) showed essentially no response by hardwood competition to sludge application for either study site. Total weed control, consisting of 0.140 kg ha $^{-1}$ a.i. of Oust ^{tm} and 1.3 kg ha $^{-1}$ a.i. of Garlon ^{tm} was performed in August of 1989 and resulted in significantly reduced coverage of herbaceous and woody competing vegetation in both plantations the following growing season. Analysis of red pine volume growth between weed control treatments did not show a significant response relative to sludge application for either plantation one year following herbicide application. Additionally, there was evidence of reduced weed control efficacy with increasing sludge application rate in the younger plantation. This suggests that weed control efficacy may be greater if weed control is performed prior to sludge application; however, given the apparent sequestering ability of the herbaceous vegetation, removal of this component may contribute to elevated levels of undesirable leachates in soilwater and groundwater.

Acknowledgements

"Any science may be likened to a river. It has its obscure and unpretentious beginning; its quiet stretches as well as its rapids; its periods of drought as well as of fullness. It gathers momentum with the work of many investigators and as it is fed by other streams of thought; it is deepened and broadened by the concepts and generalizations that are gradually evolved."

Prof. Carl P. Swanson

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I dedicate this thesis, and the commitment it represents, to Janet and Benjamin, and to my mother, and father-in-law, who's immeasurable strength and courage during the last two years has allowed me to keep everything in its proper perspective.

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Introduction

The disposal of paper-industry sludge, a necessary bi-product of the paper-making process, has become a significant problem in recent years. Increasing demands for pulp and paper products have given rise to increased production of paper industry wastes. For example, in 1980 a group of seven paper and pulp mills located along an 80 km section on the upper Wisconsin River produced 200 metric tons (Mg) of dry sludge per day (McGovern et al., 1983).

Currently, the major sludge management alternatives include incineration (thermal conversion), landfill, and land application. Various techniques for processing sludge into products (e.g., soil amendments, organic fertilizer, dried bulking agents, fuel materials, aggregate clay tile, and bricks) are available, but most of them eventually involve some form of combination of land disposal, land application or incineration. In view of the intensive costs and the regulatory and economic constraints associated with landfilling and incineration, land spreading of sludge has become an attractive alternative. The ultimate goal of landspreading mill sludge, or municipal sludge for that matter, is to dispose of the nutrient and heavy metal load. This must be accomplished in such a manner so that the ecosystem components can assimilate the elements applied, thereby avoiding groundwater contamination, impairment of biological reducing capabilities, and long-term environmental degradation.

Utilization of mill sludge produced as a result of treatment of industrial wastewater is strongly encouraged by Congress and the Environmental Protection Agency (EPA). Currently, there are five principal statutory authorities which specifically address the land application of sludge. These include the Clean Water Act (CWA) of 1977, the Resource Conservation and Recovery Act (RCRA) of 1976, the Safe Drinking Water Act (SDWA) of 1975, and the National Environmental Policy Act (NEPA) of 1969 (Peter, 1981). In particular, the CWA supports waste treatment management that results in the recycling of potential pollutants through agricultural, silvicultural, and aquacultural products. A formal policy regarding sludge management issued by the EPA in June of 1984 stated that the agency will actively promote "sludge management practices that provide for the beneficial use of sewage while maintaining or improving environmental quality and protecting public health" (Bastian, 1986).

Landspreading of paper industry sludge, in keeping with the objectives of the CWA, offers an alternative in waste management. Generally, paper industry sludge contains no harmful pathogenic organisms and has very low concentrations of heavy metals and persistent hydrocarbons, as compared to many municipal waste products. Improvement in soil properties such as organic matter content, cation exchange capacity and water holding capacity can be attributed to landspreading of sludge (Simpson et al., 1983; Thiel, 1984; Einspahr et al., 1984). Mill sludge has been shown to be successful in promoting vegetation establishment on strip mine spoil (Shoemaker and Dickinson, 1979; Hoitink and Watson, 1980). Furthermore, sludge serves as a potential source of essential nutrients. Paper mill sludges in particular are effective "slow release" fertilizers in that much of the nutrients are associated with the lignin component of the cellulose fibers, which decomposes very slowly.

While there are many beneficial aspects associated with landspreading of these wastes, potential disadvantages do exist and have been the subject of much research and controversy as well as public concern. The major environmental concerns are as follows: 1) sludge application rates which exceed the assimilatory capacity of the soil may contribute to high concentrations of undesirable leachates in the groundwater; 2) soil aeration may be reduced where the sludge is excessively loaded on the site; and 3) contaminants associated with sludge can be taken up by plants and enter the food chain. Further concern stemming from a forest management standpoint is associated with the potential increase in competing vegetation biomass. Recent work on landspreading of these wastes has shown that through careful consideration of soil type, cropping program and sludge loading rates, many of these potential problems can be eased or eliminated altogether.

In light of the aforementioned advantages and concerns, Nekoosa Papers Inc.

(presently a division of Georgia Pacific Corp.) of Port Edwards, Wisconsin is interested in establishing a sludge disposal program in young red pine (*Pinus resinosa* Ait.) stands.

The specific objectives of this study were to: (1) determine the growth and nutritional response of red pine to four application rates of a primary/secondary paper mill sludge, (2) determine the response of the herbaceous understory in terms of above- and below-ground dry matter production and nutrition, (3) determine the response of developing competing vegetation, and (4) determine the response of red pine growth and competition to complete weed control on the treated areas.

Literature Review

Paper Mill Waste Production

The production of pulp and paper products results in the subsequent production of large amounts of wastes in gaseous, liquid and solid forms. Figure 1 illustrates the fundamental pulping and paper-making processes and associated liquid and solid wastes (Nemerow, 1978). Gases evolve from the stacks of steam and power generating plants, pulping digesters, recovery evaporators and furnaces (Billings and DeHass, 1971). Gas scrubbers, electrostatic precipitators and various other methods remove potential contaminants from the gaseous effluent. Solid wastes formed during chemical makeup and recovery, which include fly ash and precipitates, are typically collected and incinerated and/or landfilled with minimal or no treatment (NCASI, 1979).

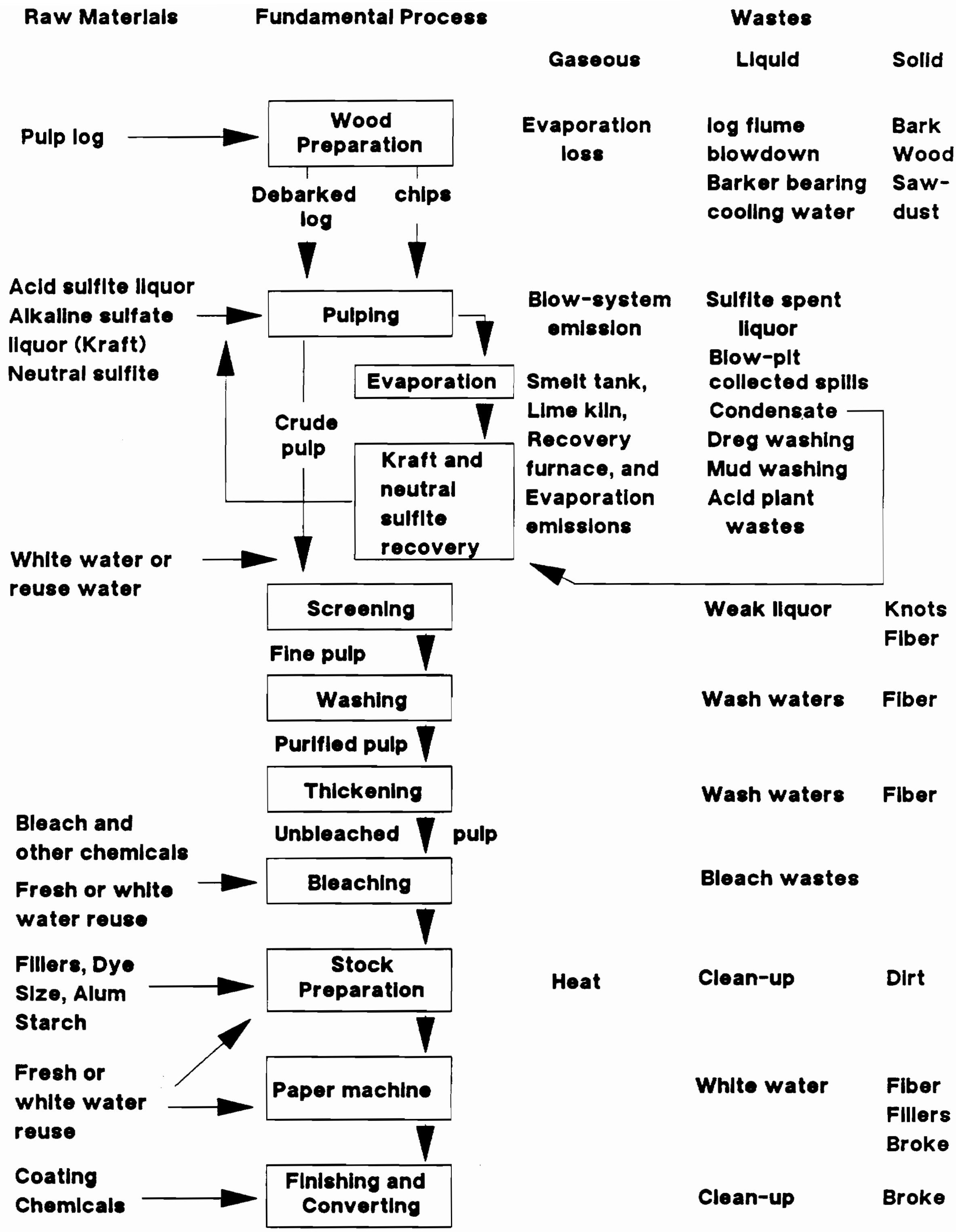

Figure 1. Fundamental pulp and paper-making process and associated wastes (Nemerow, 1978)

The remaining liquid fraction accounts for the greatest quantity of wastes and is directly associated with the large amounts of water used by the pulp and paper industry. Water serves as a reactant, reaction media and coolant, as well as a means of conveyance for raw materials, by-products and wastes (Huettle, 1982). Various steps in the production of pulp and paper result in liquid waste production. These are attributable to the extractive nature of the pulping and papermaking process. Examples of specific waste streams include spent pulping liquors, pulp wash water, bleach plant effluent, and white water from papermaking.

The quantity and strength of raw mill wastewater is a function of mill type and mill operating practices such as the degree of water reuse. Recycling reduces the quantity of wastewater discharged, and about 5% of the mills, mostly those that produce paperboard from wastewater, are described as "closed" or "self-contained" because they reuse essentially all of their process wastewater. In general, water is recycled an average of three times, each time resulting in less purity, until excessive buildup of non-recoverable solids such as cellulose fibers, coating material, fillers, adhesives, and pulping and bleaching chemicals justifies sewering (Timpe et al.,1973). Water reuse beyond an acceptable degree of contamination (approximately 1% solids), which varies with the type of paper produced, may threaten the quality of the product and may have corrosive or abrasive effects on equipment (Modani and Holly, 1973; Gehm, 1973). Typically, the flow for mills that discharge process wastewater can vary from less than 2.1×10^4 to approximately 4.2×10^5 liters per Mg (tonne) of production (U.S. EPA, 1982; NCASI, 1983).

Sewered effluent is treated for the removal of dissolved and suspended solids via primary (flotation and sedimentation) and secondary (biological) treatment. The recent trend toward tertiary waste treatment has resulted in reduced nutrient levels in discharged effluents where dissolved organics and suspended solids not removed in secondary treatment are of concern. As a result of treatment, the solids removed from the wastewater create a nutrient rich, aqueous-solid residue referred to as "wastewater sludge".

The annual production of wastewater sludge from the U.S. pulp and paper industry is approximately 2.2×10^6 dry Mg or 4.5×10^7 wet Mg prior to dewatering (NCASI, 1979). Approximately 1.9×10^6 dry Mg per year are primary and the remainder is biologically treated secondary sludge.

Sludge Characteristics

Organic Fraction

The organic fraction of solids in primary paper mill sludge is composed mainly of wood fiber, or grit from debarking and pulping. Additionally, various quantities of inorganic paper-making additives are present depending on the product being produced. In contrast, secondary mill sludge tends to be low in solids (gelatinous) and is composed primarily of microbial biomass. Secondary sludge resembles the domestic sewage sludge in many respects and is considered a low-cost source of nitrogen and phosphorus fertilizer. Abrosimova et al. (1976) described a secondary sludge as fine fibers and aggregates of bacteria, yeasts, mold, fungi and simple invertebrates, and having 2-7% N, 2-4% P, .2-.5% K, microelements, biostimulants, amino acids, ferments and vitamins. Typically, primary and secondary sludges are mixed by many mills to increase the overall rate of decomposition and fertilizer value of the sludge.

Ash and Solids Composition

Sludge produced by paper mills which manufacture de-inked and fine printing and writing papers and coated paperboard are typically considered "high ash sludge" (50-70% ash on a dry weight basis). Sludge produced from groundwood pulping processes generally contains less than 20 percent ash, while chemically digested pulps range from 20-50 percent ash content (NCASI, 1979). The ash in such cases is mainly kaolin clay, which is required in the coating process used to produce high quality paper and paper products. These sludges can be particularly beneficial when applied to coarse textured soils because of their ability to enhance soil properties.

Solids and ash content will vary dramatically depending on the type of pulping process and product manufactured. Joyce et al. (1979) studied the ash composition of primary sludge from 10 pulp and paper mills chosen as representative of the industry (Table 1). Results showed that an average of 35 percent of the sludge was retained on a 150-mesh screen. Microscopic examination showed this to be almost entirely cellulose fiber. The finer fraction passing through the 150-mesh screen contained 40 percent ash, representing 90 percent of the total ash content of the

Table 1 - The daily accumulation and solids composition of primary sludges generated at mills representative of the paper industry in the U.S. (Joyce et al., 1979).

Type of mill	Source of raw material	Net production	Ash	Total weight <150 mesh	Total organic weight <150 mesh
		metric tons/day	%	%	%
1. Deinking	wastepaper	90	41	84	73
2. Chemi-mechanical	mixed northern hardwood	180	23	62	51
3. Kraft	mixed softwoods	360	33	64	52
4a. Kraft (paper)[1]	mixed softwoods	160	5	17	15
4b. Kraft (pulp)	mixed softwoods	160	40	94	90
5. Kraft, groundwood	67% mixed softwoods, 33% mixed hardwoods	90	36	51	25
6. Groundwood, deinking	40% poplar, 60% spruce-balsam	150	46	81	69
7. Kraft, groundwood	mixed pine and hardwoods	1,350	11	50	47
8. Groundwood	20% aspen, 40% spruce, 40% balsam	55	4	24	22
9. Kraft	Southern pine	1,050	23	55	44
10. Kraft	90% Southern pine 10% Southern hardwood	975	27	59	45
		Average	26	58	48

[1] 4a and 4b are paper and pulp sludges, respectively, of the same mill.

sludge. The inorganic finer fraction was mainly parenchyma cells, tracheids and vessel elements.

Heavy Metals and Soluble Salts

Paper mill sludges tend to be consistently lower in heavy metal concentrations than industrial and municipal sludge. Thacker (1986) reported that the mean levels of arsenic, cadmium, chromium, cobalt, copper, mercury, molybdenum, nickel, lead, zinc, selenium and tin are substantially lower in pulp and paper mill sludge than in their municipal counterparts (Table 2). Only in the case of aluminum is the mean greater in mill sludge than in municipal sludge. Rock and Beyer (1983) associated high aluminum levels with the use of clays for coated papers and aluminum salts used in the coagulation of wastewater solids. Sludge found to be relatively high in heavy metal concentrations have often been associated with de-ink and wastepaper mills; however, not all sludges produced by these mills are high in these elements.

Several short-term studies by Simpson et al. (1983), Hermann and Gilbert (1982), Jacobs (1978), and Huettle (1982), have examined the uptake of heavy metals and other elements by agricultural crops grown in soils amended with mill sludge. These studies clearly demonstrate that application of these sludges do not result in any adverse levels of heavy metals being absorbed into plant tissue.

High sodium or total salt levels have been reported in some pulp and paper mill sludges. Buchanan (1978) reported minimal permeability in a clayey soil that received liquid mill sludge having a sodium concentration of 50,000 mg/dry kg.

Table 2 - Elemental content of pulp and paper industry sludges

	54 Pulp and Paper Mill Sludges (NCASI 1984)		Municipal Sewage Sludges (Chaney 1980, Sommers 1977)	
Element	Range	Median	Range	Median
	Macronutrients (% dry weight)			
Nitrogen	0.051-8.75	0.898	<0.1-17.6	3.3
Phosphorus	0.001-2.54	0.235	<0.1-14.3	2.3
Potassium	0.012-1.0	0.22	0.02-2.64	0.30
Calcium	0.028-21.0	1.4	0.10-25.0	3.9
Magnesium	0.02-1.9	0.155	0.03-1.97	0.45
Sulfur	0.020-2.00	0.468	0.6-1.5	1.1
	Heavy Metals (mg/dry kg)			
Cadmium	<0.09-56	1.2	1-3,410	15
Chromium	3.0-2,250	42	10-99,000	500
Cobalt	ND-9.7	--	1-260	10
Copper	3.9-1,590	52	84-17,000	800
Iron	97.1-10,800	1,540	1,000-15,400	1,700
Lead	<0.05-880	28	13-26,000	500
Manganese	13-2,200	155	32-9,870	260
Nickel	1.3-133	18.3	2-5,300	80
Silver	<0.1-<11	0.55	--	--
Tin	<70.6	--	40-700	150
Zinc	13-3,780	188	101-49,000	1,700
Aluminum	590-89,000	3,400	1,000-13,500	4,000
Arsenic	<0.07-8.3	1.2	1.1-230	10
Barium	17.9-1,800	160	0.01-9,000	200
Boron	<1-491	25	4-1,000	33
Chlorine	<0.06-8,500	383	--	--
Selenium	<0.01-<31	0.21	1.7-17.2	5
Sodium	300-66,700	2,200	100-30,7000	2,400
Titanium	3,100-76,000	--	--	--

Findings reported by Huettle (1982), Dolar et al. (1972), and Wilde (1979) suggest subsequent salt phytotoxicity; however, past experiences have not shown reduced soil permeability or salt phytotoxicity to be a widely occurring problem.

Nutrients

Pulp and paper mill sludges generally contain a lower concentration of nitrogen, phosphorus, potassium, calcium, magnesium and sulfur than do municipal sludges, however, these constituents are present in significant quantity so as to make land application beneficial.

There is a vast amount of variability associated with macronutrient concentration levels in pulp and paper sludge. These variations stem from differences in the type and operation of the mill, and in the wastewater and sludge treatment provided. Rock and Beyer (1982) observed that high sulfur sludges were associated with sulfite pulping operations. In addition, large calcium concentrations are most likely to be found in primary and combined sludge from Kraft pulp mills (NCASI, 1984). Secondary sludges are typically much higher in nitrogen and phosphorus than primary sludges due to the addition of these two nutrients to wastewater prior to biological treatment.

Nitrogen in the organic form accounts for roughly 70-90 percent of the total nitrogen in mill sludge. Lower percentages are typically associated with liquid or aged (lagooned) sludge. Figure 2 illustrates the transformations of nitrogen from the organic form to the inorganic form. This process, known as nitrogen mineralization,

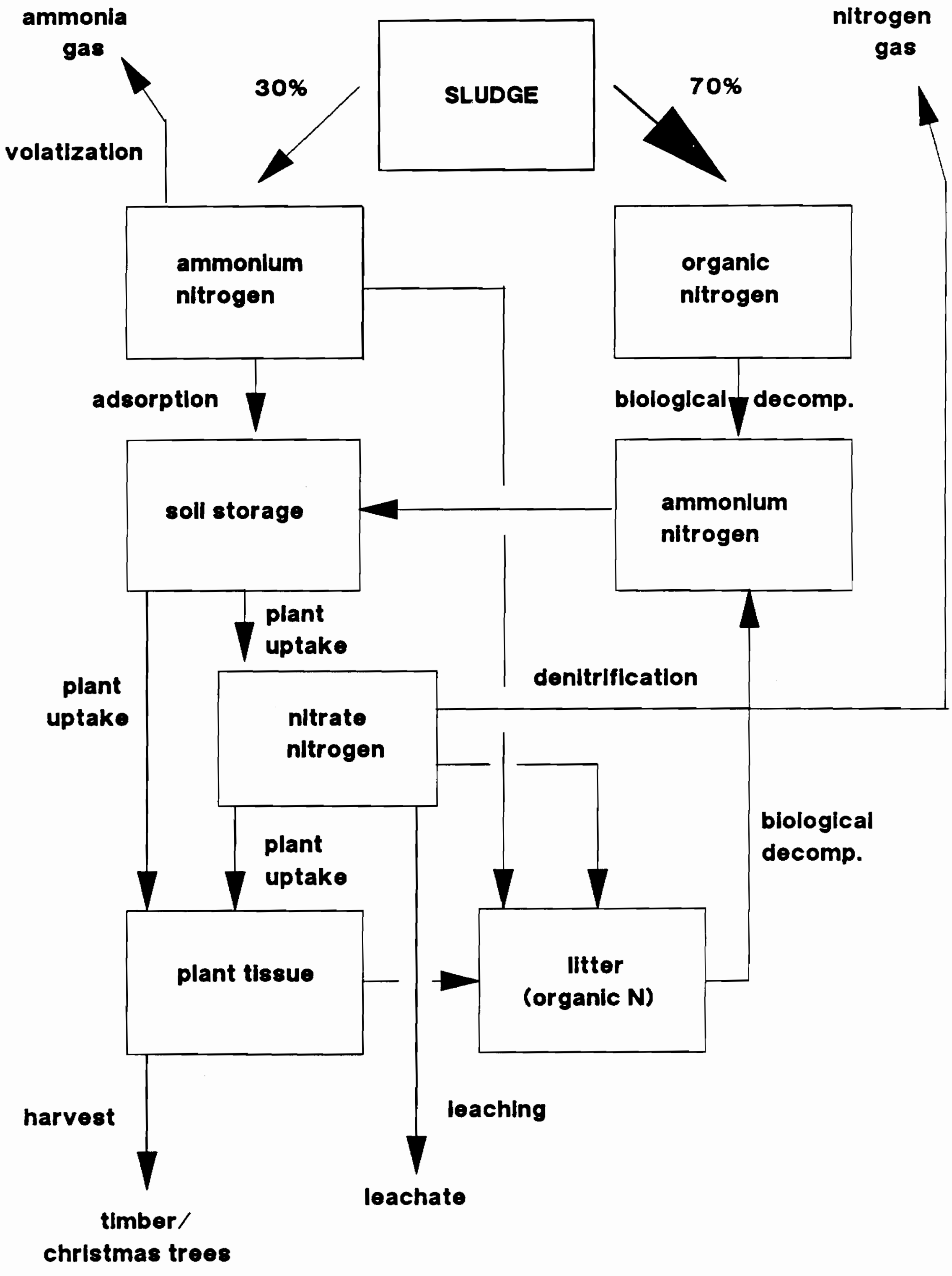

Figure 2. Nitrogen cycle (Reynolds and Cole, 1981)

is an important transformational process in land application of sludge in that inorganic nitrogen is the form most readily taken up by plants. In general, for carbon to nitrogen ratios (C:N) exceeding 20:1, the potential exists for temporary microbial immobilization, that is, microorganisms assimilate the limited nitrogen, thereby making it unavailable for plant uptake. This process will dominate until sufficient organic carbon is mineralized to CO_2, or until sufficient nitrogen fertilizer is applied so as to reach a favorable C:N ratio. Conversely, lower C:N ratios result in net nitrogen mineralization.

Primary, combined, and secondary mill sludge has exhibited a range in C:N ratios of 32-930:1, 13-81:1 and 6-115:1, respectively (NCASI, 1984). Therefore, the potential exists for temporary microbial immobilization of nitrogen in mill sludge. However, forests should presumably be more tolerant of short periods of immobilization due to longer rotation periods.

Studies by Hermann and Gilbert (1982), Simpson et al. (1983), Yerkes (1971), and Smith (1980), have revealed that land application of mill sludge has resulted in agricultural crop yields that are either: 1) greater than those control areas receiving no sludge or commercial fertilizer, or 2) equal to or greater than areas receiving fertilizer alone. Of course, enhanced soil productivity can result not only through the addition of nitrogen but also by the addition of other nutrients, and from physical conditioning of the soil as well.

Application of Sludge to Forest Land

Historically, municipal as well as pulp and paper mill sludge have been applied to agronomic crops. However, there are many areas throughout the United States and Canada with limited areas in agricultural use, and where the majority of lands are forested. Forestlands provide an alternative to agricultural areas for waste disposal when heavy metals or pathogens may be too high, or where food processors refuse to accept food crops grown on sludge-amended soils.

In general, application of sludge to forestlands has several advantages: The fact that a forest is perennial allows greater flexibility in timing sludge applications. Secondly, the root system provides protection from erosional loss and stores nutrients year-round. Longer rotation periods makes it easier for landowners to commit lands to sludge application for longer periods of time as required by the EPA. Finally, forestlands can accept "hard to dispose" wastes contaminated with high heavy metal or pathogen concentrations because the wood products are a non-food crop.

In light of state and federal legislation concerning the use of sludge, much research effort has been devoted to studying the ecological benefits of applying sludge to forestlands. Much of this effort has focused on the effect of application on tree growth, while assessing potential environmental and public health risks, namely nitrate leaching.

Taggart and Schreider (1980) studied the growth response of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and Sitka spruce (*Picea sitchensis* (Bong.) Carr) at the seedling stage following sludge application and reported that typical growth responses exceed the levels attained by the utilization of chemical fertilizers, with increases of 200 percent not uncommon. However, it should be recognized that not all tree species are equally suited to a sludge amended environment, especially at the seedling stage of development. Wilde (1979) reported poor growth and high mortality of red pine seedlings following the addition of 11 and 22 dry Mg/ha of a combined mill sludge. Planting was done, in this case, soon after sludge incorporation, and the adverse reaction of the seedlings was thought to be caused by either harmful levels of ammonia or soluble salts.

The influence of a combined sludge (80% primary) on growth of Douglas-fir seedlings was studied by Aspitarte (1980). Field plots received initial treatments of sludge incorporated at rates of 56 to 448 dry Mg/ha, ammonium nitrate, and Milorganite (composted municipal sludge), and were compared to control plots. Some of the treated and untreated plots were given surface mulch applications of sludge approximately 30 days after seedling emergence, as well as during the second growing season. Color, survival and height of the trees were recorded 4.5 and 22 months after planting. In all cases the various initial treatments improved seedling performance compared with controls. Furthermore, surface applications of sludge enhanced growth compared to similar plots without this addition.

Aspitarte (1980) evaluated the growth and survival of red alder (*Alnus rubra* Bong.) and black cottonwood (*Populus trichocarpa* Torr. and Gray) cuttings grown in riverbed sand with and without primary mill sludge amendment. Survival in amended plots was much greater than in control plots receiving no treatment. This was attributed to improved water retention by the sand.

A study evaluating the effect of a secondary liquid paper mill sludge on 40-year-old red pine growing in a sandy outwash soil was performed by Brockway (1979). In addition, a municipal sludge was applied to a 36-year-old plantation growing on a similar site which contained a mixture of red and white pine (*Pinus strobus* L.). The paper mill sludge was applied at rates of 2.0 to 15.7 dry Mg/ha. These rates corresponded to total nitrogen applications of 140 to 1,091 kg/ha. The municipal sludge was applied at rates of 5.4 to 19.3 dry Mg/ha, equivalent to total nitrogen applications of 323 to 1,156 kg/ha. Growth responses of the overstory and understory vegetation, as well as foliar nutrient levels, were determined relative to the degree of sludge application.

Analysis revealed that the understory vegetation for both study areas significantly benefitted from nitrogen and phosphorus additions. Mean foliar nitrogen concentrations in control plots ranged from 1.03 to 1.41 percent, while N levels progressively increased in plots receiving increasing sludge doses, exceeding 2% at the highest treatment rates. Phosphorus levels showed similar trends with control plots not exceeding 0.167%, while understories receiving the highest dosages typically exceeded 0.3%.

In addition, significant increases in cadmium and copper in the understory were detected on the plots receiving municipal sludge treatments; however, no toxicity symptoms were found. It was concluded that Cd and Cu levels, although quite high by agronomic standards, appeared to be within the range of acceptability for wild genotypes found in the study area.

Understory above-ground biomass was also measured and was found to increase on all plots, with the plots receiving the highest sludge treatment producing considerably greater biomass than control plots for both sites. A significant increase was noted on plots receiving the highest treatment and growing under the red pine overstory, where biomass increased from 11.0 g/m^2 to 54.6 g/m^2. Absence of a similar trend beneath white pine was thought to be a function of the greater fertility of the soil at that site. The author attributed the overall increase to a combination of sludge application and response due to overstory thinning.

Evaluation of overstory foliage on plots receiving sludge revealed elevated foliar N concentrations over those found on control plots, with increases in foliar N of up to 62%. Although foliar P levels were not higher as a result of sludge application, an increase in the N to P ratio occurred following the second growing season. This was important in that the addition of sludge effectively increased the low N:P ratios found on control plots from approximately 6.8:1 to roughly 10.5:1, with 10:1 considered the optimum for pines according to van den Driessche (1974).

Finally, analysis of the overstory growth response relative to sludge treatment showed increases in fascicle dry weight and needle length for both species. Dry weight increases as high as 50%, and needle length increases amounting to as much as 30% over controls were reported. Similar results were reported by Bockheim et al. (1988).

Significant increases in annual radial growth with treatment were seen in white pine; however, red pine did not respond on either site. Increases in radial growth at the base of the live crown failed to develop with treatment for either species on either site. These results were similar to those found by Miller et al. (1976) and Tolle (1976).

Further work performed by Archie and Smith (1981) reported enhanced growth and survival of several tree species planted in sludge-amended soils. Sludge was applied 3 years prior to planting, with 13.5 kg ha^{-1} of atrazine herbicide applied immediately prior to planting. The authors concluded that: 1) seedlings may survive better in sludge amended soils due to increased moisture retention; however, this is severely confounded by the competition of grasses and weeds which totally outperform the relatively slower-growing tree species; 2) ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) consistently survives better than all other coniferous species in sludge-amended sites; 3) Douglas-fir and Sitka spruce survive and grow consistently well in sludge, whereas western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar (*Thuja plicata* Donn ex D. Don) perform poorly; 4) the poplars, particularly Lombardy poplar (*Populus nigra* var. *italica*) and the hybrid poplar (*Populus trichocarpa* x *Populus deltoides*) perform very well in sludge, and finally; 5) all species, including western hemlock and western redcedar, had individuals that performed well in sludge-amended soils; hence, none of the species were judged totally unacceptable for planting in such sites.

Riekerk and Lutrick (1986) examined the effect of a municipal sludge on slash pine (*Pinus elliotii* Engelm.) planted 10 months prior to and 5 months following sludge application, using application rates ranging from a control to 112 dry Mg ha $^{-1}$. Results showed no improvement in growth and yield in trees planted prior to sludge application; however, trees planted 5 months following application exhibited increases in growth and yield of .002 m^3 year $^{-1}$ and 2.02 m^3 ha $^{-1}$, respectively, for every 10 tons of sludge applied per acre. Similar results were obtained by Berry (1982) on loblolly pine (*Pinus taeda* L.).

Vegetation Management in Conifer Plantations

Competition control is a common practice in forestry operations. Since a given site is capable of producing a finite amount of biomass in a given period of time, careful management of undesirable vegetation is necessary for the optimization of site capabilities with regard to crop tree production. In the context of conifer plantation management, control of competing vegetation occurs through some combination of site preparation, herbaceous weed control, or release.

Effective site preparation for conifers attempts to accomplish essentially four basic objectives: (1) reduce logging slash, thereby reducing the danger of subsequent wildfire, (2) provide suitable access and microsite for planting operations, (3) allow newly established conifers a head start over competing herbaceous and woody vegetation, and (4) remove undesirable hardwood and herbaceous vegetation, thereby facilitating site conversion to preferred species (Walstad, Newton and Gjerstad, 1987).

Industrial mechanical site preparation is used extensively in the Lake States for pine plantation establishment. Equipment commonly used to prepare sites for planting include the KG blade or V blade, brush rake, disc, drum chopper, scarifier, or trencher (Sajdak, 1988). Commonly, a one or two-pass discing treatment is used to break up dense coverage of herbaceous vegetation. Kotar and Coffman (1982) state that failure to control grasses from site preparation can reduce site index by at least 3 m and maximum annual volume growth by 40 percent.

Release techniques used in forestry are designed to selectively control competing vegetation without damaging the desired species. Several practical restraints, however, limit the options available for conducting release operations or herbaceous weed control. In most cases, mechanical cultivation and prescribed burning are restricted in forest release operations due to terrain limitations and the possibility of damage to young conifers. Therefore, only chemical, manual and occasionally biological methods are suitable for performing release operations in young conifer plantations.

In general, release of young conifers is performed within the first 3 to 7 years following plantation establishment and is justified based on the following basic ecological principles:

1. Vegetation control improves the availability of site resources (light, moisture, nutrients) for benefit of desirable tree species.

2. The more resources that are made available by reducing the level of competing vegetation, the greater the survival and growth of the timber stand are likely to be, providing other factors (e.g. nutrients, pests, disease) are not limiting.

3. Although vegetation management treatments are often singular events during the life of a forest stand, proper application of release treatments cause changes in plant community structure, composition and stand density that determine the pattern of ensuing successional stages, and help insure the dominance of commercially valuable timber species (Walstad, Newton and Gjerstad, 1987).

The specific response to release is further governed by the degree of suppression, intensity of release, conifer age or height and the species being released.

Chemical control of undesirable herbaceous weeds as well as release of young red pine from hardwood competition to increase survival and biomass production is a common silvicultural practice in the Lake States province. As a result of intensive site conversion from hardwood to conifer production, many thousands of acres were released by the Civilian Conservation Corp (CCC) in the 1930's, and this trend continues today.

The most dramatic response to release by conifers is seen in increased height growth and groundline diameter, with a positively correlated, subsequent increase in biomass also occurring (Figure 3). Strothmann (1967), who studied the influence of several combinations of light and moisture on red pine growth, found that the removal of competition for light produced a larger growth response than did the removal of competition for moisture; however, maximum response only occurred when both types of competition were eliminated.

Lambert et al. (1972) further documented increased red pine growth as a result of controlled competition. Miller and Zutter (1987) observed an increase in both height, and most notably, groundline diameter with herbaceous weed control. Woody competition did not significantly reduce tree growth.

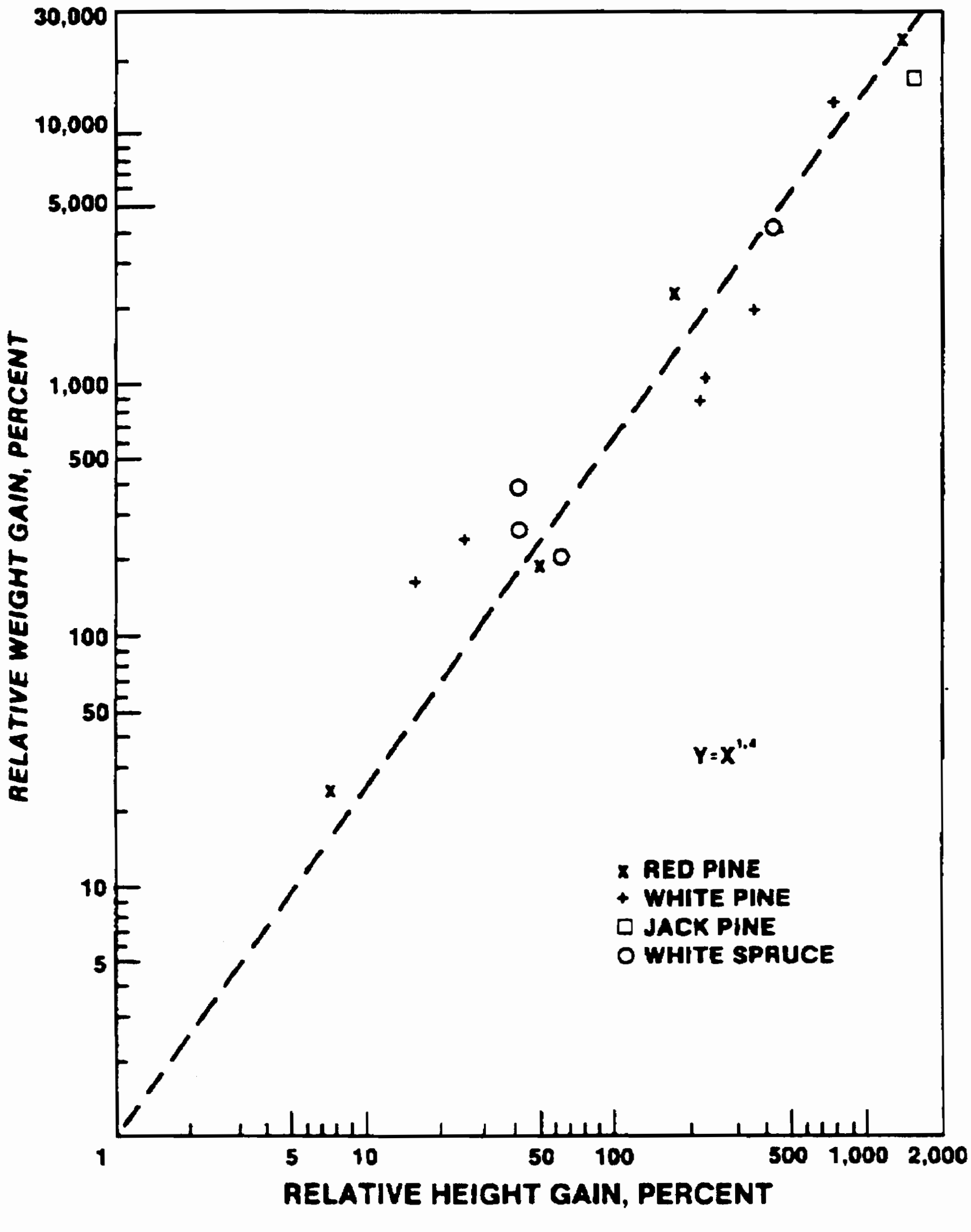

Figure 3. Relationship between relative height gain and relative weight gain (Perala, 1982)

Many managers believe that moisture competition on pine sites of site index 70 and better limits survival and growth of red pine seedlings more than lack of light. Competition for nutrients may be the main constraint on pine sites of SI 50 and poorer (Bassett, 1984). Several authors have studied the effects of moisture competition, via root competition, and have concluded improved growth is attributable to measured or inferred increases in soil moisture due to lowered evapotranspiration (Table 3).

Although conifer survival is less affected by release than is growth, a review by Perala (1982) with red pine, white pine, jack pine (*Pinus banksiana* Lamb.) and white spruce (*Picea glauca* (Moench) Voss) indicated that fully-released trees do survive better, regardless of species, with an overall mean of 80 percent, than do suppressed trees (56%). Roe (1955) found that red pine can survive 30 percent shade 1 to 5 years after planting; however, Struik (1978) emphasized that overtopping branches and side competition should be eliminated by the fifth year.

Combined Effects of Weed Control and Fertilization

Typically, trees under strong competition from woody and herbaceous competition respond only marginally to fertilization unless competing vegetation is reduced or eliminated altogether. Often, added nutrients are utilized by competing vegetation, resulting in increased growth and competitive ability of these species (Stewart, 1987). Powers and Jackson (1978) found that on a droughty site, needle weight increased 129% over unreleased controls when fertilization was combined

Table 3 - Percent change in height growth of open grown Great Lakes conifers attributed to controlling root competition (Perala, 1982).

Species			
Red Pine	White Pine	White Spruce	Reference
----------	percent	----------	
+7	---	---	Lambert et al. 1972
-1	+22	+15	Shirley 1945
---	+69	---	Sterrett and Adams 1977
+166	---	---	Strothmann 1967
---	---	+41	Sutton 1975
---	---	+58	Sutton 1975
+50	---	---	Wittenkamp and Wilde 1964

with weeding, compared with only 20% and 79% increases for fertilization and weeding applied separately. Fertilization in conjunction with weeding improved height growth by 242%, compared with only 10% and 105%, respectively, for these practices applied singly (Powers, 1983). McKee and Wilhite (1988) demonstrated that pine seedlings receiving nitrogen fertilizer and Amazine™ performed consistently better than seedlings receiving fertilizer only. Neary et. al (1985) examined the response of slash and loblolly pine (*Pinus taeda*) to weed control, fertilization, and a combination of these treatments and found that a combination of the two treatments resulted in the highest volume for both species. Baker (1973) found that growth of slash pine treated with N and P fertilizer, weed control, and irrigation (applied singularly and factorially) improved in almost direct proportion to the number of treatments applied. Swindel et al. (1988) also discuss the additive nature of cultural treatments, reporting a five-fold increase in stand volume of slash and loblolly pine over a four-year period when fertilizer or competition was applied singularly, and a ten-fold increase when these two cultural treatments were combined. Tiarks and Haywood (1986) showed volume increases over controls of 29%, 37%, 63% and 119% when woody control, fertilization, herbaceous control, and a combination of the three treatments was performed, respectively. Lastly, White and Newton (1990), in a study involving fertilization and weed control with Douglas-fir and noble fir (*Abies procera* Rehd.), concluded that silvicultural benefits may be achieved by fertilizing at a very young age, provided it is done in conjunction with good weed control.

To date, there is only one study reported of the effects of weed control following application of paper mill sludge (Neary and Comerford, 1983). As part of the study, 0.28 kg a.i./ha of Oust^{tm} was broadcast sprayed following the application of four rates of mill sludge (0, 46, 92 and 148 dry Mg/ha) to a previously harvested slash pine site. Except for controls, application of herbicide reduced weed biomass production by 51-61% relative to plots not receiving weed control. Because of a serious sludge effect on seedling survival prior to herbicide spraying, the authors were unable to determine with any certainty the impact of weed control on growth of the slash pine.

Materials and Methods

Description of Study Area

Two red pine plantations were selected for experimental application of a primary/secondary paper mill sludge. They are located in Wood and Adams Counties, Wisconsin, on lands owned and managed by Nekoosa Papers of Port Edwards, Wisconsin (Figure 4). Both study areas are situated within the Central Plain physiographic division (underlain by upper Cambrian sandstone) as outlined by Dutton and Bradley (1970). Native vegetation consisted of mixed oak (*Quercus velutina* Lam., *Q. macrocarpa* Michx. and *Q. ellipsoidalis* E. J. Hill) and jack pine.

Climate indicative of both study areas is characteristic of the midlatitude (temperate) continental climatic zone (Finch et al., 1957). The mean annual precipitation for both areas is approximately 76 to 81 cm (Holt, Young, and Cartwright, 1964), with an average annual snowfall between 101 and 127 centimeters

Figure 4. Location of study areas

(Burley, 1964). The frost-free season is approximately 120 days (Burley, 1964).

Both study areas occur within the Plainfield soil series (Typic Udipsamment) which has the following profile description:

A1 0 to 10 cm.; very dark grayish brown (10YR 3/2) sand to light brownish gray (10YR 6/2); dry weak fine granular structure; very friable; very strongly acid; abrupt smooth boundary.

B1 10 to 18 cm.; dark yellowish brown (10YR 4/4) sand; weak fine subangular blocky structure; very friable; strongly acid; clear wavy boundary.

B2 18 to 43 cm.; strong brown (7.5 YR 5/6) sand; weak medium subangular blocky structure; very friable; medium acid; clear wavy boundary.

B3 43 to 71 cm.; yellowish brown (10YR 5/6) sand; weak medium subangular blocky structure; very friable; medium acid; clear wavy boundary

C 71 to 152 cm.; yellowish brown (10YR 5/6) sand; single grain; loose; strongly acid.

This soil exhibits little profile development, having evolved in outwash sands containing a high content of quartz. In general, this soil is considered excessively drained with a low natural fertility, thereby restricting its use for agricultural production. Nevertheless, much of this soil is used for red pine pulpwood production which supplies material to numerous mills along the Wisconsin River. Site index is estimated at 55 (base age = 50) for red pine growing on Plainfield soils.

The Wood County plantation was machine planted in 1983 following clearcutting and double-disc site preparation. Seedlings (2-0) were planted at an approximate spacing of 1.8 x 1.8 m. The Adams County plantation was established similarly in 1985.

Field Methods

Establishment of Study Plots

During June, 1988, twelve 0.405 ha sludge-treatment plots were established in each plantation. The long axis of the plots (132.4 meters by 30.4 meters) were run parallel to the groundwater flow to facilitate water quality studies being done at the University of Wisconsin - Madison. Tree rows ran North-South in both plantations. Within each 0.405 ha main treatment plot, a 0.0405 ha herbicide sub-plot was randomly located.

Sludge Application

In September, 1988, a nutrient enriched primary/secondary sludge from Nekoosa's paper mills in Port Edwards (sulfite) and Nekoosa (Kraft), Wisconsin was applied to the treatment plots (Figure 5). Sludge was taken directly from vacuum coil filters at the mills' wastewater treatment facility and transported immediately to the study sites. Sludge treatments at each study site consisted of a single application of sludge, containing approximately 22% solids, spread over the canopy of each plantation using side discharge, industrial manure spreaders. Sludge was applied in strips approximately six m wide. Application treatments were the same for each site and consisted of application rates of 0, 10, 20 and 40 dry Mg/ha, which were achieved by discharging during 1, 2 or 4 passes for the 10, 20 and 40 Mg/ha treatments, respectively. Treatments were assigned randomly with three replications within each plantation (Figures 6 and 7). A summary of the sludge characteristics for

Figure 5 - Surface application of paper mill sludge

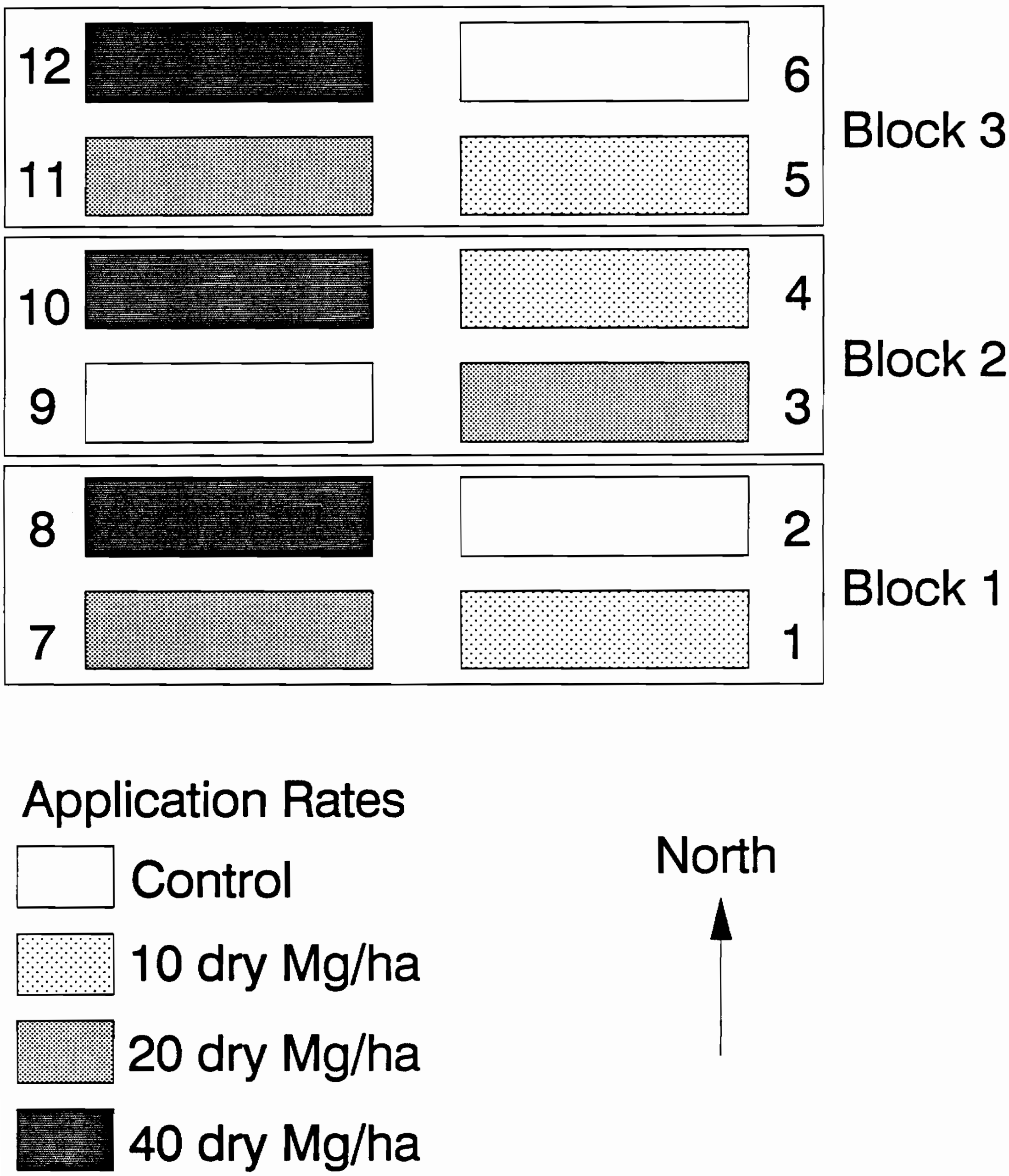

Figure 6. Sludge treatments in Adams County, Wisconsin site

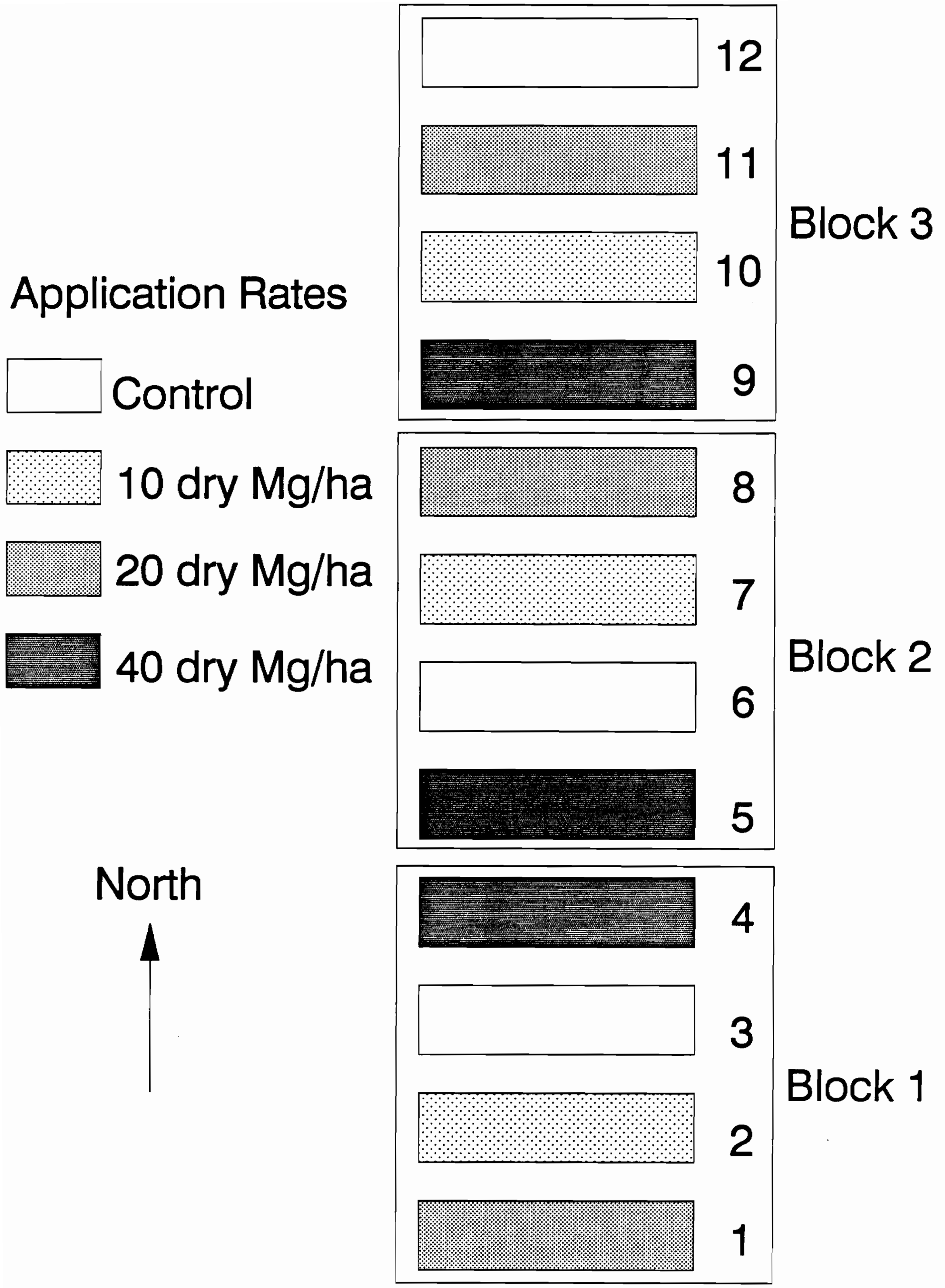

Figure 7. Sludge treatments in Wood County, Wisconsin site

each study site is presented in Table 4.

Weed Control Application

During July, 1989, weed control treatments were applied to each 0.0405 ha sub-plot. Weed control treatments consisted of 0.140 kg ha $^{-1}$ active ingredient (a.i.) of sulfometuron methyl (Oust ^{tm}) tank mixed with 1.3 kg ha $^{-1}$ a.i. of triclopyr (Garlon ^{tm}) in water. The herbicide was applied as a direct spray with a Solo 425 backpack sprayer at a rate of 280 liters ha $^{-1}$. Due to what appeared to be large amounts of hardwood competition in the Wood County plantation, an additional treatment consisting of a basal spray of 2% Garlon 4 ^{tm} in water (.03 kg ha^{-1} a.i.) was applied to all hardwood stems in the sub-plots. The herbicide application rates represent current dosages used by Nekoosa Papers in their release operations.

Tree Measurements

Within each sample plot 80 red pines were randomly selected for tree measurements. Following the cessation of height growth in 1988, 1989, and 1990, the following measurements were made:

1. Diameter - measurement was taken at ground level using a digital Mitutoyo micrometer. Values were recorded in millimeters to the nearest 1/100 of a millimeter.

Table 4 - Elemental composition and loading rates for paper mill sludge in Adams and Wood Counties, Wisconsin

	Wood County Site				Adams County Site			
Sludge application rate, Mg/ha		10	20	40		10	20	40
Element	Concentration	Application Rate			Concentration	Application Rate		
	mg/kg	--------- kg/ha ---------			mg/kg	--------- kg/ha ---------		
N	20000	200	400	800	20600	206	412	824
P	2588	25	51	103	1970	20	39	79
K	449	4	9	18	391	4	8	16
Ca	7312	73	146	292	7092	71	142	284
Mg	3940	39	79	158	2922	29	58	117
S	3621	36	72	145	2997	30	60	120
Zn	86	.86	1.72	3.44	57	.57	1.14	2.28
B	12	.12	.24	.48	12	.12	.24	.48
Mn	79	.78	1.56	3.12	54	.54	1.08	2.16
Fe	1810	18.1	36.2	72.4	1235	12.3	24.6	49.2
Cu	19	0.19	0.38	0.76	16	0.16	0.32	0.64
Al	16252	162	324	648	12487	124	248	496
Na	230	2.3	4.6	9.2	303	3.0	6.0	12.0
Mo	11	0.12	0.24	0.48	9	0.09	0.18	0.32

2. Total Height - measurement was taken from ground level to the top of the terminal bud using a meter stick. Values were recorded in centimeters to the nearest centimeter.

3. Crown Width - two measurements were taken at right angles to one another at the widest point in the crown using a meter stick. Values were recorded in centimeters to the nearest centimeter.

The experimental unit for each tree variable (height, diameter, volume calculated as d^2H, crown width) consisted of a mean of the 80 trees per .405 ha treatment plot. Tree growth for each treatment plot was calculated by subtracting the mean value the previous year from the current year.

To assess the effect of the weed control treatments, 60 and 20 trees were measured at random outside and inside the weed control subplots, respectively.

Red Pine Foliar Sampling

To determine the effect of sludge application on red pine foliar nutrition and biomass, 10 current-year fascicles were collected from 12 randomly selected trees in each treatment plot (excluding badly stunted or deformed trees). Foliar samples were bagged in the field and returned to the lab for dry weight and nutrient analysis.

Herbaceous Vegetation Sampling

To sample the herbaceous ground vegetation, four 0.25 m^2 sub-plots were randomly located within each 0.405 ha treatment plot (excluding the 0.0405 ha weed control sub-plots), in the Wood County plantation. A hand-held clipper was used to remove all of the above-ground sedge (*Carex* spp.), the predominant herbaceous component, within the sub-plot. Additionally, all of the associated herbaceous root material to a depth of 40 cm was also removed. Above and below-ground samples were bagged separately in the field and root samples were washed thoroughly and allowed to air dry. Samples were returned to the lab for dry weight and nutrient analysis.

Competing Vegetation Assessment

To evaluate the impact of sludge application on overall vegetative competition (herbaceous and woody), a competing vegetation assessment system (CVAS) similar to that developed by Brand (1986) was performed. Measurement of competing vegetation was performed within a 6.26 m^2 circular plot around randomly selected red pines. Each plot was divided into four quadrants, and in each quadrant the following variables were measured:

a) Horizontal proximity of the competing vegetation to seedling stem

b) Average height of the competing vegetation

a) Percent coverage of the competing vegetation

d) Percentage of bare ground

e) Type of competing vegetation (woody or herbaceous)

During 1988 and 1989, the assessment was performed on 20 trees in each treatment plot. In 1990, following weed control, the assessment was determined using 15 trees outside the weed control sub-plots and 5 trees within each weed control subplot.

Based on this competition assessment, a woody competition index rating was established as follows:

0 Woody vegetation absent in all four quadrants

1 Woody vegetation present in one or more quadrants, but is less than 1/3 the height of the seedling

2 Woody vegetation present in one quadrant, and equal to or greater than 1/3 the height of the seedling

3 Woody vegetation present in two or three quadrants, and equal to or greater than 1/3 the height of the seedling

4 Woody vegetation present in four quadrants, and equal to or greater than 1/3 the height of the seedling

5 Seedling overtopped

The effect of sludge application on overall herbaceous competing vegetation was evaluated using the following descriptive variables: herbaceous height, herbaceous coverage, and herbaceous volume (calculated as m^3).

Laboratory Methods

Nutrient Analysis

Above and below-ground sedge tissue and red pine foliage were oven-dried at 65° C until a constant weight was achieved (within 2%), at which time the oven dry weight was determined.

Samples were ground in a Wiley mill and passed through a 1 mm screen. The dried, ground tissue was dry-ashed in a muffle furnace at 500° C and dissolved in 6 *N* HCL. Nutrient concentrations for the herbaceous vegetation (P, K, Ca, Mg, Mn and Al) and red pine foliage (P, K, Ca, Mg, S, Zn, B, Mn, Fe, Cu, Al and Na) were determined using a Jarrell-Ash inductively coupled plasma emission spectrometer (ICAP). Total N was determined for both herbaceous vegetation and red pine foliage using a modified micro-Kjeldahl digestion procedure (Bremner and Mulvaney, 1982) and analyzed by colorimetric NH_4^+-N determination with a Technicon Autoanalyzer II.

Statistical Methods

Analysis of Sludge Effects

A randomized complete-block design was used with four treatment levels (control, 10 Mg ha $^{-1}$, 20 Mg ha $^{-1}$ and 40 Mg ha $^{-1}$) in three blocks to determine the impact of paper mill sludge on red pine growth and nutrition, and competition. Data was subjected to analysis of variance, followed by a mean separation procedure consisting of Fisher's Least Significant Difference (LSD) test at the 0.05 level. Simple linear regression was performed to determine whether response variables were significantly affected by increasing rates of sludge application.

Analysis of Weed Control Effects

Weed control effects were evaluated using a split-plot design within each plantation. Sludge treatment comprised the main plots, with the two weed control treatments comprising the sub-plots. Tree growth and measures of competing vegetation were analyzed using analysis of variance followed by Fisher's LSD test at the 0.05 and 0.10 level.

Results and Discussion

Chapter 1: Effect of Paper Mill Sludge on Growth of Young Red Pine

Introduction

The disposal of pulp and paper mill sludge has received considerable attention in recent years. Increasing costs for landfill construction and maintenance in conjunction with the decreasing number of suitable landfill sites has prompted the paper industry to seek viable alternatives for disposal of their solid wastes. Early efforts focused on the application of sludge on agricultural land, where increased crop yields were demonstrated (Hermann and Gilbert, 1982; Yerkes, 1971, Simpson et al. 1983). Other studies have shown poor growth of agronomic crops, thought to be attributed to nitrogen immobilization as a result of high C:N ratios (Dolar et al. 1972, Huettl, 1982). Other problems with paper mill sludges such as elevated levels of heavy metals, soluble salts and pathogens, coupled with annual rotations, potentially limit the land application of paper industry sludge on consumptive crops.

Increasingly, emphasis is being placed on forest land application as a major cost-effective and biologically attractive means of waste disposal (Forester et al. 1977). This is particularly true for companies that own and manage woodlands in close proximity to treatment facilities. Longer rotation periods in conjunction with the non-ingestive nature of forest products alleviates many problems such as N immobilization, heavy metals and pathogens. As these sludges are being applied more frequently to forest land, knowledge concerning their impact on tree growth is becoming a subject of increasing interest.

Previous studies have demonstrated that applications of N, P, K and lime-based fertilizers may result in increased tree growth (Brendemuehl, 1967; Fisher and Garbett, 1980; Leaf et al. 1975; McKee and Wilhite, 1988) and foliar nutrient levels (Lutrick et al. 1986, Timmer and Stone, 1978; Wittwer et al. 1975). Several researchers have investigated the effects of paper mill sludge on tree growth and foliar nutrient levels (Berry, 1985; Brockway, 1983, Smithe and Morin, 1977; Aspitarte, 1980) and found similar results. Improved growth rates and increased foliar nutrient levels were attributed to nutrient additions in the sludge. In contrast, other studies report no tree response to sludge application (Magnuson, 1978) or adverse effects on seedling development (Wilde, 1979).

This study was undertaken to determine the effect of a surface-applied, nutrient-enriched primary/secondary paper mill sludge on growth and foliar nutrient concentration of young red pine (*Pinus resinosa* Ait.) plantations in Central Wisconsin.

Results and Discussion

Tree Growth

Paper mill sludge application did not significantly affect red pine volume growth relative to controls following the first or second growing season (10 and 22 months following sludge application, respectively) for either study area (figures 8a and 8b). Other tree growth variables, including diameter, height and crown width, were similarly affected (Appendix A). Nonetheless, some important biological trends occurred; notably, red pine growth was consistently lower on sludge-amended plots following the first growing season in the younger (Adams County) plantation, with volume growth reductions relative to controls approaching 50% among the two higher application rates. In general sludge application had little or no effect on tree growth in the older plantation following the first growing season.

The initial growth reduction in the younger plantation is believed to be attributed to reduced availability of soil moisture resulting from the absorption of limited rainfall into the sludge blanket, followed by subsequent evaporation.

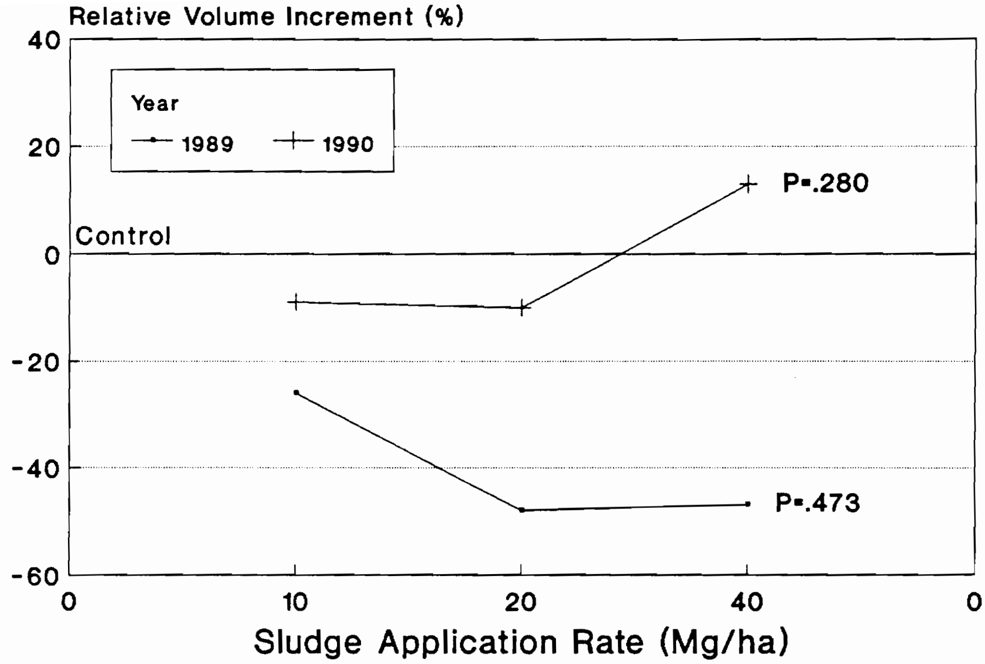

Figure 8a. Relative volume increment of red pine 10 and 22 months following sludge application for Adams County, Wisconsin

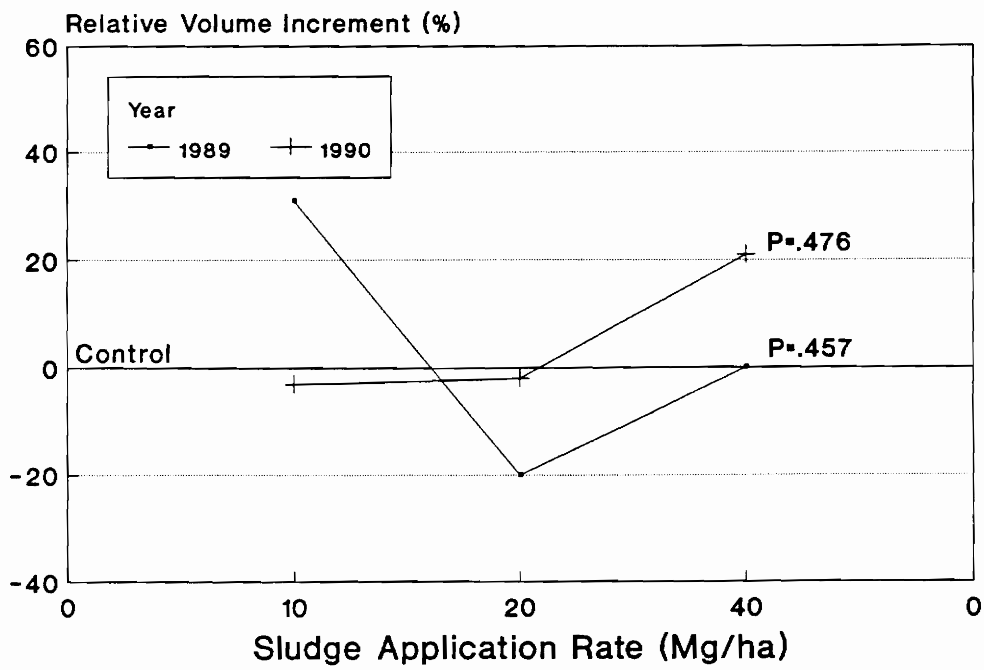

Figure 8b. Relative volume increment of red pine 10 and 22 months following sludge application for Wood County, Wisconsin

Precipitation data from the Hancock Agricultural Experiment Station located approximately 25 kilometers southwest of the study shows above-average rainfall for May of 1989 (+9.9 cm) followed by deficits of 4.4 cm and 1.52 cm for June and July, respectively. Although red pine is an efficient producer on drier soils, given the immaturity of the trees in the younger plantation, in conjunction with increased moisture interception during a period prone to droughty conditions, it is questionable whether sufficient moisture was available for adequate tree growth to occur. Additionally, given the determinant growth nature of red pine, that is, a high percentage of subsequent growth is dictated by bud formation the previous year, dry conditions in 1988 likely contributed to the poor growth response to applied sludge the following year.

Other factors which could contribute to adverse tree growth following sludge application were not considered to be of major importance. Given the narrow C:N ratio (22:1), nitrogen immobilization was unlikely a dominating process compared with nitrogen mineralization (Stevenson, 1986). Furthermore, in a companion study, there was no apparent impact from sludge application on hardwood competition 9 months following land-spreading, and although the herbaceous understory benefitted from sludge-borne nutrient additions during the first growing season, reduced moisture availability due to herbaceous competition was unlikely since there was not a concomitant increase in herbaceous vegetation biomass. Furthermore, the innocuous characteristics of the sludge (Table 4) does not lend support to reduced tree growth as a result high concentrations of soluble salts (Wilde, 1979, Huettle,

1981) or trace elements, hypothesized as causing poor seedling growth and increased mortality in other studies. Soil pH values obtained from the University of Wisconsin Soil Testing Lab support this, indicating pH values for the 0-60 cm profile to be within the range of 4.6 to 5.5, which corresponds with published values for the Plainfield soil series (Jakel, 1984). This is not to say that increasing rates of sludge application did not have an effect on soil pH, merely that dramatic changes in soil pH due to addition of large amounts of soluble salts did not occur. Additionally, sludge analysis (Table 4) reveals trace element concentrations well below median levels reported by Thacker (1986), with the exception of aluminum. Finally, given the small size of the seedlings in the Adams County site, and since equal number of passes were made over all treatment plots during the landspreading operation, it is unlikely that physical damage to seedlings from the sludge spreaders resulted in reduced growth following the first growing season.

In contrast to the younger plantation, seedling moisture stress was not considered to be a factor during the first growing season in the Wood County site due to the older nature of the seedlings and greater degree of root establishment. Unlike the Adams site, a considerable amount of seedling damage occurred to lateral branches, terminals and stems as result of the landspreading operation. However, a comparison of height growth between damaged and undamaged seedlings indicates that no significant growth reduction ensued the first ($P<.358$) or second ($P<.326$) growing seasons.

Following the second growing season, trees in both plantations exhibited some evidence of response to sludge application, with the best growth performance occurring on plots receiving the 40 Mg/ha treatment. This suggests that the initial negative impact from sludge application was transitory and did not permanently impact tree performance. Crown width appeared to be the most sensitive response variable, exhibiting increased growth relative to controls of 76% and 52% for the younger and older plantations, respectively. This response is believed to be attributable to increased decomposition of the sludge blanket, thereby resulting in an increase in available moisture, and to increased release and availability of sludge-borne nutrients.

Foliar Characteristics

The initial pine overstory growth response attributable to increasing rates of sludge application appeared 12 months following treatment as increased relative needle biomass in the younger plantation (figure 9). Red pine needle biomass was not found to be affected 12 months following sludge application in the older plantation.

Significant increases in foliar nitrogen levels with increasing application rate were found 12 months following sludge treatment in both the Wood and Adams County sites relative to controls (figures 10a and 10b). Most notably, nitrogen concentration increased 18% and 13% in the heaviest treatment plots as compared to controls in the Wood and Adams sites, respectively. Foliar phosphorus concentrations exhibited increases in the younger plantation as well, 12 months

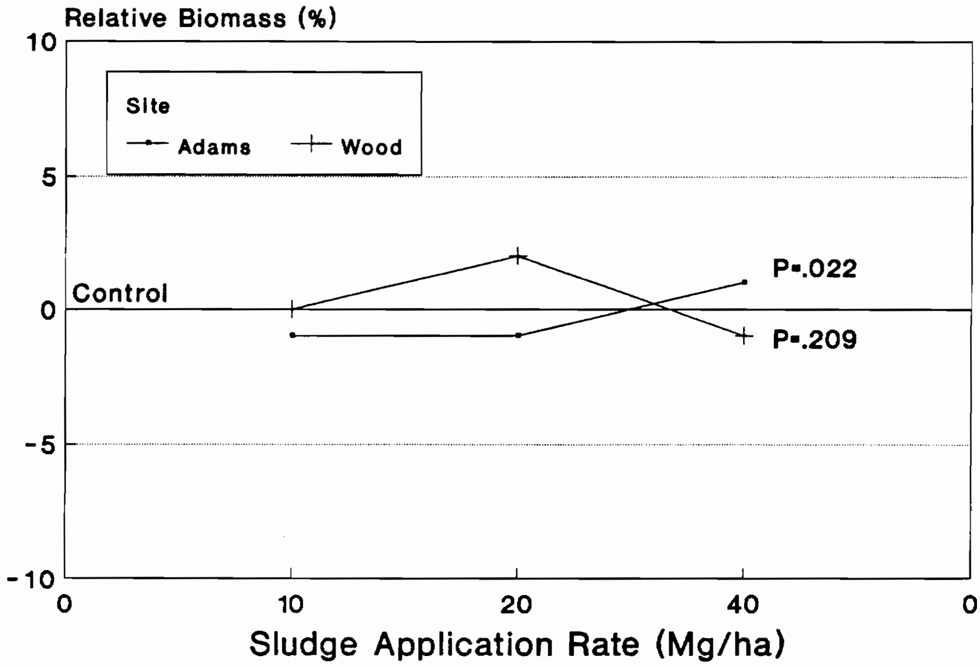

Figure 9. Relative fascicle biomass of red pine 12 months following sludge application for Adams and Wood Counties, Wisconsin

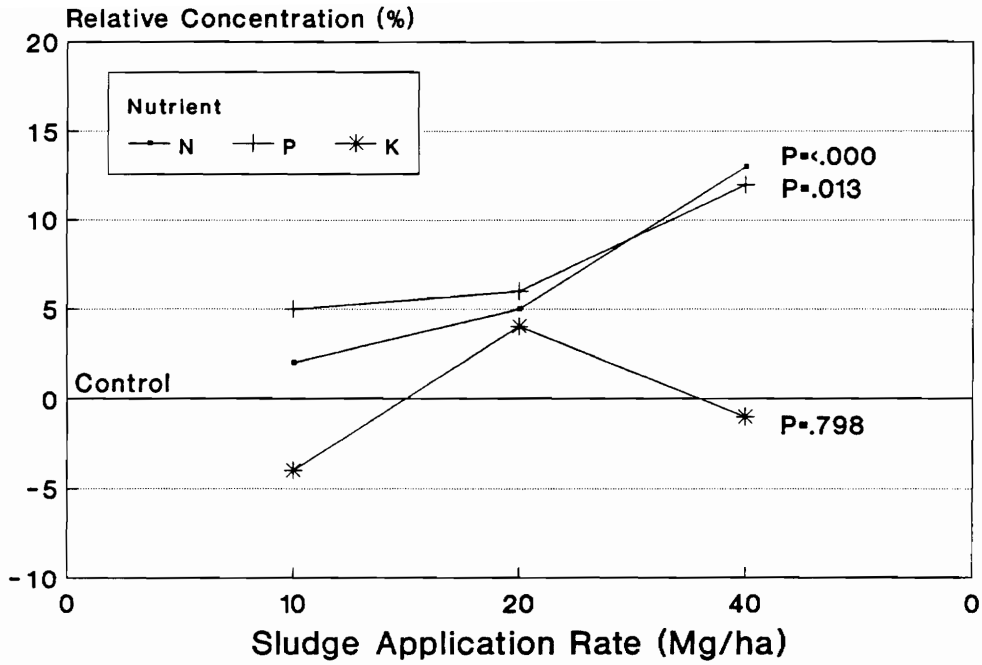

Figure 10a. Relative red pine foliar concentrations of N, P and K 12 months following sludge application for Adams County, Wisconsin

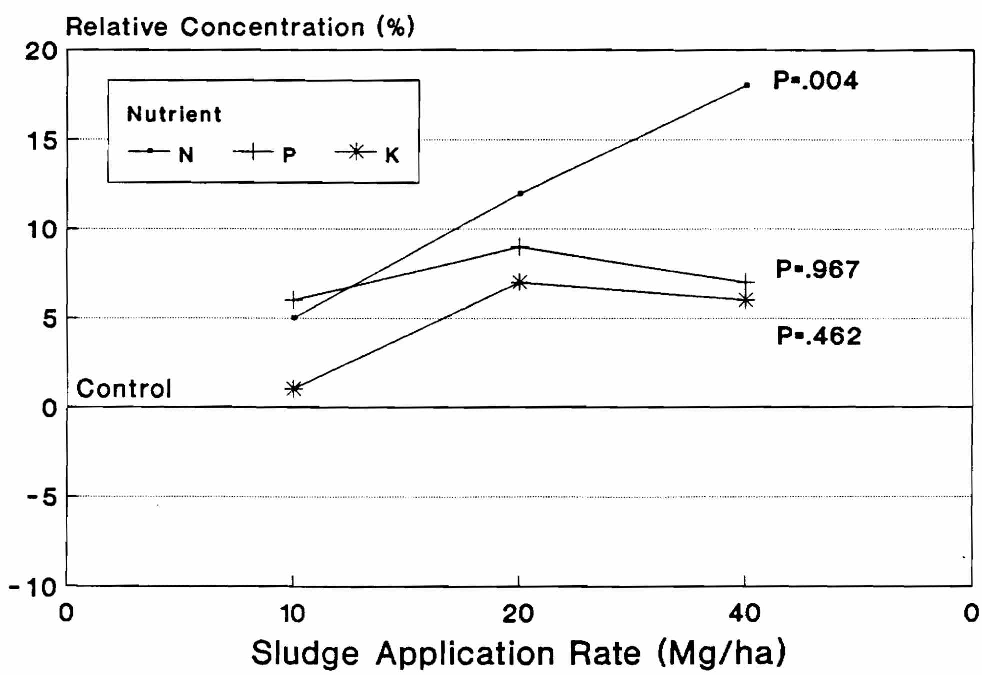

Figure 10b. Relative red pine foliar concentrations of N, P and K 12 months following sludge application for Wood County, Wisconsin

following application. Other macro-nutrients concentrations were also found to exhibit slight increases among the higher sludge rates as well for both study sites, with the exception of potassium, which was not an element present in large concentration in the papermill sludge (Appendix A). Additionally, nitrogen-phosphorus ratios were found to be highest among the 40 Mg/ha treatment plots, approaching 10:1, which according to van den Driessche (1974) is the optimum for pines. This was a result of substantially increased levels of nitrogen in proportion to relatively constant phosphorus concentrations in the papermill sludge. Few of the micro-nutrients displayed any positive response with treatment. In general, fascicle nutrient concentrations were similar to values (1.21% N, .17% P, .42% K, .23% Ca, .10% Mg and .10 % S) reported by Bockheim et. al. (1989), for 26 year old red pine in Central Wisconsin.

Increases in foliar nutrient levels 12 months following sludge application precluded slight growth response among plots receiving the highest application rate, 22 months after treatment. Studies by Mader and Howarth (1970) corroborate these findings by demonstrating red pine growth to be significantly correlated to foliage nutrient concentrations, particularly calcium and magnesium. Similar tree responses to sludge application have been found by Brockway (1983), in which a high-nutrient papermill sludge applied in June to a 40 year old red pine stand resulted in increasing nutrient concentrations relative to sludge application as early as 2 months following application, and increased fascicle weight 14 months following treatments.

Results of vector analysis generally showed luxury consumption to be the dominant foliar response to sludge-borne nutrients for both plantations 12 months following application (figures 11a - 13b). These results may suggest a gradual buildup in canopy photosynthetic potential as a result of increased foliar nutrient uptake. Miller and Cooper (1973) have shown that volume growth is maximized when pine foliar N levels approach 2%. Foliar N levels for Wood County were found to increase from 1.29% in controls to 1.52% in plots receiving the heaviest sludge treatment. Given the low inherent fertility of the Plainfield series, the increase in foliar nutrient level represents a pronounced improvement which may lead to greater tree productivity. Additionally, since sludge was applied in the fall of the year, conditions favorable for sludge decomposition, and subsequent nutrient release did not exist until the following spring. It may be possible that insufficient time had elapsed for the release of sufficient amounts of nutrients for a foliage biomass effect to occur following the first growing season. Lastly, Timmer and Stone (1978) indicate that in northern conifer plantations, increases in nutrient uptake without a concomitant increase in dry matter production may simply be late season storage for subsequent uptake. Slight responses apparent among the 20 Mg/ha treatment in the older plantation relative to N, P and K, may explain the increased needle biomass among that application rate.

Only boron, which is required by conifers in small but continuous amounts for the formation of meristematic tissue, consistently showed decreased uptake with increasing rates of sludge application, suggesting reduced availability of boron among sludge amended treatment plots (figure 14a and 14b). Furthermore, background

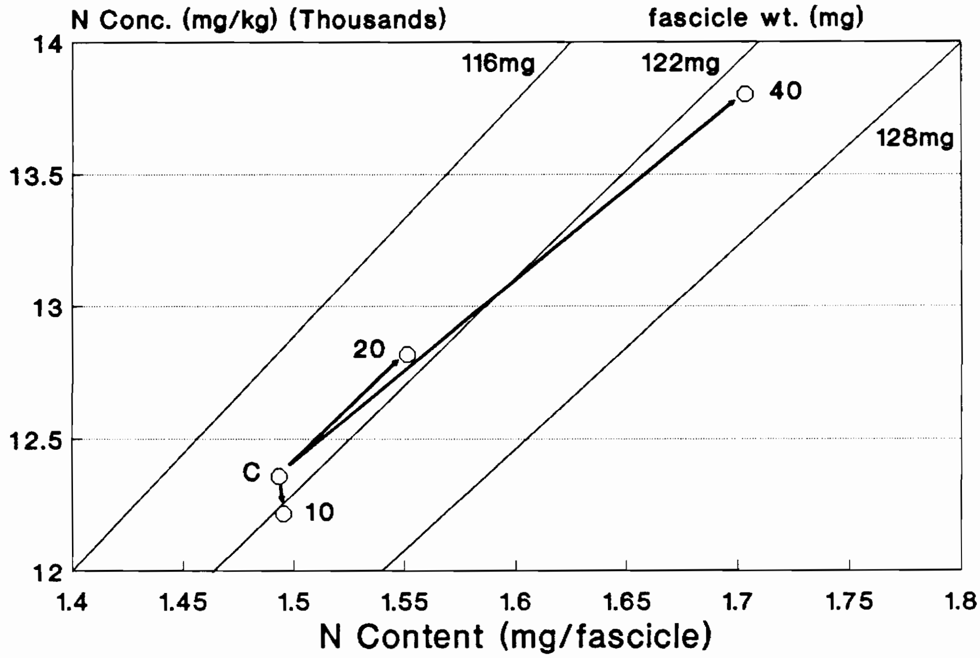

Figure 11a. Vector diagram of red pine fascicle response to sludge-borne N 12 months following sludge application for Adams County, Wisconsin

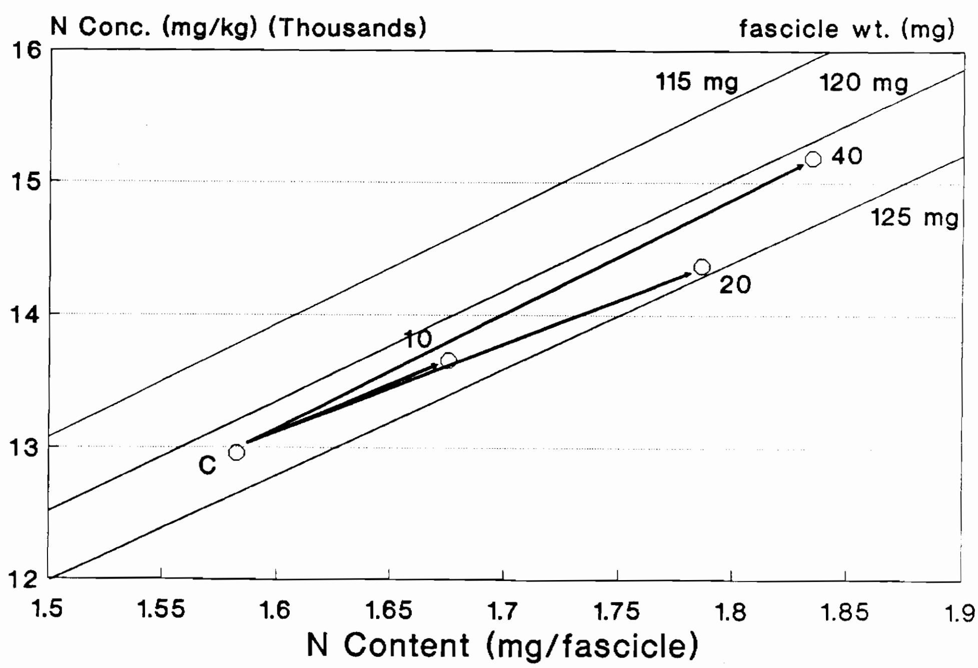

Figure 11b. Vector diagram of red pine fascicle response to sludge-borne N 12 months following sludge application for Wood County, Wisconsin

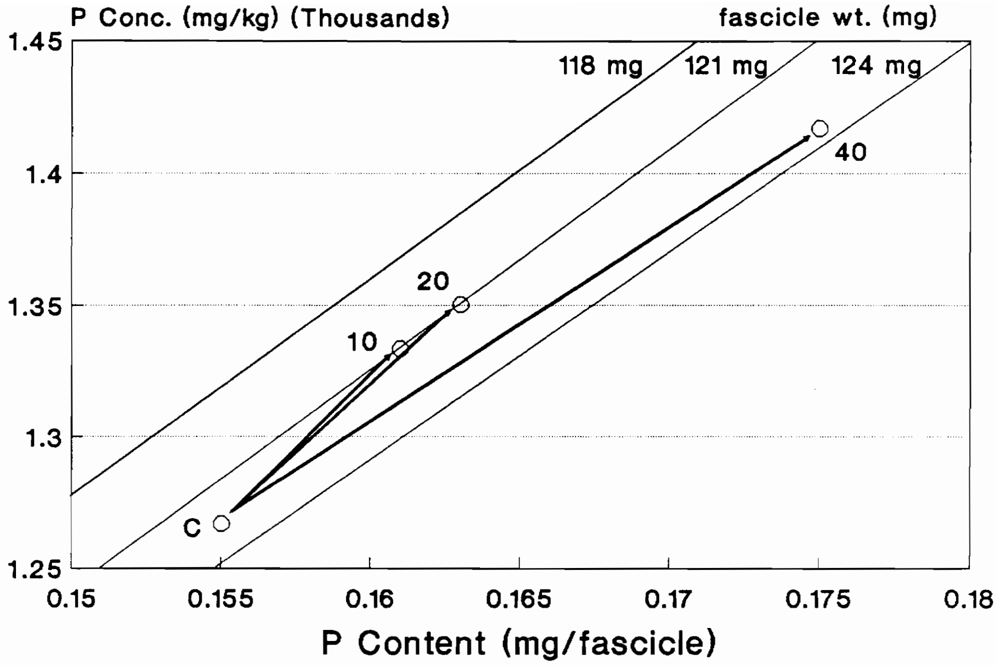

Figure 12a. Vector diagram of red pine fascicle response to sludge-borne P 12 months following sludge application for Adams County, Wisconsin

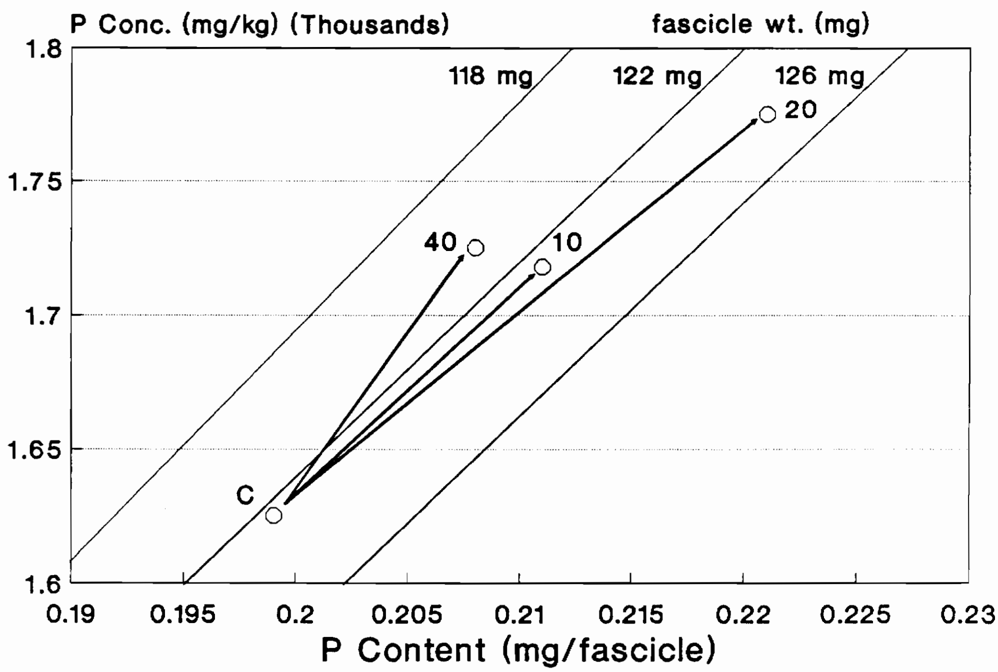

Figure 12b. Vector diagram of red pine fascicle response to sludge-borne P 12 months following sludge application for Wood County, Wisconsin

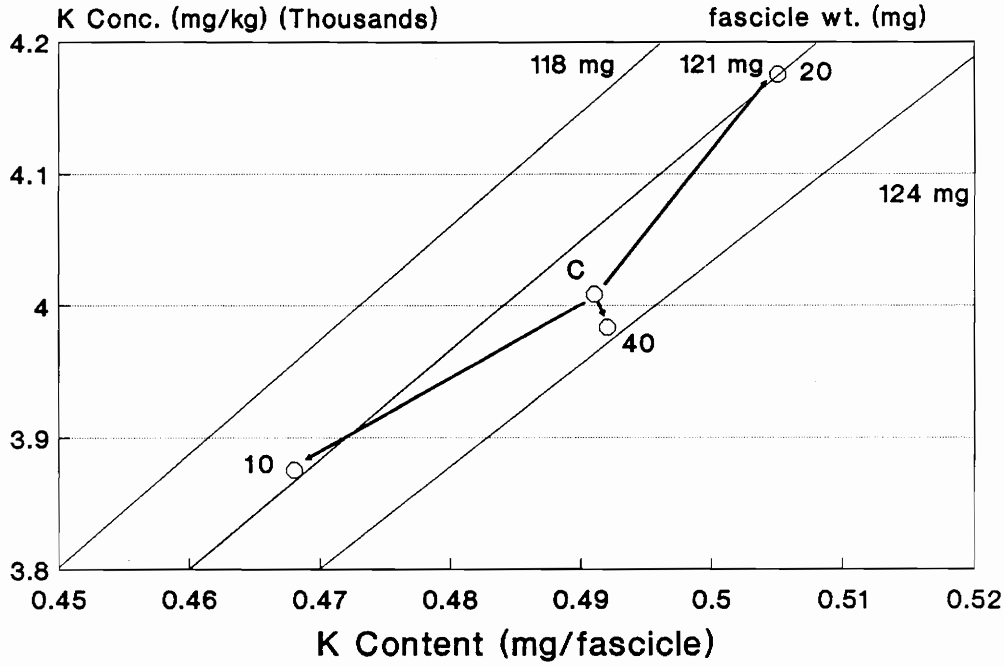

Figure 13a. Vector diagram of red pine fascicle response to sludge-borne K 12 months following sludge application for Adams County, Wisconsin

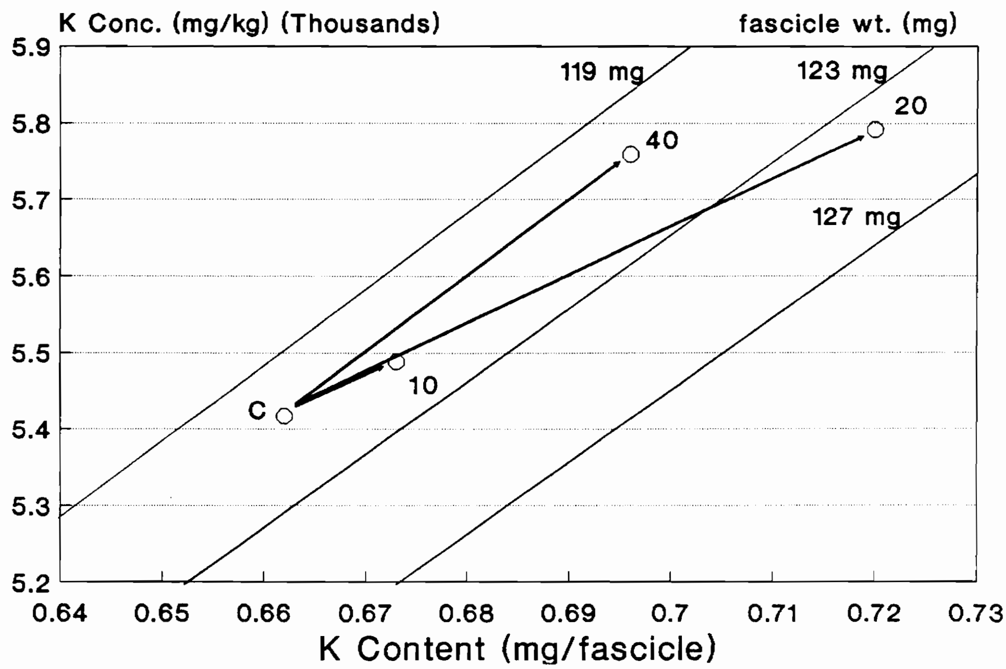

Figure 13b. Vector diagram of red pine fascicle response to sludge-borne K 12 months following sludge application for Wood County, Wisconsin

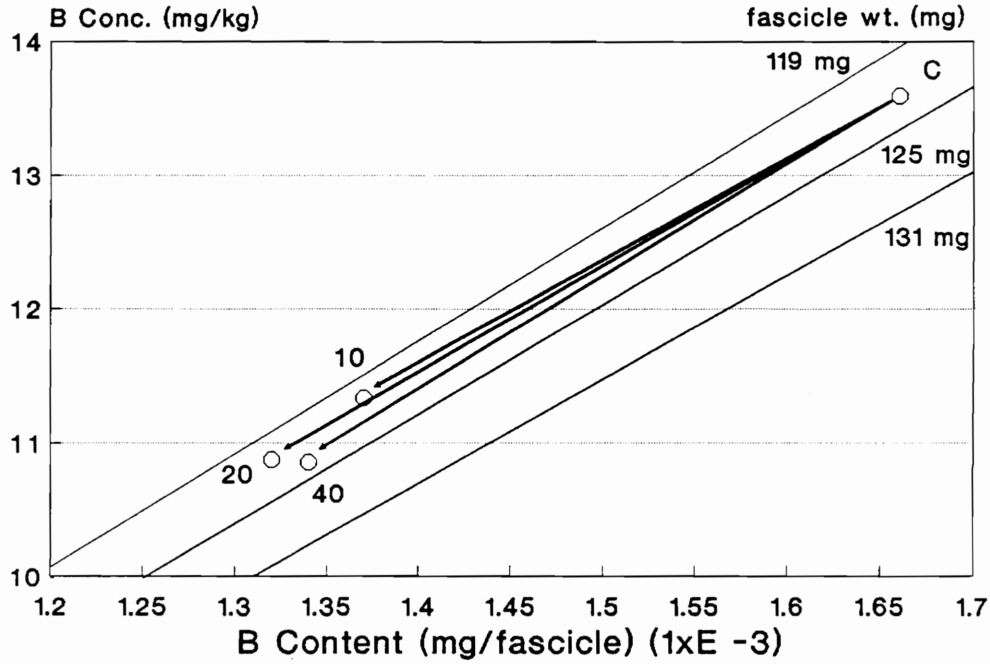

Figure 14a. Vector diagram of red pine fascicle response to sludge-borne B 12 months following sludge application for Adams County, Wisconsin

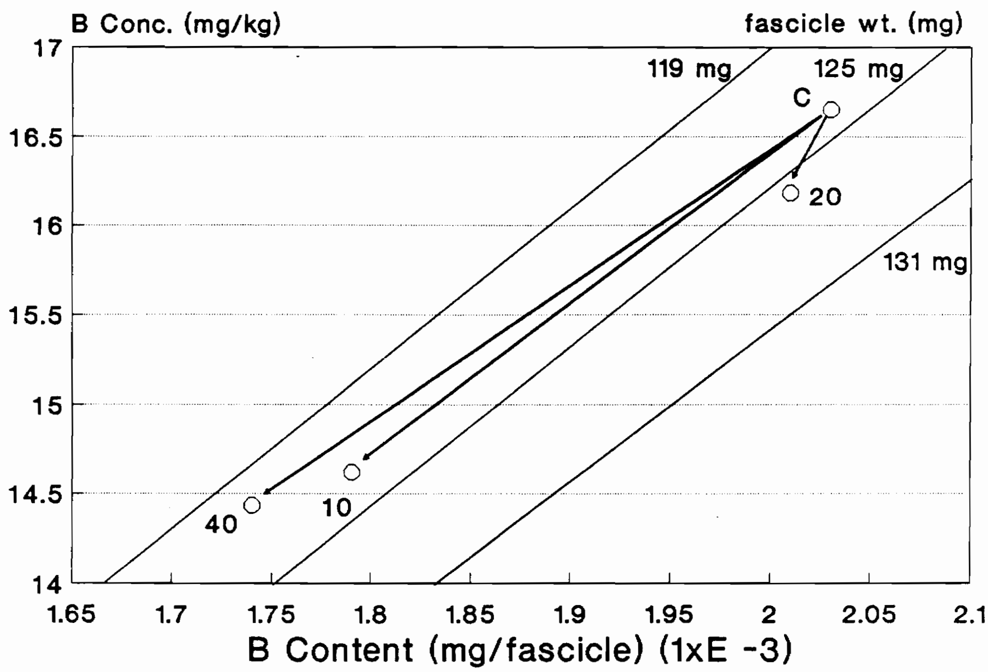

Figure 14b. Vector diagram of red pine fascicle response to sludge-borne B 12 months following sludge application for Wood County, Wisconsin

foliar boron concentrations in the red pine were indicative of low or deficient boron levels (Stone, 1968), suggesting that conditions other than sludge application also contributed to low red pine foliar boron concentrations.

Boron deficiency is in fact the most common micronutrient deficiency in forest plantations (Stone, 1968), and in the context of this study may offer some further explanation of the generally poor growth of the red pine the first growing season following sludge application. The inherently low red pine foliar boron concentrations present in both plantations, and the reduced boron levels in plots amended with sludge suggests that other factors, in addition to sludge application, were contributing to low or deficient boron levels. Reduced soil moisture levels resulting from droughty condition and increasing levels of sludge application would have reduced the movement, and subsequent availability of boron (Tisdale and Nelson, 1975). Furthermore, sandy soils low in silt, clays or micas, and low in organic matter content, as is characteristic of the Plainfield series, typically exhibit low or deficient boron concentrations due to the low ability of these soils to retain boron (Stone, 1968). As previously discussed, the addition of large amounts of sludge-borne N and P resulted in increased foliar concentration of these elements, which likely increased the boron requirement of the red pine as well (Bradford, 1966). Lastly, it has been suggested that shifts in soil pH towards neutral or alkaline conditions results in decreased availability of boron in the soil, possibly as a result of an unfavorable (increasing) calcium to boron ratio (Tisdale and Nelson, 1975). Calcium to boron ratios were found to increase in the Adams County plantation from 126:1 (control) to 154:1 (40 Mg/ha application), and from 100:1 (control) to 123:1 (40 Mg/ha application) in the Wood County site. Furthermore, regression analysis performed by researchers at the University of Wisconsin on soil pH among the sludge treatment plots showed a highly significant relationship between soil pH and sludge application rate, in which soil pH increased with increasing rate of sludge application. In view of the existing environmental and edaphic conditions, coupled with the apparent affect of sludge application on boron availability, the reduced availability of boron likely contributed to the poor growth performance of the red pine the first year following sludge application.

Conclusions

The disposal of paper mill wastewater solids has become an increasing problem in recent years, both from an economic and environmental standpoint. Silvicultural landspreading of mill waste represents one viable alternative to this growing dilemma. Increasing application rates of a primary/secondary, nutrient-enriched paper mill sludge applied to 6 and 8-year old red pine did not significantly effect red pine volume growth relative to controls in the two study sites for either growing season. Nonetheless, reduced growth trends did occur, particularly in the younger plantation, in the first year following sludge application. This may be attributable to absorption of limited rainfall by the sludge blanket, thereby reducing the amount of available soil moisture. Additionally, the reduced availability of boron, a necessary element for the formation of new tissue, may have contributed to poor red pine growth the first year following sludge application. Tree growth in the Wood County site varied considerably the first year after sludge application, making any interpretation of the effect of application rate on tree growth difficult. The initial growth response as effected by application rate appeared 12 months following treatment in the form of increased needle biomass in the younger plantation, which coincided with elevated foliar nutrient concentrations, namely N and P. Concurrently, fascicle weight was not found to be effected by sludge application in the older plantation. Tree growth appeared to respond slightly to sludge application the following year, particularly among the higher application rate, suggesting a gradual increase in canopy photosynthetic potential stemming from increased levels in foliar nutrients.

Chapter 2: Effects of Weed Control Following Papermill Sludge Application on Competing Vegetation and Tree Growth

Introduction

The disposal of papermill sludge, a bi-product of the paper-making process, has become a significant problem in the last decade. Presently, it is estimated that the U.S. pulp and paper industries produce over 3 million dry tonnes (Mg) annually (Rock and Alexander, 1983). Disposal of this material on forest land offers a cost-effective means of waste management as compared to landfilling or incineration - methods which have historically been used for disposal of this material. Utilization of these wastes has become an increasingly accepted practice in states such as Maine, Ohio and Wisconsin, where aggressive papermill sludge recycling programs are in effect. Wisconsin, the number one paper-making state, has already reduced the amount of sludge going to landfills by approximately 27%, and the industry is hopeful for a 100% reduction in sludge landfilling (Logsdon, 1988).

Due to potentially high concentrations of sludge-borne nutrients, these sludges are viewed as a low-cost alternative to commercial fertilizers. For example, nitrogen concentrations as high as 87,500 mg/kg have been reported in some papermill sludges (NCASI, 1984). Furthermore, since much of the nutrient pool is associated with stable components (i.e. lignin), these wastes tend to release nutrients slowly compared to commercially manufactured fertilizers.

Throughout the last decade, a sizeable research effort has examined the impact of papermill sludge application on tree growth. Numerous studies have shown better tree growth and survival following application of papermill sludges (Berry, 1985; Brockway, 1983; Henry, 1986; Schrandt, 1987; Shields et. al, 1986; Smithe and Morin, 1977; Aspitarte, 1980), while other studies have shown sludge application to have no impact (Magnuson, 1978), or to be detrimental to tree performance (Wilde, 1979).

Increases in herbaceous and woody competing vegetation has been suggested as one possible explanation for reduced tree growth following application of these sludges. Only one study, to date, has addressed this problem relative to the application of paper industry wastes. Brockway (1983), who applied 4, 8, 16 and 32 Mg/ha of papermill sludge to a 40 year old stand of red pine, found an increase in understory biomass of 92% among the heaviest treatment plots in contrast to controls. Visual inspection of treatment plots receiving the highest application revealed lush green growth of herbaceous vegetation late in the growing season when vegetation in control plots already had begun to discolor and approach dormancy.

Numerous studies indicate that fertilization is more effective when combined with weed control than when these treatments are applied singularly (McKee and Wilhite, 1988; Neary et al. 1985; Haywood and Tiarks, 1981). This is particularly true during the establishment phase of pine plantation management. To date, only one study has examined the efficacy of herbicidal weed reduction following application of paper industry sludge (Neary and Comerford, 1983). The authors found that the application of herbicide generally reduced weed biomass production by 57% - 61%. Unfortunately, a severe sludge effect and droughty conditions resulted in poor seedling survival, making it impossible to determine the effectiveness of the weed control on pine growth and survival.

This study was undertaken to determine the effect of three different application rates of a nutrient enriched, primary/secondary papermill sludge on herbaceous and woody competing vegetation following surface application. Herbicide was applied to evaluate the efficacy of weed control on tree growth and competing vegetation following papermill sludge application.

Results and Discussion

Competing Vegetation

Carex spp. (sedge) was the predominant herbaceous understory component in both plantations and comprised as much as 90% of the ground coverage. The application of increasing rates of papermill sludge did not significantly increase the standing above-ground biomass of sedge among treatments 9 months following sludge application (figure 15a). Similar to findings by Brockway (1983) and Neary and Comerford (1983), above-ground biomass production diminished by 56% among the highest sludge application rate relative to controls the first year following application. Previous studies have attributed this to a smothering affect by high application rates of dewatered sludge. Similarly, below-ground sedge biomass was highest on treatment plots receiving 20 Mg/ha of sludge with a subsequent drop in biomass where the heaviest application rate was used (figure 15b). There is some indication that the sedge may have responded in dry matter production the first growing season. Visual observation of the treatment plots 2 months following biomass sampling revealed denser sedge coverage among the heavier application rates.

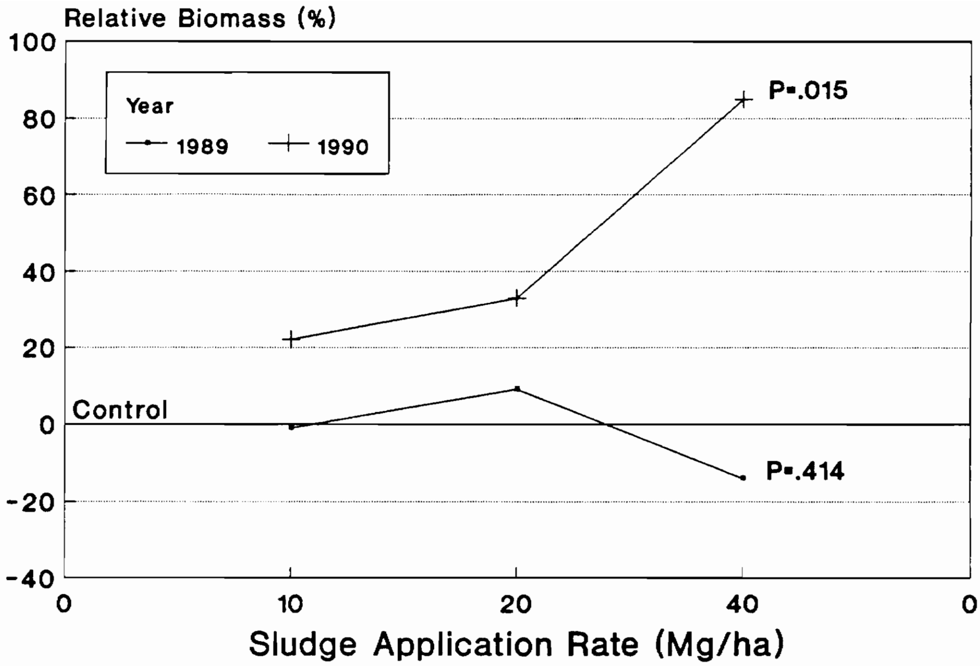

Figure 15a. Relative above-ground *Carex* spp. biomass 9 and 21 months following sludge application for Wood County, Wisconsin

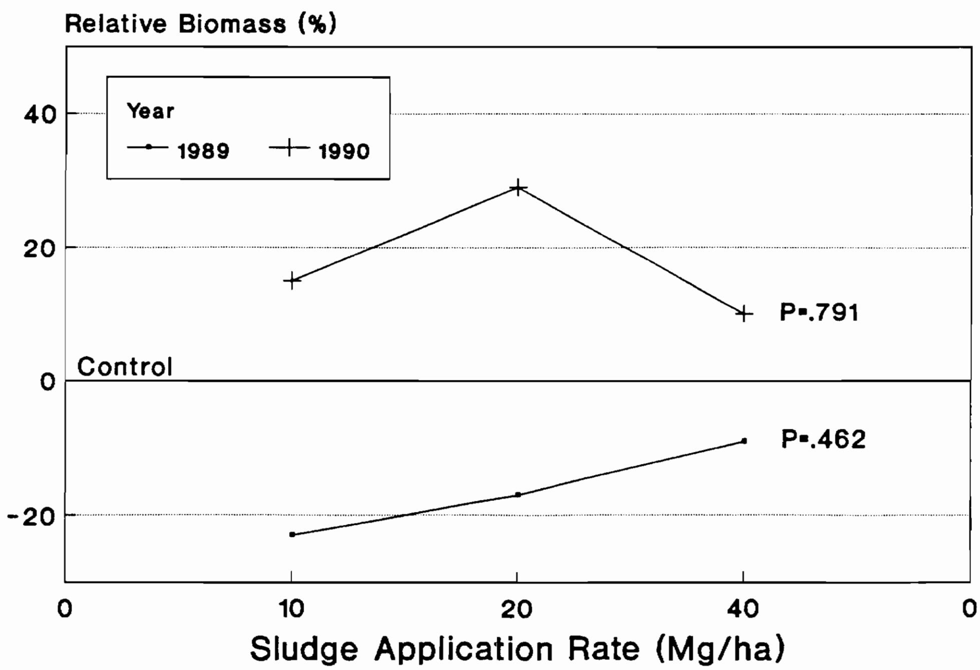

Figure 15b. Relative below-ground *Carex* spp. biomass 9 and 21 months following sludge application for Wood County, Wisconsin

By 1990, above-ground sedge biomass was found to substantially increase among all treatment plots relative to controls, with significant increases of 22%, 33% and 85% in the 10 Mg/ha, 20 Mg/ha and 40 Mg/ha treatment plots, respectively (figure 15a). Inspection of sedge growing in Wood County treatment plots revealed darker and denser sedge coverage in treatment plots receiving sludge as compared to control plots following the second year. Below-ground sedge biomass in 1990 followed a similar trend as the previous year, with non-significant increases in root biomass among the 10 and 20 Mg/ha treatments followed by a subsequent decrease in root biomass where the heaviest application rate occurred (figure 15b).

Based on results of the competing vegetation assessment system (CVAS), levels of competing hardwood competition between treatments were not significantly affected during the two years following sludge application (figure 16a and 16b). Additionally, the percent coverage of woody vegetation during 1989 closely approximated pre-treatment levels for both Adams and Wood Counties. Although woody competition index ratings differed significantly across treatment levels during 1989 for the Wood County site, the values closely approximated pre-treatment index ratings and do not suggest a sludge effect. Competition index ratings were lower in 1990 across all treatments for both study sites, reflecting the larger size of the crop trees in proportion to the surrounding hardwood competition (Appendix B).

This does not necessarily prove that hardwood competition did not respond to sludge application. The CVAS is sensitive to changes in height and crown size of hardwood competition; increases in diameter or density would not be discernible.

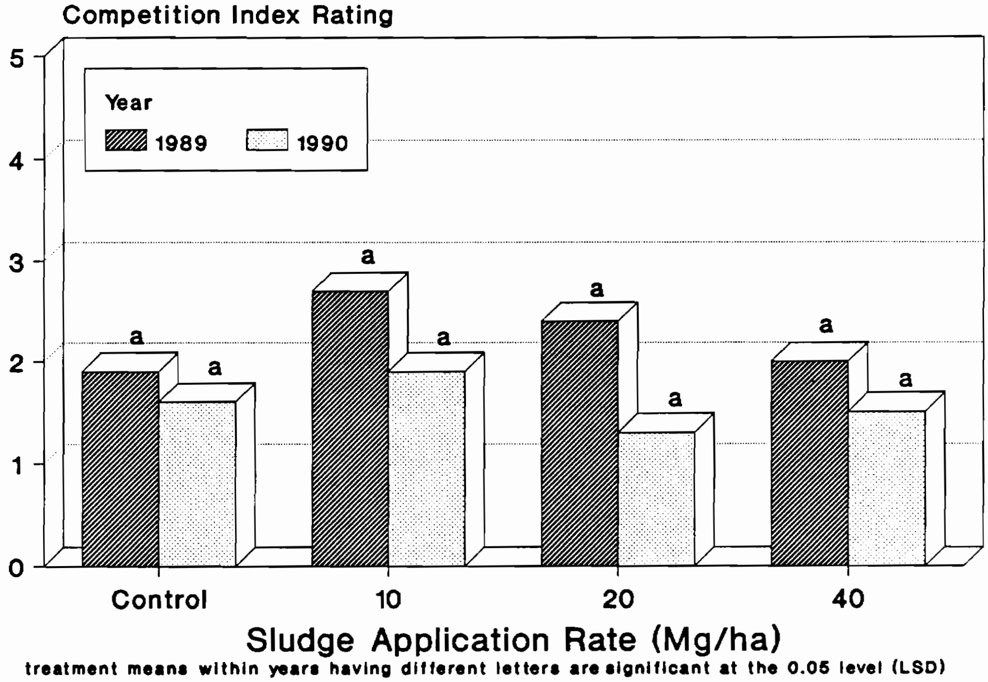

Figure 16a. Hardwood competition index ratings 10 and 22 months following sludge application for Adams County, Wisconsin

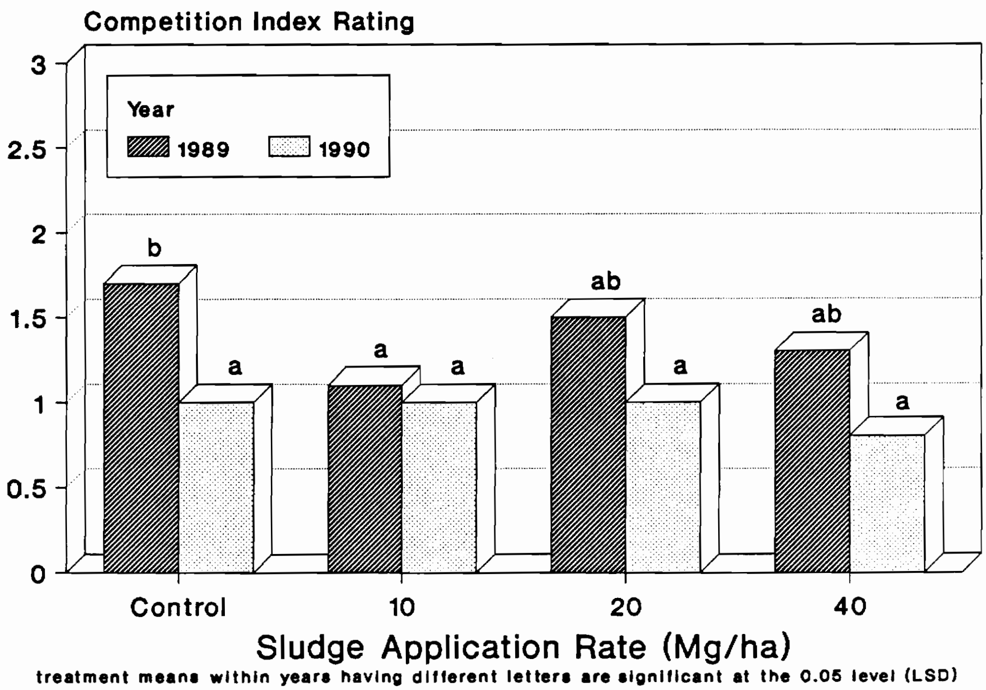

Figure 16b. Hardwood competition index ratings 10 and 22 months following sludge application for Wood County, Wisconsin

Additionally, the CVAS is not sensitive to subtle changes in hardwood competition unless a high level of sampling intensity is applied. Previous work by Safford (1973) suggests that northern hardwoods respond favorably to fertilization, but do so over a much longer time span than this study encompasses. Furthermore, Koterba et al. (1979) found no significant differences in basal area growth of northern hardwoods following applications of 5.8 and 28 dry Mg/ha of municipal sludge over a 2-year interval.

The fact that hardwood competition index values were lower in both study areas for 1990 as compared to 1989 reflects the increased height of the red pine and the lower percentage of hardwood vegetation which meet the height requirements for the CVAS, which was arbitrarily set at 1/2 the height of the crop tree. This suggests that, indeed, sludge application did not sufficiently stimulate the production of competing hardwood vegetation so as to impede with the growth of red pine, and that the red pine are, in effect, out-competing the hardwood vegetation.

The summer, above-ground, nutrient status of the *Carex spp.* (sedge), the predominant component of the herbaceous understory, was found to benefit significantly 21 months following treatment. Most notably, foliar N levels increased almost linearly with increasing sludge application rate. Background N levels of 12,900 mg/kg were increased 35%, to over 17,400 mg/kg in the heaviest sludge plots (figure 17). Similar increases in P, K, Ca and Mg occurred as well with the highest concentrations in treatment plots receiving the 40 Mg/ha application (Appendix B). By 1990, the below-ground nutrient status of *Carex* spp. had also significantly

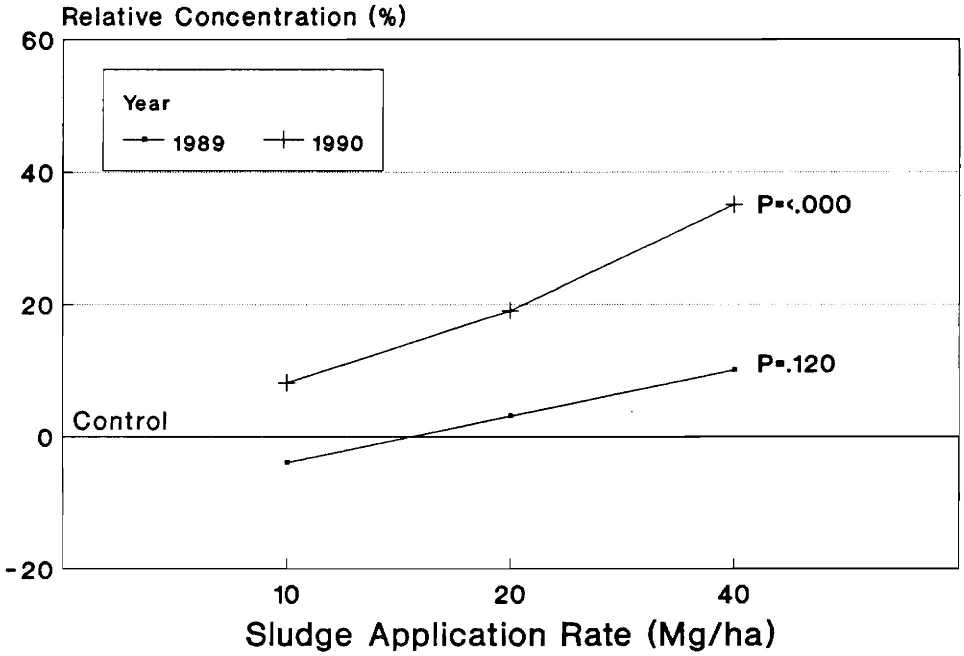

Figure 17. Relative above-ground concentration of N in *Carex* spp. 9 and 21 months following sludge application for Wood County, Wisconsin

benefitted from sludge application. Increases in N, P, Ca and Mg occurred with increasing rates of sludge application, with the highest below-ground nutrient concentrations for these elements occurring in plots receiving 40 Mg/ha of sludge.

These results compare similarly to those found by Campa (1982), who reported significantly higher phosphorus concentration levels in summer samples of herbaceous species following sludge application. Seon (1984) also found higher phosphorus levels in sedges from a pine study area the summer after a June application of sludge, and Brockway (1983), found significant increases in phosphorus and total nitrogen in the herbaceous understory as early as 2 months following application of a nutrient-enriched papermill sludge. Elevated nitrogen levels were also found in current annual growth for seven understory plants common in Douglas-fir forests (West, Zasoski, Taber, unpublished data).

By 1990, significant increases in nutrient levels on a weight per volume basis occurred in above-ground sedge tissue as a result of significantly higher sedge dry matter production in plots amended with sludge (figures 18a). Although below-ground nutrient N content increased among sludge amended plots, a significant rate relationship was not found (figure 18b). Although a complete assessment of inputs and recycled nutrients was not performed, an estimate of recovery of sludge-borne nutrients by sedge was made by subtracting total amounts of N and P (above and below-ground) in controls from those levels in sludge treatment plots. This was deemed valid by assuming inputs due to precipitation to be equal throughout the study area. Additionally, because there was no apparent sludge effect on the nutrient

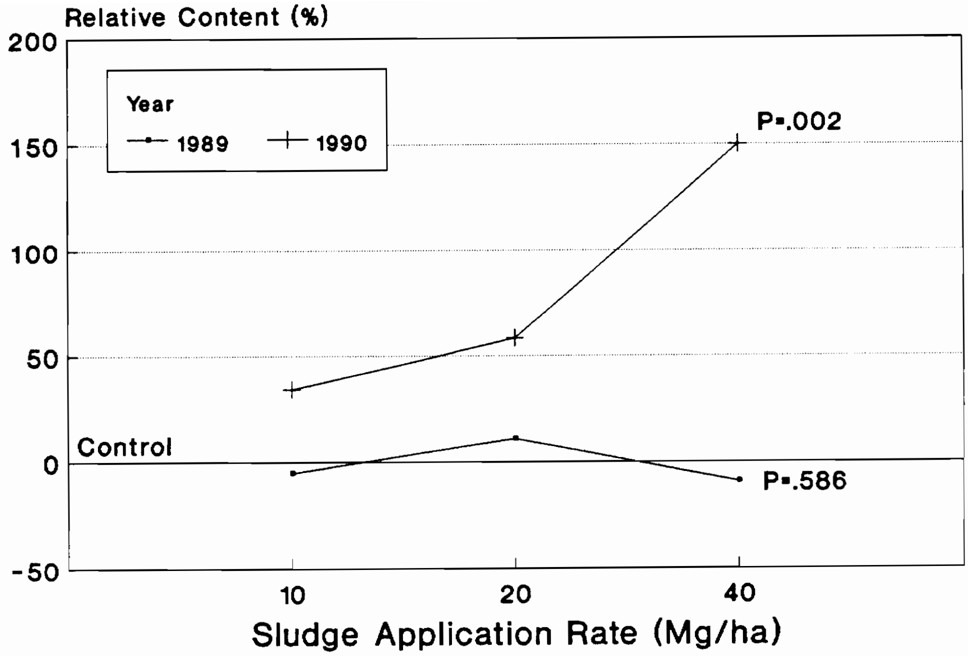

Figure 18a. Relative above-ground content of N in *Carex* spp. 9 and 21 months following sludge application for Wood County, Wisconsin

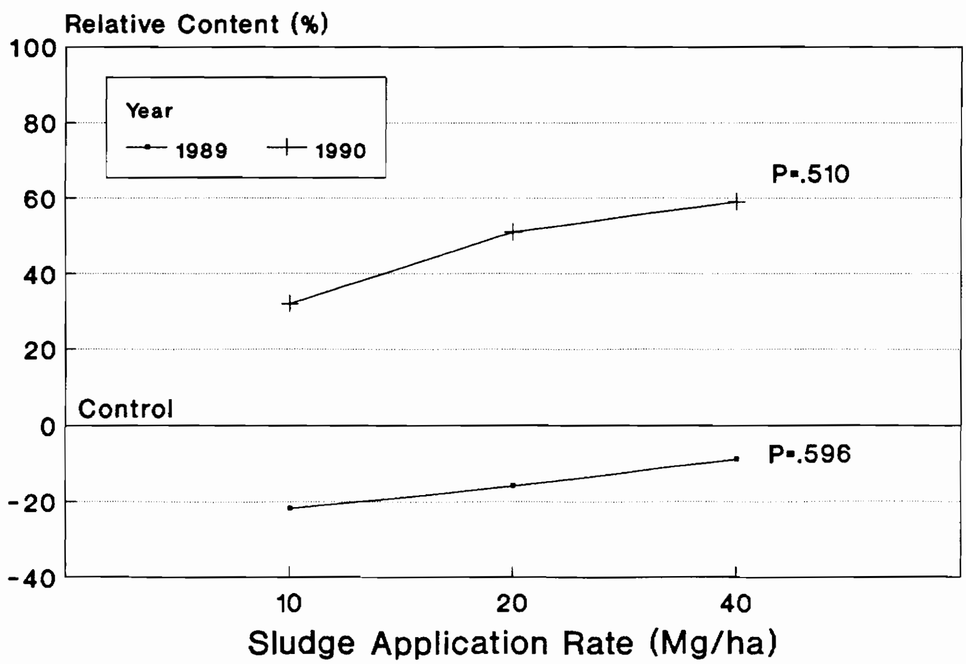

Figure 18b. Relative below-ground content of N in *Carex* spp. 9 and 21 months following sludge application for Wood County, Wisconsin

content of the sedge in 1989, nutrient input due to recycling was considered essentially equal across all treatments. Twenty months following sludge application, sedge N recovery rates were 19%, 16% and 12% for 10, 20 and 40 Mg/ha treatment plots. Similarly, P recovery rates were 24%, 15% and 11%. The reduction in nutrient recovery rate with increasing application rates suggests a reduction in nutrient availability among the higher application rates, thought to be a result of reduced decomposition rates with increasing rate of sludge application. Sludge samples taken in 1990 illustrate this, revealing reductions in dry weight over a 20 month period of 87%, 81% and 78% in 10, 20 and 40 Mg/ha plots respectively.

Weed Control

Weed control performed following the 1989 growing season dramatically reduced herbaceous and woody competition levels during 1990 in both study areas. The percent coverage of woody competing vegetation was reduced across all treatments in both plantations following herbicide application (table 5). Simultaneously, significant reductions in woody competition index rating values occurred in the Wood County study area, with woody vegetation being eliminated altogether in a number of sludge treatment plots. Herbicide application also reduced the amount of herbaceous vegetation in both study areas among weed control subplots. Herbaceous weed control was most dramatic among treatment plots receiving 40 Mg/ha of sludge, with reductions in percent coverage of 55% and 46% in Adams and Wood County sites, respectively. Additionally, the height of the

Table 5 - Effects of weed control on competing vegetation for Adams and Wood Counties, Wisconsin

	Adams County				Wood County			
Sludge application rate, Mg/ha	0	10	20	40	0	10	20	40
1990								
bare ground (%)								
weed control	52.1b	70.9b	11.0a	15.9a	31.9a	36.3b	34.2b	53.2b
no weed control	27.1a*	26.8a	54.9b	71.1b	9.2a	8.7a	3.7a	1.1a
woody coverage (%)								
weed control	0.5a	0.9a	1.3a	2.7a	0.5a	0.3a	0.0a	0.0a
no weed control	21.8b	28.2b	25.2b	27.5a	8.3b	7.4b	9.3b	12.0b
herb. coverage (%)								
weed control	47.5a	28.3a	43.7a	26.2a	67.6a	63.5a	65.8a	46.8a
no weed control	51.1a	45.0b	63.8a	57.7a	82.4a	83.9b	87.0a	86.9b
herb. height (cm)								
weed control	33.7a	32.6a	33.4a	32.9a	35.3a	36.2a	36.3a	35.1a
no weed control	38.0a	39.8b	44.8b	46.3b	38.4b	41.0a	41.8a	45.3b
herb. volume (cm^3)								
weed control	1.0a	0.7a	1.0a	0.6a	1.5a	1.5a	1.5a	1.1a
no weed control	1.3a	1.2b	1.8a	1.7a	2.0a	2.1b	2.3a	2.5b
Comp. Index Rating								
weed control	0.3a	0.3a	0.3a	0.2a	0.1a	0.1a	0.0a	0.0a
no weed control	1.6a	1.9b	1.3a	1.5a	1.0b	1.0b	1.0b	0.8b

* Between weed control means followed by different letters are significant at the 0.10 level (LSD)

herbaceous vegetation and volume of herbaceous vegetation was lower among weed control subplots for all application rates on both sites. In general, herbaceous weed control was highly variable in subplots receiving herbicide, consequently, few of the differences were significant at the 0.05 level. Neary and Comerford (1983) noted similar findings, in which grasses were reduced, but not eliminated by herbicide application among four papermill sludge application rates, and in which no significant differences in weed cover occurred between herbicide treatments.

Although previous studies have shown weed control to significantly affect tree growth and survival following chemical fertilization and sludge application, weed control efficacy, in the context of this study, generally diminished among the heavier sludge application rates. For example, in weed control sub-plots, total volume growth increased 62% and 34% in the controls and 10 Mg/ha treatment plots, respectively, but was reduced by 8% in the 20 Mg/ha plots and by 15% when the heaviest treatment was applied relative to red pine not receiving herbicide application (figure 15a). In comparison, tree growth in the Wood County plantation was generally poorest in weed control subplots for all growth parameters among all sludge treatments (figure 15b).

This interaction effect may be due to poor penetration of Oust^{tm}, a soil activated herbicide, among the higher sludge rates. The fact that growth parameters in weed control subplots among the higher sludge rates are lower than non-weeded subplots also suggests an antagonistic response between herbicide and sludge. The generally poor response in the Wood County plantation is believed to be attributable

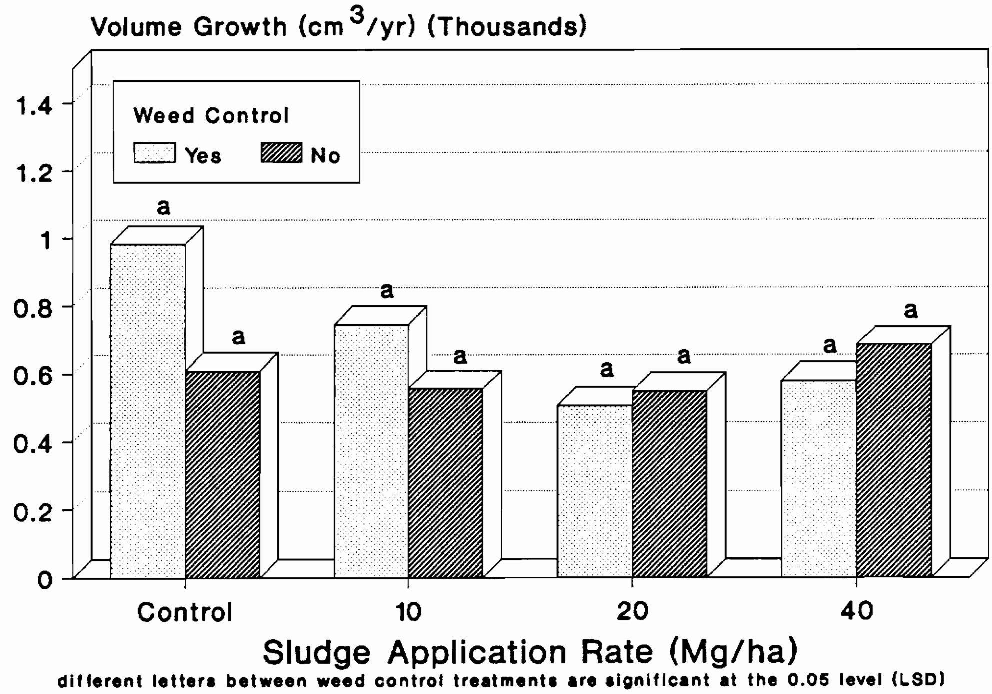

Figure 19a. Volume growth of red pine 11 months following weed control and 22 months following sludge application for Adams County, Wisconsin

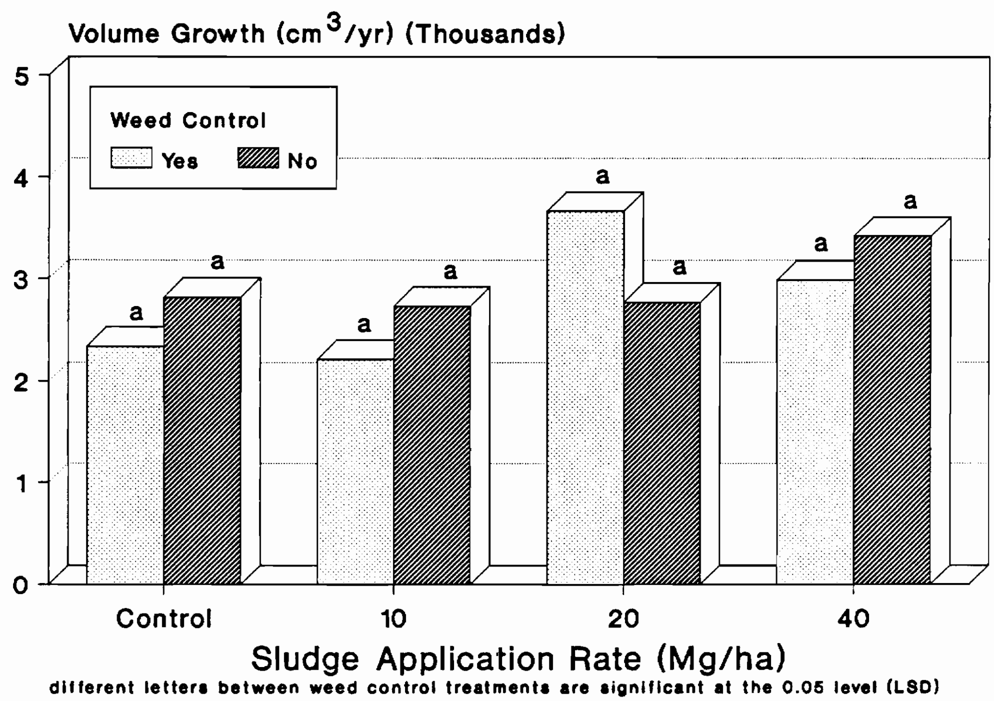

Figure 19b. Volume growth of red pine 11 months following weed control and 22 months following sludge application for Wood County, Wisconsin

to poor timing of the herbicide application. At the time of application, seedlings were undergoing lammas shoot production. Windy conditions in conjunction with increased crown closure conditions in the older plantation made it difficult to protect trees during herbicide application, which likely resulted in substantial amounts of herbicide being deposited on actively growing shoots, resulting in damage to subsequent bud formation. Garlon 4[tm], a foliar active component of the herbicide application, has been shown to cause temporary damage and growth suppression where contact with conifers occurs.

The fact that the red pine did not respond to weed control following sludge application raises question concerning the use of costly cultural treatments in this instance. It is widely accepted that weed control is considered more effective on higher quality sites where levels of competing vegetation are potentially high and where crop trees are more likely to be responsive to intensive silvicultural treatments. The site index for red pine in both study areas was estimated at 55 (base age of 50), indicating somewhat marginal sites. As evident in the competition index levels, which for the most part did not exceed a rating of 2, hardwood competition was inherently low for both study sites, comprising, on average, only 25% or less of the immediate area surrounding an individual red pine. In addition, with the possible exception of the younger Adams County plantation, herbaceous vegetation was no longer likely a factor governing stand growth due to the establishment of the root system. These factors suggest a situation in which: (1) crop trees were not under extreme stress due to interspecific competition, and (2) growth response to release and herbaceous weed control would be small.

Conclusions

Four application rates (0, 10, 20 and 40 Mg/ha) of a nutrient enriched, primary/secondary papermill sludge applied to 6 and 8 year old red pine plantations resulted in significant increases in foliar and root N, P, K, Ca and Mg concentrations as well as above-ground biomass production 20 months following sludge application. Concurrently, the percent coverage and competition index values of hardwood competition were apparently not affected by increasing rates of sludge application.

Total weed control performed 11 months following sludge application resulted in significantly higher proportions of bare ground in weed control subplots, with reductions in the percent coverage of woody and herbaceous vegetation, herbaceous height and herbaceous volume occurring. Competition index values which qualitatively assess the amount of hardwood competition directly impacting crop trees was reduced in both study sites, most notably in the Wood County site where an additional basal spray application was performed.

Tree growth parameters in both study areas were generally considered unresponsive to herbicide application, which raises questions about the efficacy of weed control following application of these wastes. Given the potentially high amounts of sludge-borne nutrients and their potential impact on competing vegetation, weed control clearly constitutes a viable management tool, however, in situations where crop trees are already established and where competing vegetation levels are not excessively high, little gain may be realized through use of intensive vegetation management. More importantly, the reduction or removal of the herbaceous understory may lead to increased concentrations of undesirable leachates in the soilwater and groundwater.

Summary

The increased production of pulp and papermill sludges in recent years has prompted the pulp and paper industry to seek alternatives over landfilling and incineration as waste disposal methods. Many state regulations mandate that acceptable disposal methods not only dispose of the nutrient load in a manner which is not harmful to site quality, but also provide some benefit as well. The disposal of these wastes on forestland is considered one such alternative. This study was designed to assess the impact of different application rates of a surface applied, nutrient enriched, primary/secondary papermill sludge on growth of young red pine and competing vegetation, as well as the efficacy of total weed control on tree growth and competition following sludge application.

The initial positive response of red pine to sludge application appeared 12 months following sludge application with increases in foliar concentrations of several important macronutrients, which coincided with increased foliar dry matter production relative to sludge application rate in the younger plantation. Vector analysis, a technique which allows for diagnostic and predictive interpretation of

nutrient responses showed that luxury consumption was the dominant foliar response among most nutrients 12 months after sludge application. It is possible that sufficient time had not elapsed for an increase in foliar dry matter production to occur, and that increases in foliar nutrition levels in 1989 may suggest a gradual buildup in photosynthetic potential, followed by a biomass response in future years.

Results following the first year indicate that higher sludge application rates may have a detrimental impact on growth of young red pine. In the case of this study, this was thought to be due to absorption, and subsequent evaporation, of limited precipitation in the sludge blanket among the higher application rates.
By the second year (20 months following sludge application), roughly 80% of the sludge blanket had decomposed and there was some indication of tree response to sludge application, particularly among the higher application rates.

The popularity of silvicultural landspreading of papermill sludges in recent years has raised questions concerning the impact of sludge-borne nutrients on herbaceous and woody competing vegetation and the efficacy of weed control following application of these wastes. Weed control performed 11 months following sludge application reduced herbaceous and woody vegetation in both study areas 9 months later, without a corresponding increase in crop tree performance. This raises the question as to whether the added cost of intensive vegetation management is justifiable when weed control is performed following application of mill wastes. On marginal sites, such as those in this study, where stands are established or nearing establishment, and where competing vegetation levels are not excessively high, weed control may not be justifiable. In such cases, intensive vegetation control would merely detract from the economic attractiveness landspreading offers over other waste disposal approaches. Clearly more research needs to be done which examines the effectiveness of vegetation management performed in conjunction with waste disposal, more specifically, studies centered on the impacts of timing and rates of weed control relative to different methods and rates of paper mill sludge application.

Lastly, since increased red pine growth was apparently not sacrificed by competition for sludge-borne nutrients and increased dry-matter production of the herbaceous understory, herbaceous competition, in the context of this study's use of paper mill sludge, can be viewed as beneficial in that nutrients otherwise predisposed to leaching are retained. Since prevention of groundwater contamination with undesirable leachates is paramount in application of these sludges, chemical control of herbaceous competition, or woody competition for that matter, may simply result in the improvement of stand growing conditions at the expense of environmental quality.

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Appendix A

Table 1 - Growth and percent growth relative to controls for red pine 10 and 22 months following sludge application for Adams County, Wisconsin

Sludge application rate, Mg/ha	0	10	20	40
1st Year				
Diameter (mm)	6.32a	4.62ab (73)	4.02ab (64)	3.84b (61)
Height (cm)	23.34a	19.85ab (85)	15.55b (67)	16.67b (71)
Crown Width (cm)	20.80a	12.55b (60)	12.63b (61)	14.28ab (69)
Volume (cubic cm)	359.2a	264.6a (74)	188.1a (52)	189.6a (53)
2nd Year				
Diameter (mm)	6.89a	6.62a (97)	8.00a (116)	8.56a (124)
Height (cm)	24.08a	22.04a (92)	26.39a (110)	29.72a (123)
Crown Width (cm)	9.23a	11.51a (125)	16.10a (174)	16.27a (176)
Volume (cubic cm)	607.7a	554.7a (91)	549.1a (90)	684.2a (113)
2-Year Interval				
Diameter (mm)	13.21a	11.24a (86)	12.02a (91)	12.40a (94)
Height (cm)	47.42a	41.89a (88)	41.94a (88)	46.39a (98)
Crown Width (cm)	30.03a	24.06a (80)	28.73a (96)	30.55 (102)
Volume (cubic cm)	967.0a	819.3a (85)	737.3a (76)	873.8a (90)

Table 2 - Growth and percent growth relative to controls for red pine 10 and 22 months following sludge application for Wood County, Wisconsin

Sludge application rate, Mg/ha	0	10		20		40	
1st Year							
Diameter (mm)	8.38ab	9.76a	(116)	6.33b	(75)	7.71ab	(92)
Height (cm)	18.93a	23.50a	(124)	15.37a	(81)	19.92a	(105)
Crown Width (cm)	6.67a	9.82a	(147)	4.57a	(69)	6.69a	(100)
Volume (cubic cm)	1740.5ab	2278.7b	(131)	1395.6a	(80)	1748.6ab	(100)
2nd Year							
Diameter (mm)	8.83a	8.36a	(95)	9.14a	(104)	11.68a	(132)
Height (cm)	31.67a	29.58a	(93)	27.64a	(87)	33.64a	(106)
Crown Width (cm)	16.51a	14.27a	(86)	14.90a	(90)	24.87a	(151)
Volume (cubic cm)	2826.1a	2737.5a	(97)	2775.1a	(98)	3423.2a	(121)
2-Year Interval							
Diameter (mm)	17.21ab	18.12ab	(105)	15.47a	(90)	19.39b	(113)
Height (cm)	50.61a	53.08a	(105)	43.01a	(85)	53.56a	(106)
Crown Width (cm)	23.18a	24.09b	(104)	19.47a	(84)	31.56b	(136)
Volume (cubic cm)	4566.6a	5016.2a	(110)	4170.7a	(91)	5171.8a	(113)

Table 3 - Foliar nutrient levels of red pine 12 months following sludge application for Adams County, Wisconsin

Sludge application rate, Mg/ha	0	10	20	40
Nutrient				
	mg kg^{-1}			
Nitrogen	12220a	12400a	12800ab	13800b
Phosphorus	1270a	1330ab	1350ab	1420b
Potassium	4010a	3870a	4170a	3980a
Calcium	1710b	1580ab	1470a	1680b
Magnesium	980a	1090b	1070b	1300b
Sulpher	790a	790a	790a	840a
N:P ratio	9.6:1	9.3:1	9.5:1	9.7:1
	mg kg^{-1}			
Zinc	29.8a	29.2a	27.2a	31.0a
Boron	13.6b	11.3ab	10.9a	10.9a
Manganese	217.3a	244.9a	207.6a	215.0a
Iron	44.3a	44.2a	48.5a	47.4a
Copper	3.0a	3.0a	3.0a	3.0a
Aluminum	227.6a	221.3a	209.6a	207.3a
Sodium	61.8a	61.6a	61.4a	61.1a

* Means followed by different letters are significantly different at the 0.05 level (L.S.D.)

Table 4 - Foliar nutrient levels of red pine 12 months following sludge application for Wood County, Wisconsin

Sludge application rate, Mg/ha	0	10	20	40
Nutrient				
	mg kg^{-1}			
Nitrogen	12900a	13600ab	14400b	15200c
Phosphorus	1620a	1720ab	1770b	1730ab
Potassium	5420a	5490a	5790a	5760a
Calcium	1670b	1700ab	1680a	1770b
Magnesium	1100a	1170ab	1170ab	1210b
Sulpher	880a	910a	970b	970b
N:P ratio	8.0:1	7.9:1	8.1:1	8.8:1
	mg kg^{-1}			
Zinc	31.8a	33.3a	34.1a	36.8a
Boron	16.6a	14.6a	16.2a	14.4a
Manganese	160.9a	173.7a	185.4a	183.5a
Iron	50.1a	48.4a	52.8a	49.2a
Copper	4.4a	4.2a	5.2a	4.3a
Aluminum	265.3a	277.8a	269.1a	238.4a
Sodium	62.7a	64.4a	64.1a	64.4a

* Means followed by different letters are significantly different at the 0.05 level (L.S.D.)

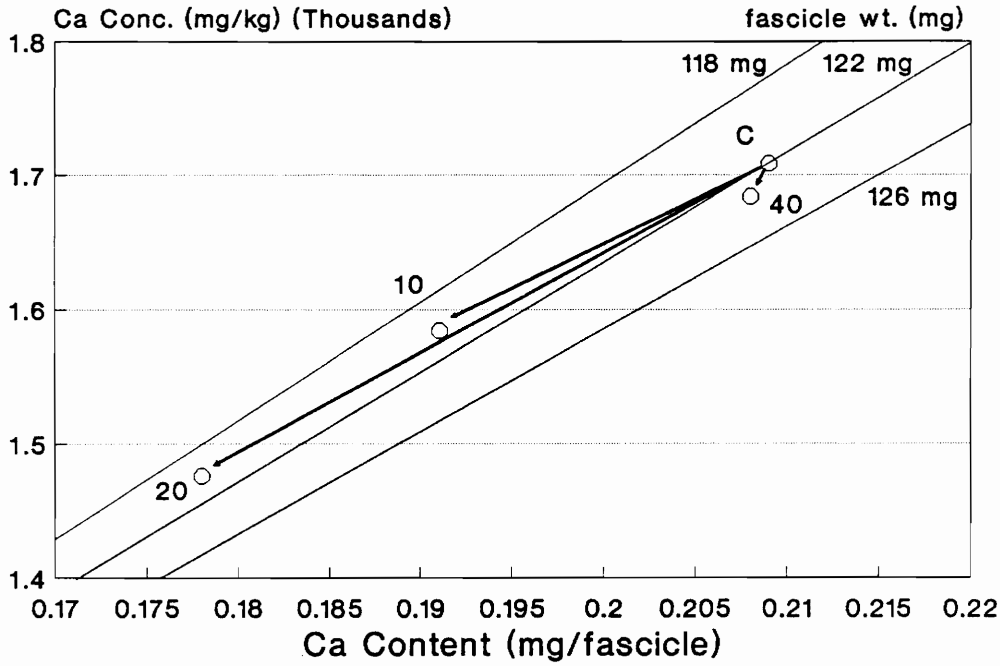

Figure 1a. Vector diagram of red pine fascicle response to sludge-borne Ca 12 months following sludge application for Adams County, Wisconsin

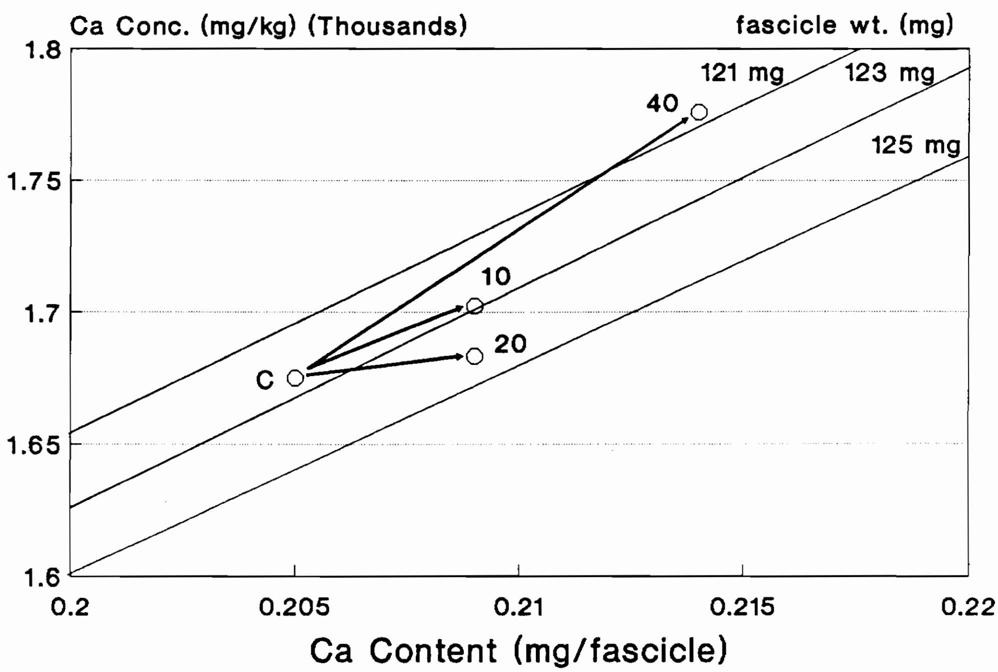

Figure 1b. Vector diagram of red pine fascicle response to sludge-borne Ca 12 months following sludge application for Wood County, Wisconsin

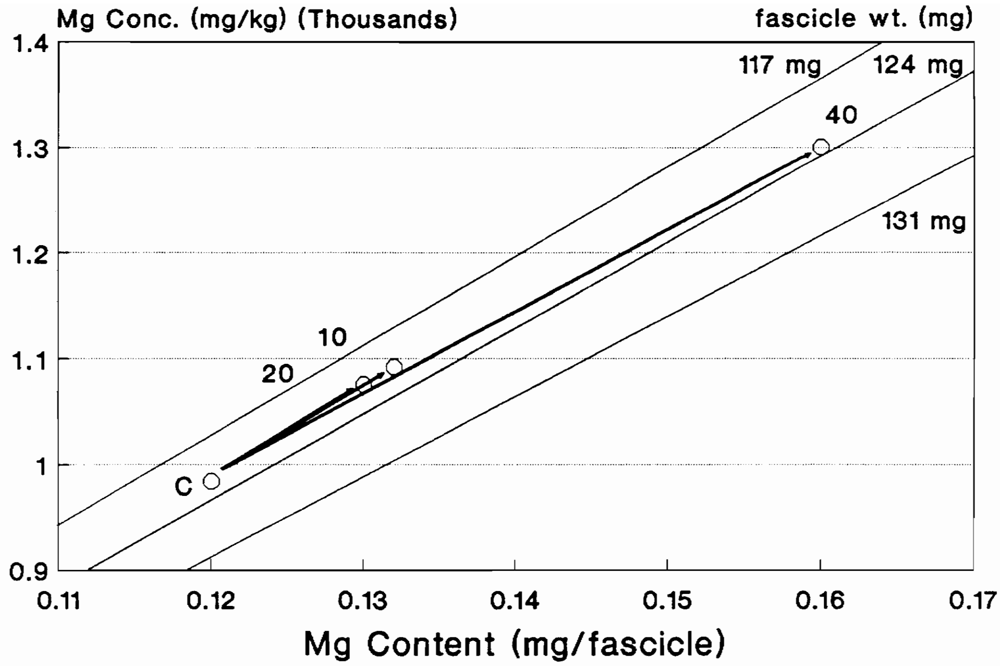

Figure 2a. Vector diagram of red pine fascicle response to sludge-borne Mg 12 months following sludge application for Adams County, Wisconsin

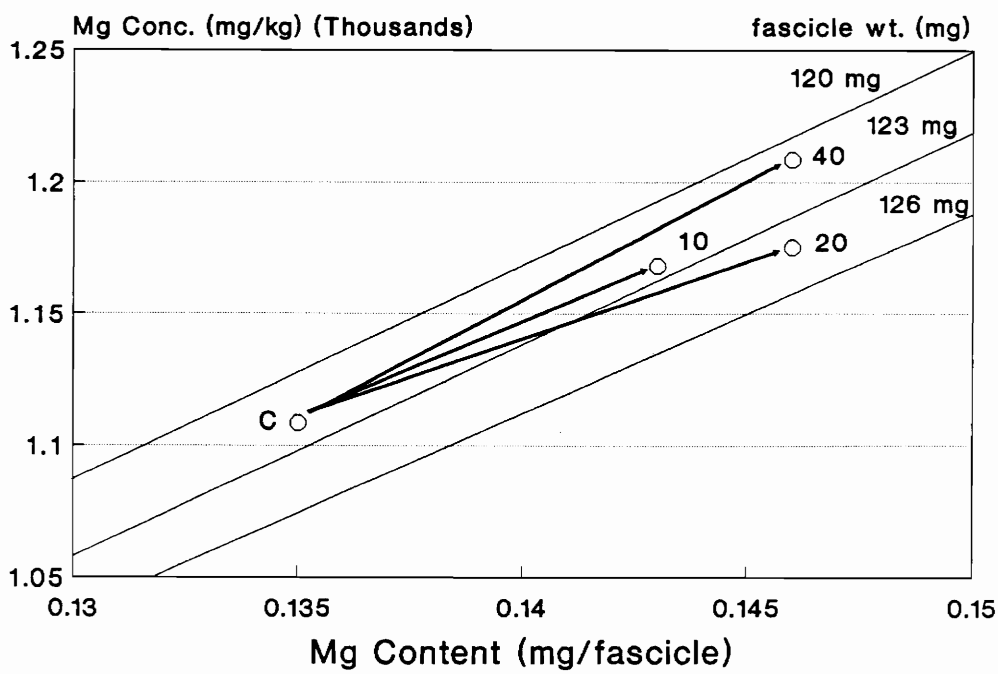

Figure 2b. Vector diagram of red pine fascicle response to sludge-borne Mg 12 months following sludge application for Wood County, Wisconsin

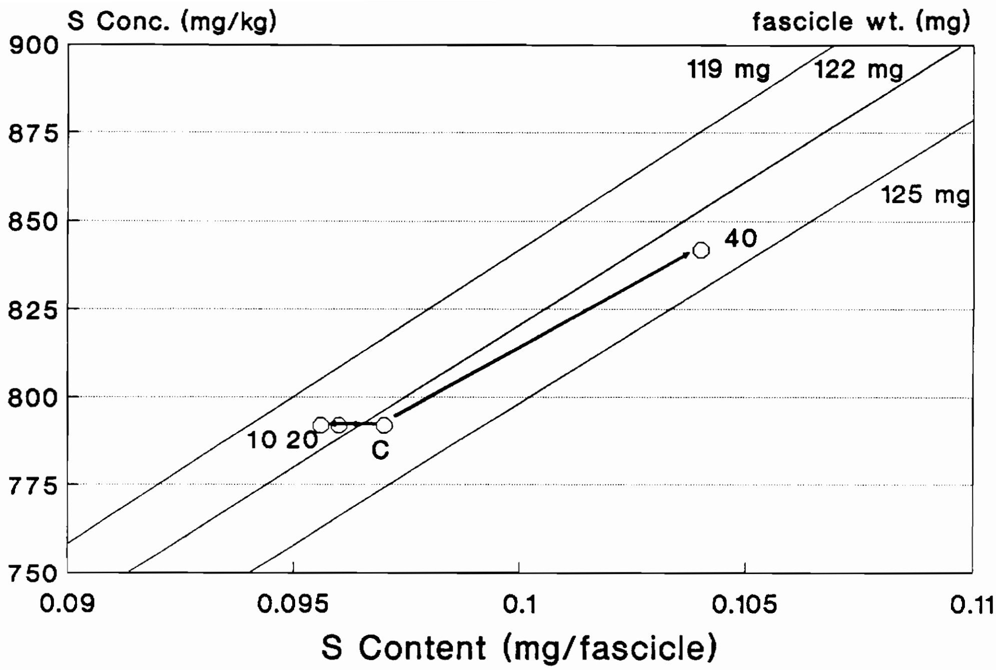

Figure 3a. Vector diagram of red pine fascicle response to sludge-borne S 12 months following sludge application for Adams County, Wisconsin

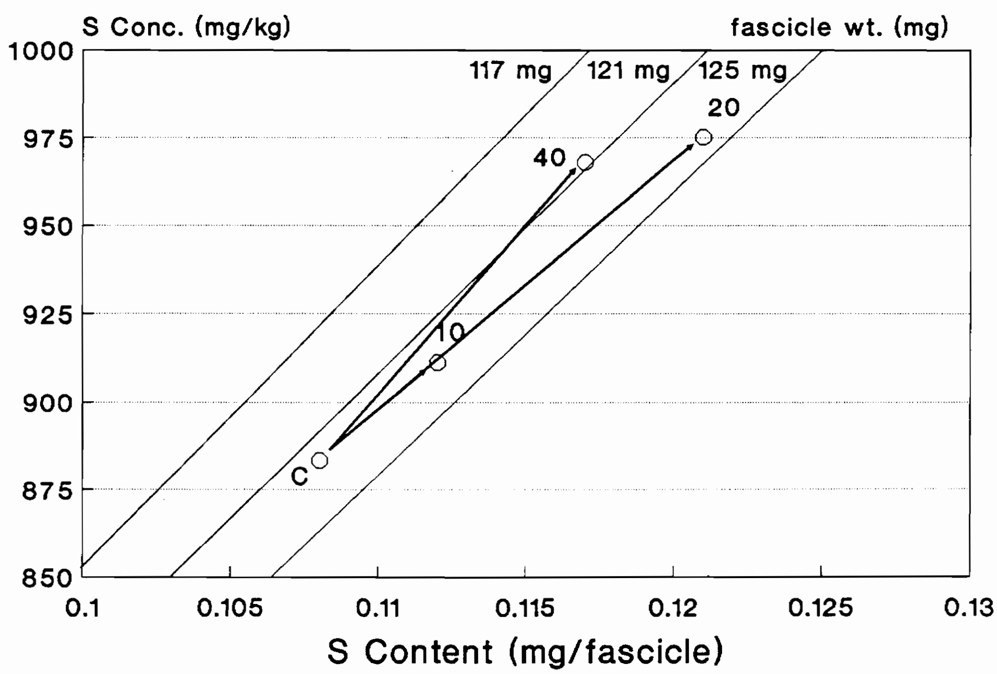

Figure 3b. Vector diagram of red pine fascicle response to sludge-borne S 12 months following sludge application for Wood County, Wisconsin

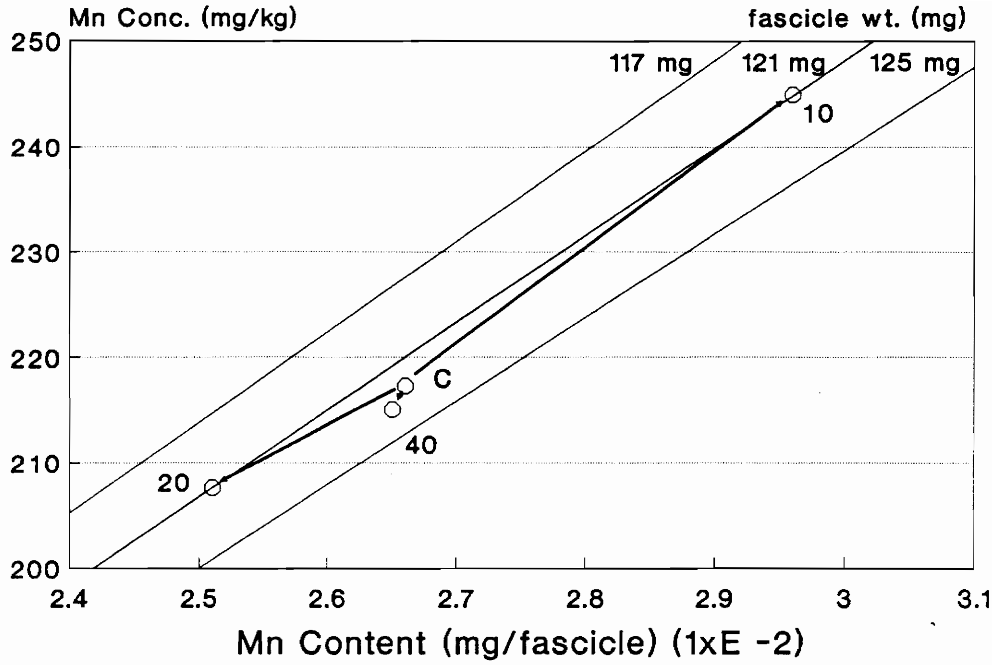

Figure 4a. Vector diagram of red pine fascicle response to sludge-borne Mn 12 months following sludge application for Adams County, Wisconsin

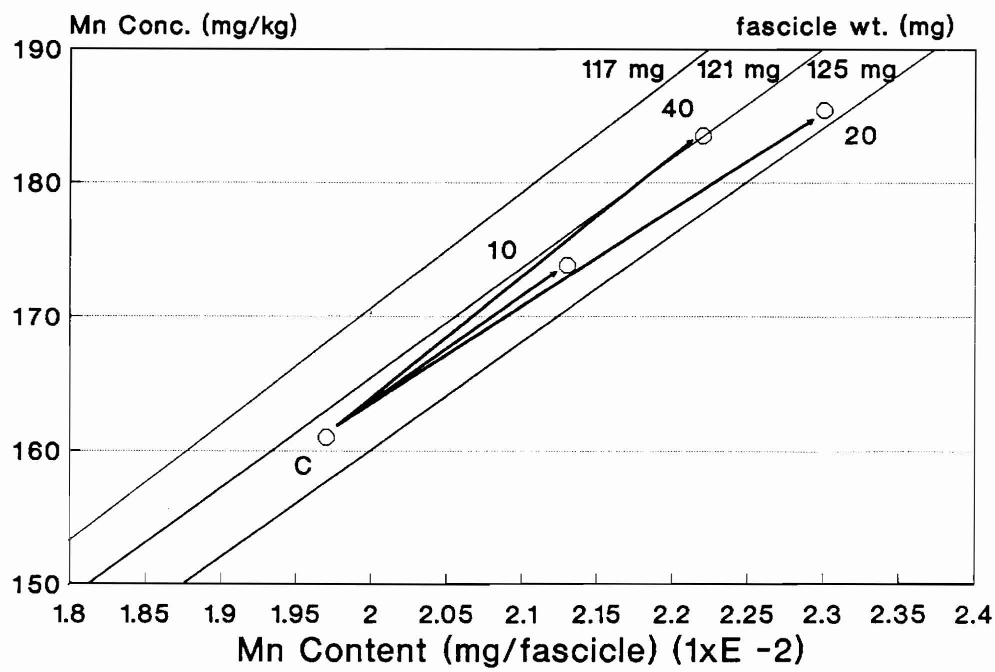

Figure 4b. Vector diagram of red pine fascicle response to sludge-borne Mn 12 months following sludge application for Wood County, Wisconsin

Appendix B

Table 5 - Above-ground nutrient concentrations and content of *Carex* spp. 9 and 21 months following sludge application for Wood County, Wisconsin

	1989 Growing Season				1990 Growing Season			
Sludge application rate, Mg/ha	0	10	20	40	0	10	20	40
Nutrient	mg/kg							
N	15375a	14798a	15824a	16951a	12902a	13985b	15387b	17433c
P	1249a	1287a	1558b	1621b	933a	1253b	1399b	1745c
K	13597a	13953a	14571a	15294a	10716a	11397ab	11555ab	13567b
Ca	3207a	3348a	3280a	3008a	2624a	2830a	2824a	3211b
Mg	1225a	1456ab	1721b	2014c	1047a	1436b	1444b	2142c
Mn	363a	300a	317a	264a	334a	270a	457a	261a
Al	117a	129a	182a	280a	133a	168a	850b	138a
	kg/ha							
N	24.0a	22.9a	26.7a	21.8a	31.8a	42.6ab	50.2b	79.4c
P	1.9a	2.0a	2.6a	2.1a	2.3a	3.8b	4.6b	7.9c
K	21.2a	21.5a	24.6a	20.2a	26.5a	34.4ab	37.5b	61.1c
Ca	5.0a	5.2a	5.5a	4.0a	6.4a	8.5ab	9.2b	14.4c
Mg	1.9a	2.2a	2.9a	2.6a	2.6a	4.4b	4.7b	9.6c
Mn	0.5a	0.5a	0.5a	0.4a	0.8a	0.8a	1.5a	1.2a
Al	0.2a	0.2a	0.3a	0.3a	0.3a	0.5a	2.9b	.64a

* Means followed by different letters are significant at the 0.05 level (LSD)

Table 6 - Below-ground nutrient concentrations and content of *Carex* spp. 9 and 21 months following sludge application for Wood County, Wisconsin

	1989 Growing Season				1990 Growing Season			
Sludge application rate, Mg/ha	0	10	20	40	0	10	20	40
Nutrient	mg/kg							
N	8512a	8773a	9062a	8631a	8223a	9535b	9913b	11960c
P	1094a	1045a	1237a	1178a	932a	1232b	1144b	1405c
K	3543a	3541a	3490a	2813a	3345a	3669a	3323a	3299a
Ca	4855a	4445a	5191a	4994a	3097a	3449ab	3802ab	4296b
Mg	1018a	1076a	1362b	1591c	899a	1161b	1235b	1445c
Mn	592a	488a	589a	487a	558a	515a	432a	490a
Al	1969a	1794a	1847a	2081a	1974a	2092a	2110b	2081a
	kg/ha							
N	51.8a	40.3a	43.7a	46.9a	86.4a	113.8ab	130.5ab	137.7b
P	6.4a	4.8a	6.0a	6.3a	9.8a	14.5ab	15.3ab	16.1b
K	20.2a	16.2a	16.6a	15.0a	35.2a	43.2a	43.0a	37.5a
Ca	29.1a	20.1a	25.0a	26.7a	32.3a	42.1a	5.06a	50.4a
Mg	6.2a	4.9a	6.6a	8.5a	9.4a	13.8ab	16.8b	16.7b
Mn	3.6a	2.2a	3.0a	2.6a	5.7a	6.3a	5.8a	5.8a
Al	12.5a	8.3a	9.2a	11.4a	20.7a	26.1a	29.5a	23.8a

* Means followed by different letters are significant at the 0.05 level (LSD)

Table 7: Response of herbaceous and woody vegetation 10 and 22 months following sludge application for Adams County, Wisconsin

Sludge application rate, Mg/ha	0	10	20	40
Pretreatment				
bare ground (%)	24.6	26.4	13.9	15.4
woody cover (%)	15.9	25.7	20.6	18.5
herbaceous cover (%)	59.5	47.8	65.5	66.1
herbaceous ht. (cm)	30.3	31.1	31.7	32.6
herbaceous volume (m^3)	1.2	1.0	1.3	1.4
C.I. Rating	2.1	2.0	2.2	2.0
1989				
bare ground (%)	30.1a	24.9a	26.2a	42.4a
woody cover (%)	21.4a	27.0a	20.2a	17.9a
herbaceous cover (%)	48.5a	48.2a	53.6a	39.7a
herbaceous ht. (cm)	32.0a	32.2a	35.7a	34.7a
herbaceous volume (m^3)	1.0a	1.0a	1.2a	0.9a
C.I. Rating	1.9a	2.7a	2.4a	2.0a
1990				
bare ground (%)	27.1a	26.8a	11.0a	15.9a
woody cover (%)	21.8a	28.2a	25.2a	27.5a
herbaceous cover (%)	51.1a	45.0a	63.8a	57.7a
herbaceous ht (cm)	38.0a	39.8ab	44.8bc	46.3c
herbaceous volume (m^3)	1.3a	1.2a	1.8a	1.7a
C.I. Rating	1.6a	1.9a	1.3a	1.5a

* Means followed by different letters are significantly different at the 0.05 level (LSD)

Table 8: Response of herbaceous and woody vegetation 10 and 22 months following sludge application for Wood County, Wisconsin

Sludge application rate, Mg/ha	0	10	20	40
Pretreatment				
bare ground (%)	5.4	5.6	8.9	3.2
woody cover (%)	16.5	8.1	14.7	11.7
herbaceous cover (%)	78.1	86.3	76.5	85.1
herbaceous ht. (cm)	28.3	29.4	28.4	28.9
herbaceous volume (m^3)	1.4	1.6	1.3	1.5
C.I. Rating	1.7	1.0	1.3	1.3
1989				
bare ground (%)	7.1a	10.9ab	11.0ab	16.3b
woody cover (%)	13.9a	7.3a	15.4a	8.7a
herbaceous cover (%)	79.1a	81.9a	73.7a	75.0a
herbaceous ht. (cm)	35.9a	39.0a	39.9a	37.7a
herbaceous volume (m^3)	1.7a	2.0a	1.8a	1.8a
C.I. Rating	1.7b	1.1a	1.5ab	1.3ab
1990				
bare ground (%)	9.2a	8.7a	3.7a	1.1a
woody cover (%)	8.3a	7.4a	9.3a	12.0a
herbaceous cover (%)	82.4a	83.9a	87.0a	86.9a
herbaceous ht. (cm)	38.4a	41.0ab	41.8ab	45.4b
herbaceous volume (m^3)	2.0a	2.1a	2.3a	2.5a
C.I. Rating	1.0a	1.0a	1.0a	0.8a

* Means followed by different letters are significantly different at the 0.05 level (LSD)

Table 9 - Volume growth of red pine 12 months following weed control and 22 months following sludge application for Adams and Wood Counties, Wisconsin

Sludge application	Adams County Site				Wood County Site			
rate, Mg/ha	0	10	20	40	0	10	20	40
Diameter (mm)								
weed control	10.07a	8.98a	7.42a	7.19a	8.07a	6.98a	12.2a	11.00a
no-weed control	6.89a	6.62a	8.00a	8.56b	8.83a	8.36a	9.14b	11.68a
Height (cm)								
weed control	31.00a	26.50a	24.60a	27.06a	24.84a	20.96a	37.29a	27.15a
no-weed control	24.08a	22.04a	26.39a	29.72a	31.67a	29.58a	27.64a	33.64a
Crown Width (cm)								
weed control	16.35a	18.91a	15.47a	14.19a	12.53a	7.11a	22.37a	22.17a
no-weed control	9.23a	11.51a	16.10a	16.27a	16.51b	14.27a	14.9b	24.87a
Crown Length (cm)								
weed control	29.60a	26.67a	23.45a	27.86a	20.53a	22.42a	33.19a	22.06a
no-weed control	24.35a	21.67a	25.13a	28.66a	31.36a	25.29a	26.52a	27.95a
Total Volume (cm^3)								
weed control	982a	746a	507a	579a	2344a	2217a	3666a	2991a
no-weed control	607a	555a	549a	684a	2826a	2737a	2775a	3423a

* Mean separation letters of significance are between weed control treatments

** Means, within the same study site, followed by different letters are significant at the 0.05 level (L.S.D.)

Vita

Michael Joseph Young was born January 7, 1963 in Minneapolis, Minnesota. Following graduation from Robbinsdale Senior High School in 1981, the author began work as a partner with his father's sales firm. In the fall of 1983, Michael married his partner-in-life, Janet Marie Kulbeck. The desire to return to school brought the author and his new wife to the University of Wisconsin - Stevens Point in 1984, where Michael completed a Bachelor of Science in Forestry and Soils in December of 1988. Immediately following, the author began graduate studies at Virginia Polytechnic Institute and State University, where he completed the requirements for a Master of Science degree within the Department of Forestry.

Presently, the author is working as a research specialist within the Forest Biology section at Virginia Tech. In addition to golf and tennis, Michael enjoys hunting and fishing of all types. The birth of their first child, Benjamin Joseph Young, in October of 1990, has brought enormous joy to Michael and Janet's life.

The author desires to see the advancement of forestry as a science. Michael will begin serving as the Assistant Director of the Hardwood Research Cooperative at North Carolina State University in April of 1991.

Michael J Young