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EVALUATION OF NORTHERN PINE PLANTATIONS
AS DISPOSAL SITES FOR MUNICIPAL
AND INDUSTRIAL SLUDGE

presented by

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EVALUATION OF NORTHERN PINE PLANTATIONS AS DISPOSAL SITES FOR MUNICIPAL AND INDUSTRIAL SLUDGE

By

Dale Gordon Brockway

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ABSTRACT

EVALUATION [illegible] PLANTATIONS [illegible] MUNICIPAL [illegible] SLUDGE

The effect of [illegible] pine plantations [illegible] water quality and [illegible] understory and trees was also determined [illegible] soils in northern Michigan. Industrial [illegible] was applied to a 40-year-old red pine (*Pinus resinosa* [illegible]) in June of 1976 at rates of 2.0, 4.0, 7.9 and 15.7 tonne/ha (dry weight). The sludge rates were equivalent to total nitrogen [illegible] of 139, 278, 549 and 1,091 kg/ha, respectively. Municipal [illegible] cadmium, was applied to a 36-year-old red pine and white pine (*Pinus strobus* L.) plantation in July of 1976 at rates of [illegible] tonne/ha (dry weight), equivalent to total nitrogen [illegible] of 321, 578 and 1,156 kg/ha, respectively.

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ABSTRACT

EVALUATION OF NORTHERN PINE PLANTATIONS
AS DISPOSAL SITES FOR MUNICIPAL
AND INDUSTRIAL SLUDGE

By

Dale Gordon Brockway

The effect of sewage sludge applications in thinned pine plantations was examined for changes in forest litter, soil, water quality and vegetation growth. Nutrient status of understory and trees was also determined on four coarse textured outwash soils in northern Michigan. Industrial sludge from a paper mill was applied in a 40-year-old red pine (Pinus resinosa Ait.) plantation in June of 1976 at rates of 2.0, 4.0, 7.9 and 15.7 tonne/ha (dry weight). The sludge rates were equivalent to total nitrogen applications of 140, 278, 549 and 1,091 kg/ha, respectively. Municipal sludge, high in cadmium, was applied to a 36-year-old red pine and white pine (Pinus strobus L.) plantation in July of 1976 at rates of 5.4, 9.7 and 19.3 tonne/ha (dry weight), equivalent to total nitrogen applications of 323, 578 and 1,156 kg/ha, respectively.

Litter nutrient levels were significantly increased on both sites following sludge application. The addition of nitrogen to the litter precipitated a structural change wherein a second and third zone of fermentation could be discerned along the margins of the sludge layer in the litter profile. Forest litter pH significantly increased with

treatment. Carbon to nitrogen ratios were narrowed to ratios as low as 24:1. No appreciable increase in the rate of litter decomposition was observed on either site over a two-year period.

Increases in nutrient transfer from the litter layer to the underlying soil were limited to soluble forms of major nutrients: NO_3-N, NH_4-N, P and K. Increases in the levels of these nutrients occurred primarily in the 0-5 cm soil layer; however, increases in soil NO_3-N down to 30 cm were observed under the industrial sludge treatments. Organic-N, the largest N fraction in the sludges, was largely retained in the litter layer as were zinc, cadmium and the remaining elements.

The quality of water moving from the treated plots was monitored using wells inserted into the surface of the water table aquifer and porous cup suction lysimeters. During 1976 all measured chemical elements remained below 0.1 ppm. Following snow melt in 1977, nitrate levels exceeded the 10 ppm potable water standard under plots receiving the highest sludge treatment rates. Maximum sludge dosage rates which would not exceed established water quality standards were computed to be 19.1 tonne/ha (1,144 kg N/ha) for the municipal sludge tests and 9.5 tonne/ha (660 kg N/ha) for the industrial sludge tests.

Understory plants on the industrial sludge treatment site assimilated as much as 128% total N and 370% total P more than controls. Above-ground biomass of the understory increased by as much as 92% over controls. Understory plants on the municipal sludge test site assimilated as much as 144% total N and 188% total P more than controls. Above-ground biomass production increased by as much as 132% over

controls. Cadmium concentrations in understory vegetation increased to a maximum of 22.7 ppm on the site receiving municipal sludge, presenting a possible food chain build-up problem in the ecosystem. Foliar nitrogen concentrations increased in sludge fertilized pine trees. Significant increases in needle length and dry weight were also evident. There was little evidence on either site that roots of overstory trees had begun to develop in the enriched litter nutrient reservoir. The sludge treated pine trees showed evidence of expanding the photosynthetic production base as a prelude to future volume growth responses.

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CHAPTER I

INTRODUCTION

Background

Production of wastes is an intrinsic function of all living things. The ability of a population to adequately deal with its produced wastes can, to a large degree, determine its continued success in the ecosystem. Civilizations have suffered greatly from disease spawned in improperly treated human and domestic animal waste. Recent decades have witnessed a progressive degradation of surface water resources as inadequately treated industrial and municipal wastes have been wantonly discharged into rivers and lakes.

In the United States 90.5 billion liters (24 billion gallons) of domestic sewage was discharged in 1975 (Freshman 1977). Although the pathogen hazard present in this waste has been largely abated as a result of advances in biology and chemistry, waste discharge of this magnitude represented a significant nutrient loss, 733 million kg of nitrogen, 674 million kg of phosphorus and 428 million kg of potassium or 9%, 16% and 11%, respectively, of the national fertilizer consumption of these elements. The value of these discharged nutrients amounted to 561 million dollars.

Primary, secondary and tertiary stages of waste treatment have reduced the nutrient levels in discharged effluents. During the primary and secondary stages of this biological sewage treatment, however, solid materials are concentrated into a nutrient rich sludge (Peterson et al. 1973), 1 dry tonne of sludge per 4.2 million liters of sewage, which, in itself, constitutes a significant disposal problem (Figure 1). Sludge incineration and landfills pose substantial environmental or economic limitations when compared to the alternative of land spreading (Forester et al. 1977). Many recent research efforts have, therefore, focused upon land application of sludges. Land spreading is being investigated not only as a way of abating the environmental pollution hazard posed by sludge but also as a method of fertilizing systems under intensive crop management.

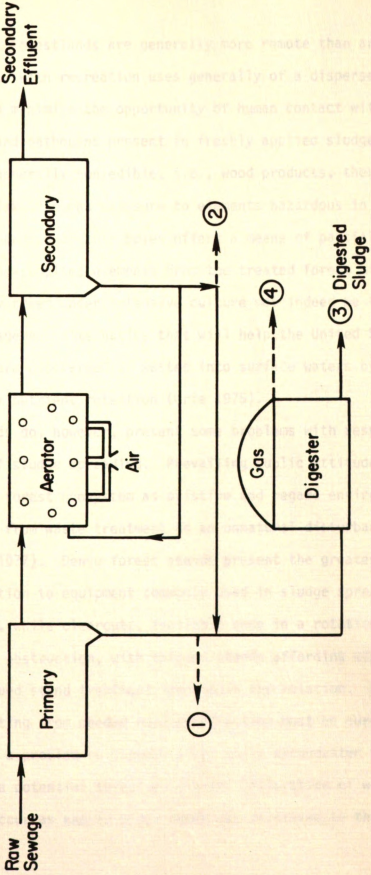
Of the two cultural systems available for sludge land spreading, agricultural lands impose a more stringent set of application constraints than do forest lands. Sludges often present a heavy metal hazard which can limit their use in the production of food crops (Urie 1971). Chaney (1973) cites the following maximum metal limits for sludges used on food crops: 2,000 ppm Zn, 800 ppm Cu, 100 ppm Ni, Cd 0.5% of Zn, 100 ppm B, 1,000 ppm Pb and 15 ppm Hg. Of the above elements some present a phytotoxic potential, i.e., Zn, while others, such as Cd, have been implicated in deterioration of animal tissues, notably in Itai-itai disease. Food crop production using certain sewage sludges constitutes then an economic risk to the grower and a health risk to the consumer unless precautionary measures are taken.

Lands engaged in the production of forest crops present a set of environmental conditions which make them favorable sites for disposal

Primary
Aerator
Air
Secondary
Gas
Digester
Digested
Sludge

Figure 1. Sludge production during biological sewage treatment.[1]

[1] R. B. Dean and J. E. Smith. 1973. The properties of sludge. In: Recycling Municipal Sludges and Effluents on Land. Ed. by D. R. Wright, R. Kleis and C. Carlson. Nat. Assoc. State Univ. and Land-Grant Colleges, Washington, D.C., p. 40.


Raw Sewage
Primary
Aerator
Air
Secondary
Secondary Effluent
1
2
3 Digested Sludge
4
Gas
Digester

of sewage sludge. Forestlands are generally more remote than are agricultural lands, with recreation uses generally of a dispersed nature which would minimize the opportunity of human contact with unpleasant odors and pathogens present in freshly applied sludge. Forest crops are generally non-edible, i.e., wood products, thereby diminishing the risk of human exposure to elements hazardous in the food chain. The harvest of tree boles offers a means of partially removing the sludge-supplied elements from the treated forest site. Nutrient uptake by trees under intensive culture may indeed be the best wildland management alternative that will help the United States proceed toward "zero discharge" of wastes into surface waters by offering long-term nutrient retention (Urie 1975).

Forestlands do, however, present some problems with respect to the practice of sludge spreading. Prevailing public attitudes conceptualize the forest ecosystem as pristine and regard environmental changes resulting from waste treatment as an unnatural disturbance (Smith and Evans 1977). Dense forest stands present the greatest degree of obstruction to equipment commonly used in sludge spreading, i.e., tank trucks, while clearcuts, available once in a rotation, present the least obstruction, with thinned stands affording adequate access for continued stand treatment throughout the rotation. Site disturbance resulting from needed road construction must be curtailed. Surface runoff is a problem on steeper sites while groundwater nitrate enrichment poses a potential threat on others. Alteration of wildlife populations may occur as exotic plant seeds are delivered to the site, native forage become locally scarce or forage nutrition changes. The hazard of food chain transmission of potentially lethal elements to wildlife populations cannot be overlooked.

Study Objectives

The primary objective of this study was to determine the sewage sludge loading rates which can be utilized in pine plantations growing on coarse textured outwash sands without impairing groundwater quality or the integrity of the forest ecosystem. In meeting this goal two study sites near Wellston, Michigan were examined, the first a red pine plantation on the Udell Experimental Forest and the second a red pine and white pine plantation on the Pine River Experimental Forest. At each site soil percolate and groundwater quality were monitored, changes in soil nutrient levels and surface soil physical properties were measured, nutrient enrichment and physical changes in the forest litter layer were determined and nutrient uptake and growth of understory and overstory plants were evaluated.

CHAPTER II

LITERATURE REVIEW

Historical Perspective

Traditional approaches to disposal of sewage have primarily relied upon dilution via discharge into available surface water resources. Since the onset of the industrial revolution, growing populations have, to a great extent, compounded the degree of water quality degradation. The Rivers Pollution Prevention Act of 1876 was enacted in Britain, representing the earliest attempt by western man to diminish pollution of surface waters while, at the same time, spawning the practice of sewage farming (Haith and Chapman 1977).

Section 13 of the Rivers and Harbors Act of 1899 represented the first attempt in the United States to prohibit the discharge of refuse into navigable waters (Sullivan 1973). This law, however, suffered from lack of enforcement until the mid-twentieth century. The Water Pollution Act of 1948 gave states the primary enforcement responsibility in water pollution cases with assistance to be provided by the federal government. However, this law lacked substance until the passage of the Federal Water Pollution Control Act of 1956 which authorized large scale grants to assist states in planning and building sewage treatment facilities.

Public awareness of the national environmental crisis culminated in the passage of the National Environmental Policy Act of 1970 which sought to eliminate the practice of sludge dumping in ocean waters off the east coast (Sullivan 1973) and the Federal Water Pollution Control Act Amendments of 1974 (PL 92-500) which attempted to focus attention on the need to develop waste management techniques which are cost-effective and environmentally sound (Morris and Jewell 1977). Land application of waste effluents and sludges was cited as a major alternative in eliminating pollutant discharge into navigable waters by 1985. While section 301 of PL 92-500 specified all sewage must receive secondary stage treatment, increasing the national production of sludge, sections 402 and 403 authorized ocean dumping of sludge only by permit issued in the public interest. As a result, land treatment of sludges has received increased interest.

Of the sludge treatment alternatives currently available, incineration and landfills pose formidable problems when compared to land spreading. Incineration requires currently expensive fossil fuels and poses an air pollution hazard. Landfills also require high cost fuels during dewatering, constitute a waste of valuable nutrients and pose a potential groundwater pollution threat. Although not without its problems, land spreading presently appears to offer the greatest potential for water pollution abatement and use of the valuable nutrient resource contained in sewage sludge.

Estimates by Sommers (1977) based on national sludge production concluded that less than 1% of the agricultural land in the United

States would be required for application of sewage sludge at a fertilization rate of 100 kg N/ha/yr. Although agriculture possesses the land base to process domestic sludge production, the use of wildlands, more specifically forestlands, offers several significant advantages by comparison. Heavy metal accumulations in croplands, which could present a genuine hazard in terms of food chain transmission to human consumers, are far less troublesome in forestlands where products are generally non-edible in nature (Smith and Evans 1977). The longer rotations of forests can immobilize and redistribute a tremendous amount of applied nutrients for as long as 50 years or more while shorter cropland rotations cannot provide this storage and redistribution function. Forest sites offer remoteness and lower population densities thereby diminishing the risk of human contact with pathogens present in sludges and the degradation of environmental aesthetics near population centers. Surface application of sludges on forest sites allows for volitalization loss of ammonia, an aid in curtailing soil percolate nitrate levels, while sludge incorporation into a mixed plow layer thwarts this process. Many forest soils are deep, porous and well drained, with an abundance of animal and root channels offering optimal infiltration and negligible overland flow. These soils often contain high aluminum levels which allow the fixation of large amounts of phosphorus and a surface organic matter layer which can capture significant amounts of other nutrients. Agricultural soils often develop traffic pans which impede percolation and lack a surface layer of organic matter. Forests offer a more highly diverse and stable ecosystem than do cropland monocultures which remain highly vulnerable to environmental perturbation.

Forestland offers the largest single land type area in the United States, 305.3 million ha or 33.2% of all lands, available for sewage sludge disposal, excluding the Great Plains and the Southwest. Limited use for this purpose is currently a result of the absence of workable delivery systems and uncertainty regarding appropriate sludge dosage rates.

In France, authorities were hesitant to apply waste sludges to forestlands (Rieben 1976). Although wastes enjoyed limited use in agriculture, high costs of transportation to sites low in productivity, uncertainty as to impact on environmental homeostasis and public objections to the practice were among the reasons cited. Evers (1977) reported, however, that a working group has recently issued guidelines for utilization of urban wastes in German forests. Although they have no legal status, they are expected to aid land managers in sludge application decisions. Hungarian officials have already established forest land spreading as the most feasible method of sewage purification and utilization (Tihanyi 1975).

Sludge Composition

Prior to the advent of synthetic fertilizer manufacture, organic wastes, in spite of their long standing undefined chemical nature, were considered of great value to agriculture. As national interest now returns to utilization of organic wastes as fertilizers, analytical advances have allowed an improved chemical definition of the sewage media under consideration.

Sewage sludges are commonly nutrient-rich liquids containing an average of 5% solids (Kardos et al. 1977). Typical paper mill sludges will vary widely in their composition, many having a carbon to nitrogen ratio (C:N) as high as 150:1 as a result of a high cellulose fiber content. Total nitrogen content in domestic sludges may range from 1% to 15% by dry weight but is more commonly 3% to 6%, 40% to 75% of this being present as organic nitrogen. Phosphorus content is typically between 1% and 4% by dry weight while that of potassium ranges from 0.2% to 1.0%. Municipal sludges derived from industrialized urban centers usually contain concentrations of zinc, copper, cadmium, lead and mercury in excess of those present in soils. Pesticides are often also present in sludges as are the ubiquitous pathogenic microorganisms (McCalla et al. 1977).

Important Nutrients

The primary goal of sludge land spreading is to dispose of the contained nutrient load in a manner such that the ecosystem components can immobilize and assimilate the elements applied thus avoiding contamination of groundwater, impairment of biological production and long-term degradation of environmental aesthetics. One of the foremost hazards is contamination of groundwater with nitrate-nitrogen.

Prober et al. (1973) have presented the detailed standards for water quality established by the U.S. Public Health Service and report that current nitrate levels for potable water should not exceed 10 ppm. Although forest watersheds are sources of high quality water, fertilization can lead to quality degradation (Sopper 1975). Added nitrogen can generally be internalized by forest ecosystems but nitrate levels can exceed 10 ppm when dosage rates exceed 300 to 400 kg N/ha as has been reported by Kreutzer and Weiger (1974) under Scotch pine and Norway spruce and Otchere-Boateng and Ballard (1978) when urea was applied to coarse textured soils low in organic matter. Digested sludge applied to conifers in Germany at greater than 300 kg N/ha resulted in soil percolate with peak nitrate concentration as high as 160 ppm, suggesting the possibility of groundwater pollution (Huser 1977).

Despite these findings, numerous other researchers contend that high nitrogen dosage rates not necessarily need always lead to soil percolate nitrate enrichment. Cole et al. (1975) found no substantial nitrate leaching under second growth Douglas-fir growing on a gravelly, sandy loam outwash when fertilized with 448 kg N/ha as urea. Tamm (1975) reported similar results when ammonium nitrate and urea were applied to a site recently clearcut. Nitrogen applied in sewage sludge at a rate of 300 kg/ha to a hardwood forest growing on acidic, loamy soil in Germany resulted in no significant soil percolate nitrate enrichment (Keller and Beda-Puta 1976). Johnson and Urie (1976) maintained percolate nitrate levels below 10 ppm by adjusting their application rate of raw recreation campground vault wastes to 116 kg N/ha. Except for the study of Perkins et al. (1975) where elevated nitrate levels in Heavenly Valley Creek were traced directly to discharges from a secondary sewage effluent treatment project under subalpine fir in the Tahoe basin watershed, almost no direct evidence exists which demonstrates that soil percolate nitrate levels exceeding the 10 ppm USPHS limit in fact cause significant degradation of groundwater or surface water quality beyond the immediate locality.

Nitrate groundwater pollution nonetheless continues to be of major concern, a fact which has focused attention upon the various steps of nitrogen transformation. Encouraging ammonia volitalization can be an important tool in abating soil water nitrate pollution as nitrate precursor levels are decreased (Urie et al. 1978). King (1973) has determined that as much as 36% of the total nitrogen in a surface applied sludge can escape to the atmosphere, this primarily as ammonia gas, while as little as 16% of the total nitrogen escapes as gas from sludge incorporated into the surface soil. Madandrappa (1975) reported an average of 7 days to volatilize as little as 3.75% of the total nitrogen applied as urea while Beauchamp et al. (1978) have estimated the half life of volatile ammonia for sludge applied in the field to range from 3.6 to 5.0 days. Terry (1976) concluded that conditions favoring volatilization of ammonia in sludges include rapid drying of the sludge, application to soils low in clay and soil pH values near 7.5.

Increasing soil pH to 6 and soil nitrate levels to 100 ppm will stimulate the activity of nitrate reductase present in forest soils and thereby lead to the ultimate volatilization of N_2O and N_2 as gases (Theobald and Smith 1974). This denitrification process, however, is of low activity in acidic soils. High carbon to nitrogen ratios will stimulate denitrification resulting in significant loss as nitrate is reduced to N_2O and N_2 gases (Epstein et al. 1978). At a carbon to nitrogen ratio of greater than 27:1 very little nitrate is produced (Heilman 1974). In sludges of high cadmium, zinc and lead content, Wilson (1977) reported a depressed nitrification rate following land application. Temperatures below 5°C restricted nitrification while Harris (1976) reported an absence of nitrate production in freezing weather. Despite this lack of production, nitrate has been detected percolating through sandy soils during the winter season.

Phosphorus, primarily as ortho-phosphate, is a major concern as a key nutrient in pollution of surface water resources. Forest soils often can adsorb large amounts of phosphorus (Powers et al. 1975) particularly those low in pH and high in iron and aluminum (Ballard and Fiskell 1974). Phosphorus present in sludge presents no real water pollution hazard when applied to soil in that it is removed and held tenaciously by rapid sorption, slow mineralization and insolubilization, plant uptake or microbiological immobilization (Tofflemire and Chen 1977). Humphreys and Pritchett (1971) have confirmed that little if any phosphorus leaching occurs in forest soils.

Potentially Hazardous Elements

Trace elements present in sewage sludge may benefit plant production by supplying needed micronutrients to forest species.

Certain trace elements, however, represent a threat to plants and animals. Allaway (1977) noted two opposing view points regarding the heavy metal hazard in sewage sludges. The first contends that concentration of undesirable elements in productive soils constitutes unnecessary pollution even if the residues are not assimilated by plants. The opposing view believes that accumulation of potentially toxic elements can be allowed in productive soils up to the point of creating a problem. Forestland sludge spreading management is not compatible with the former viewpoint, but must, instead, attempt to avoid the point of ecosystem poisoning alluded to in the latter viewpoint.

Trace elements commonly found in sewage sludge include cadmium, zinc, copper, boron, lead, nickel, chromium, molybdenum, iron and manganese. Of these, the greatest hazard is that presented by cadmium, an element implicated in both plant and animal disturbances. Generally, soluble cadmium represents a greater health risk than that of organic cadmium in plant tissue (Allaway 1977). Potable water levels should not exceed the 10 ppb cadmium limit set by the USPHS. Although Sidle and Kardos (1977c) have shown cadmium to be less readily leached from land spread sludge than zinc, Baker et al. (1977) reported cadmium hydroxide to be one hundred times more soluble than zinc hydroxide and thus more biologically active. Precipitation of cadmium carbonate occurs in sandy soils at pH greater than 7 (Street et al. 1977); however, under more acidic soil conditions the very mobile divalent cation is dominant. Soil cadmium levels exceeding 0.1 ppm have been shown to reduce crop yields by causing damage to root tissue (Turner 1973). Various plants show different abilities to accumulate cadmium in their tissues. Page et al. (1972) have noted, however, that foliar cadmium levels are proportional to soil solution cadmium concentrations. It was reported that 0.1 ppm cadmium in soil solution can lead to foliar cadmium levels as high as 9 to 90 ppm. Cadmium levels below 1 ppm in items consumed by man and animals are known to be toxic (Baker et al. 1977). In Japan the Ministry of Health Standards has established a maximum limit of 0.4 ppm cadmium for unhulled rice used for human consumption (Jones et al. 1975). This action followed the discovery of the local occurrence of Itai-itai disease, a painful degenerative illness occurring as a result of cadmium accumulation in the kidneys and coincident bone deterioration (Allaway 1977). Cadmium concentrates in foliage rather than seeds and fruits (Allaway 1977), a fact which accounts for the low levels of cadmium found in ring-necked pheasants fed corn grain grown with a cadmium-enriched sludge (Melsted et al. 1977). Cadmium accumulated only in the pheasant duodenum, kidney and liver, tissue generally not consumed by humans but largely consumed by other predators of this species. Cadmium food chain transfer remains, nonetheless, a major concern with grazing and browse-consuming herbivores.

Zinc has been implicated in depressed crop yields by King and Morris (1972). Like cadmium, zinc is very mobile in its divalent ionic form and easily leached from land applied sludge (Laggerwerff et al. 1976). Zinc applied in sludge remains available to plants over many years (Chaney et al. 1977) and has been implicated in plant toxicities at levels greater than 500 ppm in foliage (Allaway 1977). Because zinc deficiencies are widespread, however, in plants and animals, it is hoped that zinc present in sludges can supplement food crop levels. Current potable water standards allow 5 ppm for zinc (Prober et al. 1973).

Copper is less easily leached from sludge than are cadmium and zinc and readily converts to amphoteric copper with its continued stability dependent on acidity (Laggerwerff et al. 1976). Although it has been implicated in plant toxicities on organic soils, copper is readily adsorbed in the upper 15 cm of mineral forest soils (Sidle and Kardos 1977a and b). This process generally results in high quality water yield meeting the 12 ppb copper limit and little threat of copper toxicities to plants or animals.

Stone and Baird (1956), Neary (1974) and Minroe (1975) have demonstrated the sensitivity of pines to excessive boron applications. Boron toxicity is generally confined to sewage effluent irrigation where large quantities of soluble boron compounds are concentrated in needle tips as a by-product of transpiration (Allaway 1977). Boron is generally present in sludges at non-toxic levels.

The remaining trace elements listed are not considered hazardous when applied in waste sludges. Lead applied to soil forms a relatively insoluble carbonate which dissociates only under extremely acidic conditions. Chromium once introduced into soil oxidizes to the trivalent state and precipitates as an insoluble hydroxide which can dissociate only at very low pH. Nickel is adsorbed tenaciously on soil exchange sites and molybdenum forms a very insoluble ferro-molybdate compound (Lindsay 1973). Iron has not been demonstrated to be toxic. Manganese, while mobile under reducing conditions in its divalent form, is naturally abundant and not toxic in forest systems. Pratt et al. (1977) have suggested that sludge mining for trace elements or decreasing sludge dosage rates where required may help diminish future toxicity hazards encountered in land spreading of sludges.

Pathogens and Pesticides

Menzies (1977) included Salmonella, Shigella, Pseudomonas, Klebsiella and Escherichia coli bacteria, Entamoeba histolytica protozoa, Ascaris lumbricoides nematode ova and various viruses among the pathogenic agents commonly present in sewage sludges. Pathogens can survive in soils treated with sludge; however, survival rates are dependent upon soil moisture, formation of spores, temperature, incident sunlight and presence of chemically and biologically antagonistic agents (Morrison and Martin 1977). Drying and solar radiation appear to induce the greatest mortality among sludge borne pathogens, while soil particles are often effective in entrapping and immobilizing them. Menzies (1977) has pointed out that the standard practice of using E. coli counts cannot be relied upon as an accurate index of pathogen survival in sludges applied to soil.

Edmonds (1976) reported that few bacteria from an anaerobically digested, dewatered sludge applied to a clearcut forest site on gravelly glacial outwash penetrated greater than 5 cm of soil. The soil acted as an effective biological filter allowing only slight bacterial penetration to groundwater. Bacterial contamination from surface runoff in the first season following treatment appeared much more likely than contamination from bacteria percolating to groundwater. No pathogenic bacteria could be isolated from this soil 267 days after sludge application.

The following precautions were advised for protection from the pathogen hazard present in sewage sludges: (1) adequate treatment of human wastes, (2) allow ample time for pathogen die-off following sludge application before opening land to human use, (3) limit rates of waste applications to a site to avoid pathogen population build up, (4) avoid areas near large populations when applying sludge to land, (5) maintain high levels of immunity and health care for animals and humans, and (6) use geologic and hydrologic knowledge to avoid contamination of water resources (Morrison and Martin 1977).

Pesticides also represent a hazard in many sewage sludges. Although they are often very potently toxic compounds, McCalla et al. (1977) suggested that organic matter and clay particles present in soil are effective inactivators of these materials.

Water Quality Implications

A major objective of sludge land spreading management is to insure the continued yield of high quality water, low in or devoid of any hazardous material. Nitrate, zinc and cadmium exceeding 10 ppm, 5 ppm and 10 ppb, respectively, are unacceptable in water flowing from sludge treated watersheds. Runoff contaminated with pathogens and pesticide residues is equally unacceptable.

Managers must not only guard against off-site contamination but should also insure on-site environmental integrity. Nitrate enrichment of soil water may be minimized by encouraging denitrification on treated sites. Maintaining soil pH near neutral levels will ensure minimal problems with trace elements (Urie 1975). Continuous monitoring of free soil water and the unconfined aquifer provide data relevant to meeting these goals.

Soil and Vegetation Considerations

Barring disturbance, the nutrients in a forest are cycled to meet the needs of the stand components. Nutrient cycling is facilitated by litter decomposition, a process that (1) produces a humus layer which improves site fertility and soil moisture relations and (2) slowly releases nutrients which are readily available for plant assimilation. Excessive buildup of organic matter on the forest floor, as occurs during stand thinning, can, however, adversely effect the chemical balance of this decomposition process by temporarily upsetting the litter carbon to nitrogen ratio (R. E. Miller et al. 1976).

Sludge distributed on the surface to forested sites is applied directly to the litter layer and surface soil. Nutrients applied in this manner have been shown to accelerate the decomposition rate of forest litter (Bramryd 1976). This phenomenon was ostensibly a result of narrowed carbon to nitrogen ratios (Turner 1977) which stimulated the metabolic activity of indigenous microbial saprophytes, ammonifiers and nitrifiers (Shumakov et al. 1974). Although fungi appear to be the dominant microorganism in forest soils and litters (Miller 1973), bacterial populations are primarily increased by nitrogen additions, resulting in accelerated litter decay rates (Kelly 1973).

Forest soils are highly variable in nature and their suitability for processing sewage sludge depends on their microfloral and macrofaunal populations and their complement of organic matter and colloidal particles. Sludge organics underwent extensive decomposition once applied to soil. A major portion was converted to soluble inorganics, the remainder becoming soil humus following substantial modification (Broadbent 1973). The primary effect of adding inorganic nitrogen to the soil was to stimulate further mineralization of organic nitrogen (Broadbent 1965). Stanford and Smith (1972) have estimated the "half-life" mineralization rate for nitrogen in entisols, alfisols, aridisols, ultisols and mollisols to be approximately 12.8 ± 2.2 weeks. Ammonium produced during mineralization which did not undergo nitrification was reported to exchange for potassium on the exchange complex resulting in potassium leaching losses (Crane 1972). Nitrate, conversely, was very poorly held in soil and, as Koenig (1976) pointed out, was highly susceptible to leaching losses. Trace elements in sludge, as illustrated in Germany by Moll et al. (1977), were generally immobilized in the upper 10 cm of soil, even when applied to a dune sand low in organic matter and cation exchange capacity.

The forest floor is the most biologically active interface of the soil system and, to a great degree, determines the composition of solutions passing down through the soil below it (McColl 1973). Adding sludge nutrients to this interface was found to (1) increase soil moisture and aggregate stability, (2) initially increase hydraulic conductivity followed by a decrease resulting from soil pore clogging by the products of microbial decomposition and (3) increase soil carbon dioxide levels while decreasing soil oxygen, root growth and nutrient uptake (Epstein 1973). As CO_2 tension increases in soil, hydrogen ions from carbonic acid replace cations on soil particles resulting in leaching losses of valuable bases (McColl and Cole 1968).

While many researchers have reported that nutrient additions to forest soils depress mycorrhizae levels, Berry and Marx (1977) indicated that sewage sludge application rates of 34 to 69 metric tons per hectare stimulated the formation of ectomycorrhizal assocciations with and resultant growth increase among loblolly pine seedlings. Menge (1975) counted fewer mycorrhizal root tips on loblolly pine receiving 356 kg N/ha/yr than on controls. However, Berry and Marx (1976) demonstrated a dynamic interaction between dried sewage sludge and Pisolithus tinctorius which shows great promise for growing pines on eroded forest sites.

The literature is replete with accounts of the many benefits derived by plant species from nutrient applications. Macy (1936) treated the concept of "critical nutrient percentage" in some detail, contending that a crucial minimum level exists for every nutrient in each plant species below which metabolic processes are impaired. In their extensive bibliography on forest fertilization research, White and Leaf (1956) stated that forest plants have their critical nutrient requirements adjusted to low levels as an adaptation to low ambient soil fertility conditions, while agricultural plants have been selectively bred for higher yields, resulting in a greater nutrient demand. Pritchett (1977) has stated that forest site quality can improve through fertilizer application, thus enhancing plant growth and nutrient status.

Numerous fertilizer benefits to growth are cited in the literature. While Mitchell and Kellogg (1970) found little volume increase in a 50-year-old Douglas-fir stand treated with less than 200 kg N/ha, Morrison et al. (1976) reported an excellent growth response in 45 year old jack pine fertilized with nitrogen at rates up to 448 kg/ha. Twenty-year-old Douglas fir treated with nitrogen demonstrated increased basal area, stem height, branch length, needle length and width and number of needles per branch (Brix and Ebell 1969). Nitrogen fertilized balsam fir produced darker green needles, heavier terminal buds, greater number of buds and longer leaders, lateral shoots and needles (Timmer et al. 1977). White et al. (1971) reported that 392 kg diammonium phosphate/ha increased both fine root and total root biomass in slash pine 145% and 58%, respectively, whereas, Rawson (1972) found diameter increases exceeding 500% for radiata pine in New Zealand treated with superphosphate. Leaf et al. (1975) reported increased leader and radial growth in red pine fertilized with potassium.

Improvement of foliar nutrition through fertilizer application is commonly noted. Wells (1970) and H. G. Miller et al. (1976) in the United States and Hippeli (1976) and Franz and Bierstedt (19756) in Germany are among those who have improved foliar nitrogen status in pines with nitrogen fertilizer applications. Baker (1970) and Timmer and Stone (1978) have shown similar results in western hemlock and balsam fir, respectively. Weetman and Algar (1974) have determined that maximum basal area growth occurs in 40-year-old jack pine when foliar nitrogen is maintained near 1.7%. Bulgarian white pine is seen to improve its foliar phosphorous levels when phosphorous fertilizer is applied (Donov 1977) while red pine foliar potassium was found to increase 140% when supplied with potassium soil additions (Wittwer et al. 1975).

As with commercial fertilizers, sludge nutrient additions were seen to augment plant growth and improve plant nutrition (Smith and Evans 1977). Urie et al. (1978) reported a doubling of vegetation production in rye growing in wildlife openings treated with 14.6 metric tons of sludge per hectare, this equivalent to 446 kg N/ha. Increased height and diameter growth of red pine in Pennsylvania was observed following sewage waste application (Sopper 1973). Nitrogen content of the herbaceous understory was reportedly increased 63% following treatment with raw sewage wastes (Johnson and Urie 1976) while crude protein content of grass treated with sludge increased 26% (King and Morris 1974).

An important step in recycling the nutrients delivered to a site in sewage sludge is the harvesting of useful products and the nutrients they contain. Kardos et al. (1977) have reported nutrient harvests as high as 390 kg N, 62 kg P and 380 kg K/ha/yr from three cuttings of reed canarygrass on a site treated with sewage effluent. Additionally, the potential immobilization of elements in non-consumable woody plant parts exists. Urie (1971), however, cautions that tree bole removal at harvest cannot be looked upon as the total answer to immobilization of harmful elements, as a great proportion of any tree's assimilated nutrients are left on-site in the form of leaves and branches. Cooley (1978) has determined that harvesting whole poplars during the dormant season removed 80% of the nitrogen accumulated during irrigation with sewage oxidation pond effluent, while harvesting only stems removed approximately 30%.

CHAPTER III

STUDY SITES

Geography

The sites examined in this study are located in the northern portion of the Manistee National Forest near Cadillac, Michigan. The first site is on the Udell Experimental Forest 7 km west of Wellston, Michigan and legally located in NE¼, SE¼, Section 18, Township 21 North, Range 14 West, in Manistee County (see Figure 2). The second site is on the Pine River Experimental Forest 13 km east of Wellston, Michigan and legally described as N½, SE¼, Section 17, Township 21 North, Range 12 West, in Wexford County.

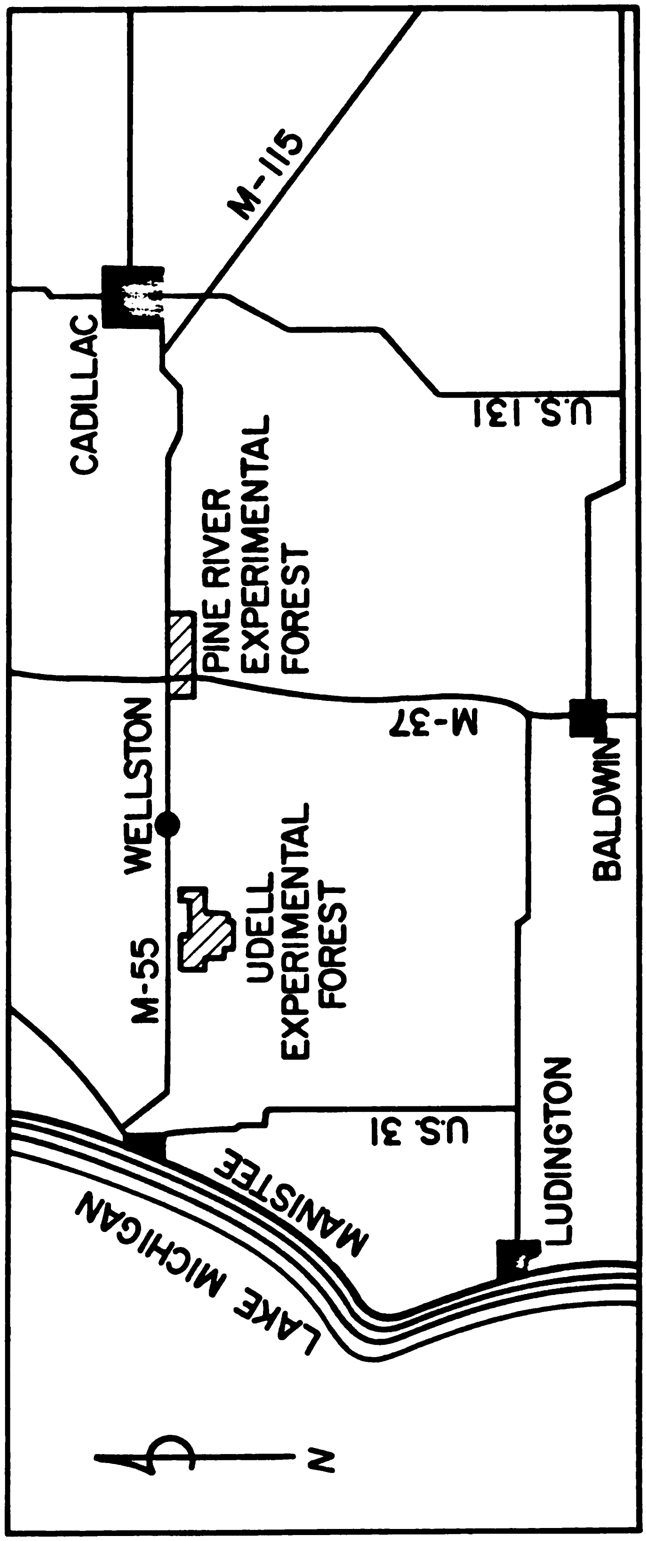
Both sites lie in the Manistee-Grayling Plain physiographic region of Michigan's lower peninsula (Sommers [Ed.] 1977). Surface topography ranges from nearly level to gently rolling hills. Both sites lie in the watershed of the Manistee River which drains westward to its terminus at Lake Michigan's eastern shore.

Geology

Surface formations on both sites are dominated by a medium altitude outwash plain of stratified, coarse unconsolidated deposits. These materials are primarily sands and gravels which were deposited during the Port Huron substage of Valdern late Pleistocene

Figure 2. Udell Experimental Forest and Pine River Experimental Forest.[1]

[1]Udell Experimental Forest, Wellston, Michigan. Lake States Forest Experiment Station. Forest Service, U.S.D.A.


M-115
CADILLAC
U.S. 131
PINE RIVER
EXPERIMENTAL
FOREST
WELLSTON
M-37
BALDWIN
UDELL
EXPERIMENTAL
FOREST
M-55
U.S. 31
LUDINGTON
MANISTEE
LAKE MICHIGAN
N

continental glaciation (Urie 1977). Depth to a bedrock of Lower Marshall Sandstone (Martin 1936) which is Mississippian in age (Sommers [Ed.] 1977) ranges from 180 m (590 ft.) to 210 m (690 ft.) (Urie 1977).

Soils and Hydrology

Udell

Soils on the Udell study site consist primarily of the Rubicon and Croswell (Entic Haplorthods) series (Watson 1977). The northern half of this study site is underlain with Rubicon sand of 0-2% slope with little or no erosion. The southern portion is underlain with Croswell sand of 0-2% slope with little or no erosion. Both of these soils are typical of sandy outwash plains in Northern Michigan. Original vegetation on these soils consisted of red pine with minor mixtures of white pine, jack pine and hardwoods (Weber et al. 1966).

Rubicon sand is generally well drained, while Croswell sand is described as moderately well drained. Minimum infiltration rates for soils of this region are generally in excess of 300 mm per hour (Sommers [Ed.] 1977), with runoff being very slow. These soils have a low available moisture capacity and a low native fertility and are unsuited for general farming (Weber et al. 1966). A typical soil profile description for the Rubicon series is presented in Figure 3 and a typical soil profile description for the Croswell series is seen in Figure 4.

Figure 3. Soil horizon description for the typifying pedon of the Rubicon series (Soil Conservation Service 1976).

Typifying Pedon: Rubicon Series

Profile	Depth	Description
A1	0-1"	Black (10 YR 2/1) sand, flecked with light brownish gray (10 YR 6/2); weak fine granular structure; very friable; common roots; very strongly acid; abrupt smooth boundary; ½ to 3 inches thick.
A2	1-6"	Light brownish gray (10 YR 6/2) sand; very weak medium structure; very friable; common roots; very strongly acid; clear smooth boundary; 2 to 7 inches thick.
B21ir	6-10"	Dark brown (7.5 YR 4/4) sand; weak medium granular structure; very friable; many roots; medium acid; clear wavy boundary; 4 to 12 inches thick.
B22ir	10-18"	Dark yellow brown (10 YR 4/4) sand; weak coarse granular structure; very friable; common roots; medium acid; clear irregular boundary; 0 to 20 inches thick.
B3	18-36"	Yellowish brown (10 YR 5/6) sand; very weak coarse subangular blocky structure; very friable; medium acid; chunks of orstein occur at depths of 18 to 24 inches and represent about 15 percent of the surface area of the horizon exposed; chunks are 4 to 6 inches in diameter; colors are yellowish brown (10 YR 5/6) representing 60 percent of the mass and dark reddish brown (5 YR 3/4) and pale brown (10 YR 6/3) representing the remaining colors, sand; massive; few roots; weakly to strongly cemented; medium acid; clear irregular boundary; 4 to 20 inches thick.
C1	36-60"	Light yellowish brown (10 YR 6/4) sand with some coarse sand in upper portion; single grained; loose; slightly acid.

Figure 4. Soil horizon description for the typifying pedon of the Croswell series (Soil Conservation Service 1975).

Typifying Pedon: Croswell Series

Profile	Depth	Description
Ap	0-8"	Dark grayish brown (10 YR 4/2) sand; weak medium granular structure; very friable; medium acid; abrupt smooth boundary; 6 to 10 inches thick.
A2	8-12"	Pinkish gray (7.5 YR 7/2) sand; single grain; loose; very strongly acid; abrupt irregular boundary; 4 to 10 inches thick.
B21ir	12-20"	Dark brown (7.5 YR 4/4) sand; weak medium subangular blocky structure; very friable; strongly acid; gradual wavy boundary; 2 to 8 inches thick.
B22ir	20-30"	Brown (7.5 YR 5/4) sand; few fine distinct yellowish brown (10 YR 5/8) mottles; single grained; loose; strongly acid; gradual wavy boundary; 10 to 20 inches thick.
C1	30-60"	Light yellowish brown (10 YR 6/4) sand with common medium distinct yellow (10 YR 7/8), strong brown (7.5 YR 5/8) and reddish yellow (7.5 YR 6/8) mottles; single grain; loose slightly acid.

This area is among the richest groundwater aquifers in Michigan, with water yields from wells 25 cm in diameter commonly exceeding 1,893 liters (500 gal.) per minute (Sommers [Ed.] 1977). Hydrologically this site is connected via Pine Creek with the Manistee River to the north, toward which its groundwater slowly moves. The water table on this site is commonly within 3 m of the soil surface during the wet season and somewhat deeper during drier periods.

Pine River

Soils on the Pine River site are found to consist primarily of the Grayling (Spodic Udipsamment) and Menominee (Alfic Haplorthod) series (Soil Conservation Service 1958). The western third of the study site is underlain with Grayling sand of 7-12% slopes with little or no erosion. The eastern portion is underlain with Menominee sand of 3-6% slope with little or no erosion. Grayling soils are typical of coarse textured outwash plains in this region, while Menominee soils have incorporated within them higher proportions of smaller sized particles and may be found on old lake plains as well as outwash plains. Native vegetation on Grayling soils consists of jack pine and scrub oaks, whereas that on Menominee soils is comprised of northern hardwoods and aspen.

Grayling sand is well drained and very rapidly permeable with very slow runoff. Available water in this soil is very low commonly leading to droughty conditions. Native fertility is very low making this soil unsuitable for general farming. A typical soil profile description for the Grayling series may be seen in Figure 5.

Figure 5. Soil horizon description for the typifying pedon of the Grayling series (Soil Conservation Service 1976).

Typifying Pedon: Grayling Series

Profile	Depth	Description
A1 and A2	0-3"	Black (N21) (A1), and grayish brown (10 YR 5/2) sand, (A2); coated and uncoated sand grains mixed throughout the horizon, giving a salt and pepper appearance; moderate organic matter content in upper part; weak medium granular structure; very friable; very strongly acid; abrupt smooth boundary; 2 to 4 inches thick.
B21ir	3-9"	Dark brown (7.5 YR 4/4) sand; weak coarse granular structure; very friable; strongly acid; clear smooth boundary; 4 to 8 inches thick.
B22ir	9-15"	Strong brown (7.5 YR 5/6) sand; very weak coarse granular structure; very friable; medium acid; clear irregular boundary; 4 to 14 inches thick.
B3	15-23"	Brown (7.5 YR 5/4) sand; single grained; loose; medium acid; gradual smooth boundary; 3 to 10 inches thick.
C	23-60"	Light brown (7.5 YR 6/4) sand; single grained; loose; medium acid.

Menominee sand can be well drained or moderately well drained, having rapid permeability in upper horizons and moderate permeability in finer textured lower horizons. Surface runoff is slow to medium. This soil has a moderate available water capacity and is low to medium in fertility suiting it to farming use in many cases (Weber et al. 1966). A typical soil profile description for the Menominee series appears in Figure 6.

This study site appears to be hydrologically connected via an intermittently flowing drainageway to the Pine River which subsequently flows into the Manistee River. Depth to groundwater below this site is estimated to be greater than 25 m throughout the year.

Present Vegetation

This region is identified as the Pine-Oak-Aspen forest association (Sommers [Ed.] 1977). Today the forest cover here is a mosaic of red, white and jack pines, northern hardwoods, aspen and scrub oaks.

The Udell site is dominated by an overstory of red pine (*Pinus resinosa*, Ait.) which were planted in 1936. This forty-year-old pole-sized plantation averaged 13 m (42.8 ft.) in height with a prethinning average basal area of 42.2 m^2/ha (184 ft^2/A) in early 1976 (Figure 7). Post thinning basal area was 22 m^2/ha (95.6 ft^2/A), nearly a 50% reduction. Using regression equations developed by Alban (1976), the site index was estimated to be 52 for red pine, a medium quality site (Buckman 1962).

Figure 6. Soil horizon description for the typifying pedon of the Menominee series (Soil Conservation Service 1976).

Typifying Pedon: Menominee Series

Profile	Depth	Description
Ap	0-9"	Very dark grayish brown (10 YR 3/2) loamy sand; light brownish gray (10 YR 6/2) dry, very weak medium granular structure; very friable; many fine roots; medium acid; abrupt smooth boundary; 6 to 10 inches thick.
B21ir	9-18"	Dark brown (7.5 YR 4/4) sand; weak medium subangular blocky structure; very friable; many fine roots; medium acid; gradual wavy boundary; 6 to 14 inches thick.
B22ir	18-32"	Yellowish brown (10 YR 5/4) sand; single grained; loose; common fine roots; medium acid; clear wavy boundary; 5 to 20 inches thick.
A2	32-35"	Pale brown (10 YR 6/3) light loamy sand; weak fine subangular blocky structure; very friable; common fine roots; medium acid; abrupt irregular boundary; 0 to 6 inches thick.
IIB2t	35-45"	Dark brown (7.5 YR 4/4) clay loam; thin to thick pale brown (10 YR 6/3) coatings of A2 on ped faces, and in root and worm channels; moderate medium angular blocky structure; firm; few thin discontinuous reddish brown (5 YR 4/4) clay films; few fine roots; 3 percent pebbles; slightly acid; abrupt wavy boundary; 6 to 40 inches thick.
IIC	45-66"	Brown (7.5 YR 5/4) light clay loam; weak medium angular blocky structure; firm; 5 percent pebbles; strong effervescence; moderately alkaline.

The understory flora consisted primarily of braken fern, sweet fern, blueberry, a variety of grasses and sedges, mosses, lichen and numerous seedlings and suppressed saplings of oak, cherry and maple. An exhaustive listing of vascular plants identified (Gleason and Cronquist 1963; Zimmerman 1972; Voss 1972; Pohl 1954) on the Udell site may be found in Table 30 in the appendix.

The Pine River study site contains red pine and white pine (Pinus strobus, L.) established in 1940 as the predominant overstory species. In early 1976 the average height of the red pine was 12 m (39.6 ft) and that of white pine was 11.3 m (37 ft) (Figure 8). The prethinning average basal area of these conifer poles was 23.1 m^2/ha (100.4 ft^2/A), thereafter reduced to 16.9 m^2/ha (73.8 ft^2/A) for red pine and 18.3 m^2/ha (79.6 ft^2/A) for white pine. Site index was estimated to be 55 for red pine, medium to high quality (Buckman 1962), and 51 for white pine. Forks and crooks were common among white pine boles indicating a history of weevil, Pissodes strobi, attacks (Wilson and McQuilkin 1963).

Under the red pine a less productive understory of sparse bracken fern, sweet fern, blueberry, lichen, moss, grass, sedge and hardwood seedlings was present. Under the white pine a vigorous understory of greater density dominated by aspen, oak, cherry, maple, ash and sassafras seedlings, blueberries, lilies, sweetfern, bracken fern, brambles, grasses and sedges proliferated. An understory of this composition was classified by Hazard (1937) as the "Maianthemum-Vaccinium" indicator type having moderate productivity for white pine.

Figure 7. Red pine plantation on Udell Experimental Forest.

Figure 8. White pine on Pine River Experimental Forest Plantation.

A listing of floral species found on the Pine River site may be seen in Table 31 in the appendix.

Climate

The climate at Wellston is a blend of continental and semi-marine conditions. Its proximity to Lake Michigan is largely responsible for the marine-like influence.

The mean annual temperature for this area is about 7°C with the extremes averaging -6.3°C in January and 18.9°C in July. The average length of the growing season is 136 days, between May 18 and October 1.

Precipitation is evenly distributed throughout the year with the greatest portion arriving between May and October, characteristically as afternoon showers or thundershowers. Annual precipitation averages 805 mm. Lying in the "Lake Snow Belt," annual snowfall has averaged 1,942 mm.

Prevailing winds are from the southwest at an average of 16 km per hour. Afternoon relative humidity ranges from 48% in May to 77% in December (Strommen 1971).

Study Design

Udell

The plantation evaluation study was established on the Udell Experimental Forest in May 1976. The experimental design consisted of a completely randomized design. Fifteen rectangular 0.2 ha plots (Gessel et al. 1960) were laid out in a 40-year-old red pine plantation

(Figure 9). Three replications of five treatments: (1) control (plots A, B and C), (2) 2.0 (plots 3, 7 and 12), (3) 4.0 (plots 4, 6 and 8), (4) 7.9 (plots 2, 10 and 11) and (5) 15.7 tonnes of sludge per hectare (plots 1, 5 and 9) were employed.

The plots were flagged and tagged to facilitate identification. The study area was posted with warning signs.

Pine River

The sludge study was established on the Pine River Experimental Forest in June 1976. The experimental design consisted of a randomized complete block design to account for the slope variations on the site. Twenty-four circular 0.1 ha plots (Gessel et al. 1960) were laid out in the 36-year-old plantation, 12 plots in red pine and 12 plots in white pine (Figure 10). Six replications of four treatments: (1) control (plots 1, 5, 10, 17, 28 and 30), (2) 5.4 (plots 4, 6, 11, 18, 27 and 29), (3) 9.7 (plots 2, 7, 9, 19, 21 and 23) and (4) 19.3 tonnes of sludge per hectare (plots 3, 8, 15, 16, 20 and 24) were employed in the red pine and white pine portions of the plantation.

The plots were flagged and a wooden identification stake was installed at each plot center. The entire study area was posted with warning signs.

Figure 9. Study plots in a 40-year-old red pine plantation on the Udell Experimental Forest.

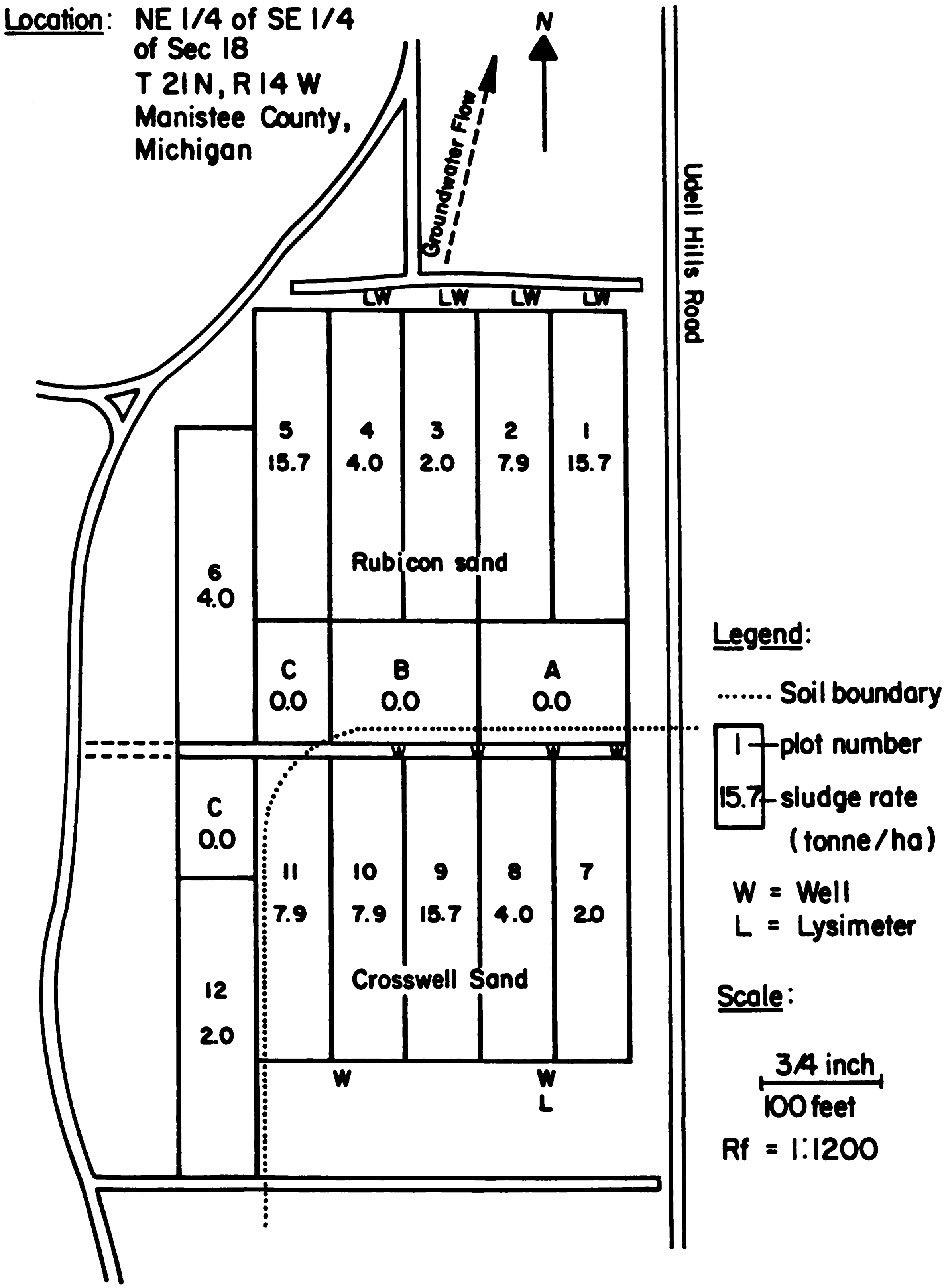

Location: NE 1/4 of SE 1/4 of Sec 18
T 21 N, R 14 W
Manistee County, Michigan
N
Groundwater Flow
Udell Hills Road
LW LW LW LW
5 15.7
4 4.0
3 2.0
2 7.9
1 15.7
6 4.0
Rubicon sand
C 0.0
B 0.0
A 0.0
W W W W
C 0.0
11 7.9
10 7.9
9 15.7
8 4.0
7 2.0
12 2.0
Crosswell Sand
W
W
L
Legend:
.... Soil boundary
1 plot number
15.7 sludge rate (tonne/ha)
W = Well
L = Lysimeter
Scale:
3/4 inch
100 feet
Rf = 1:1200

Figure 10. Study plots in a 36-year-old red pine and white pine plantation on the Pine River Experimental Forest.

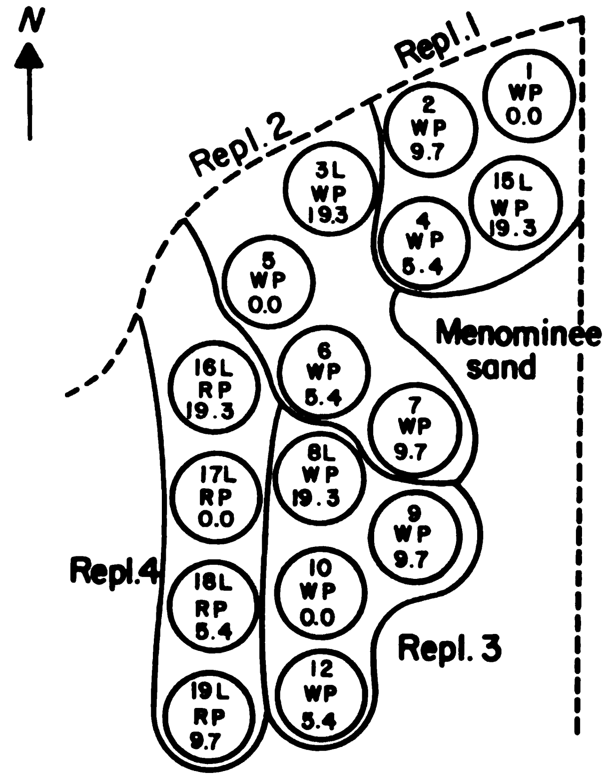
Location N 1/2 of SE 1/4 of Sec. 17
of T21N, R12W
Wexford County, Michigan

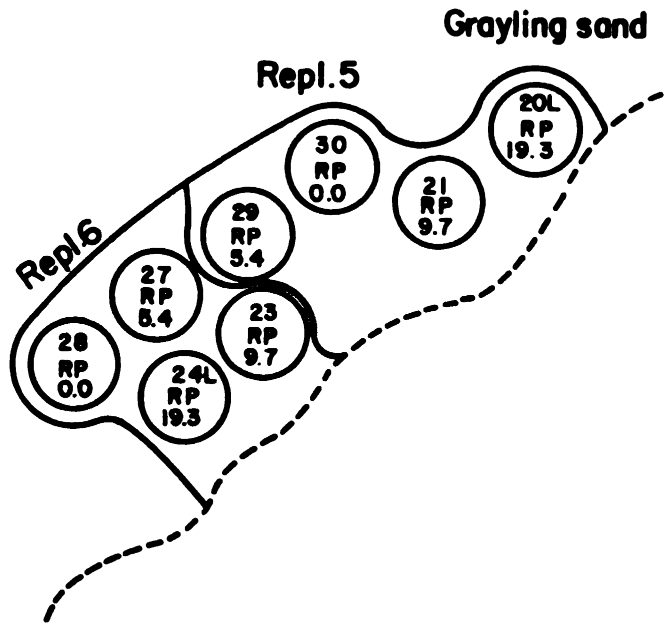
Legend L = Lysmeters (2)

20 — plot*
RP — cover type
19.3 — sludge rate (tonne/ha)

Scale 3/4 inch / 200 feet

Rf = 1 : 2400





CHAPTER IV

MATERIALS AND METHODS

Sludge Treatment

Prior to treatment the pine plantations on both sites were thinned, removing every other tree row. The cleared rows facilitated stand access for sludge distribution equipment and created stand stocking levels of 14 to 23 m^2/ha (60 to 100 ft^2/A) basal area, near those recommended by Benzie (1977) for maximum growth.

The red pine plantation on the Udell Forest received industrial sludge applications in late June 1976 at dosage rates ranging from 2.0 to 15.7 tonne/hectare (dry weight). The sludge employed was a raw paper mill sewage sludge produced by Packaging Corporation of America located at Filer City, Michigan. This sludge was concentrated from the effluent of an aerated wastewater treatment system. The wastewater was supplemented with ammonia and liquid phosphoric acid prior to treatment to stimulate bacterial activity in the aerated lagoon. An all-terrain tanker was used to distribute sludge upon the site by spraying from the tanker over the slash and litter layers (Figure 11).

The red pine and white pine plantation on the Pine River Forest received municipal sludge applications in July 1976 at rates ranging from 5.4 to 19.3 tonne/hectare (dry weight). The sludge applied was obtained from the Sewage Treatment Facility at Cadillac, Michigan.

Figure 11. All-terrain tanker sludge application on Udell site.

Figure 12. Portable pipeline and fire hose sprayer sludge application on Pine River site.

This was produced by a biological secondary sewage treatment process in which the wastewater also underwent ammonia stripping and phosphorus removal. The sludge received an average of 90 days anaerobic digestion prior to application (Urie et al. 1978). A portable pipeline and fire hose sprayer was used to distribute sludge upon the litter surface of this site (Figure 12).

Sludge samples were obtained directly from the distributing spray nozzles during treatment. Samples were preserved with concentrated sulfuric acid (2 ml/liter), stored at 4°C and analyzed by SERCO Laboratories of Roseville, Minnesota. Nitrate was determined using automated cadmium reduction and ammonia was measured with the Orion Ion-electrode. Total Kjeldahl nitrogen was analyzed using the phenolate method and total phosphorus was determined by automated digestion with stannous chloride. Boron was measured with the curcumin method and total solids determined by the gravimetric method. The remaining elements, cadmium, calcium, chromium, copper, total iron, lead, magnesium, manganese, nickel, potassium, sodium and zinc were analyzed by atomic absorption spectrophotometry.

Weather Data

Local weather information for the two study sites was obtained on a weekly basis from U.S. Forest Service weather stations established in the Udell Hills (Station #15) and at the Wellston Field Laboratory. Detailed data concerning temperature and rainfall was recorded from May 1975 through July 1978.

Water Quality Analysis

A major consideration in evaluating site suitability for sludge disposal is assessing groundwater nutrient enrichment potential. To this end, wells inserted into the surface of the water table aquifer and porous cup ceramic suction lysimeters intercepting freely moving soil percolate were employed.

The location of the 10 wells and 5 lysimeters used on the Udell site can be seen in Figure 9. The wells were constructed of 3 cm diameter galvanized steel pipe bearing a 1 meter long screened well point at their lower terminus. Each well was inserted into the water table aquifer to remove samples from the upper 1 m of the saturated zone for monitoring the chemical quality of groundwater as it flowed from the study plots. The lysimeters were constructed of 5 cm diameter PVC plastic pipe with a porous ceramic cup epoxyed to its lower end and a rubber stopper and access tubing epoxyed to its upper end. Each lysimeter was inserted into the soil to near the saturated zone to intercept soil percolate during the plantation's dormant season.

Four galvanized steel wells were installed in a drainageway near the Pine River site to monitor the quality of groundwater flowing from these study plots. Lysimeters installed on these plots were placed, two per plot, as seen in Figure 10, in replication #4 and in all plots receiving 19.3 tonne of sludge/ha.

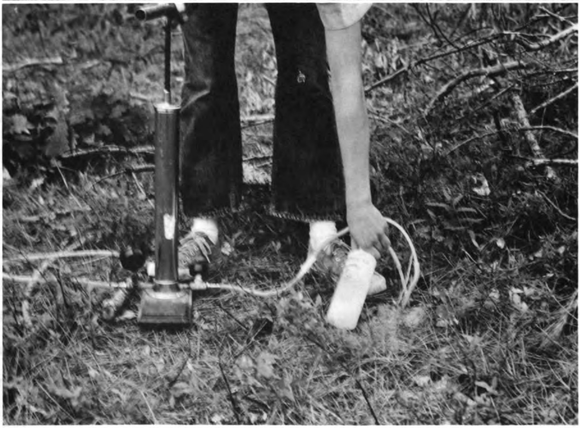
Grover and Lamborn (1970) have pointed out that porous cup soil water samplers may add to samples excessive amounts of K, Ca and Na while screening out P. Hansen and Harris (1975) have reported that, in addition to phosphorus screening, sample nitrate concentrations are often affected by plugging of the ceramic cup. In spite of these shortcomings, it was indicated that ceramic cup lysimeters may be used to obtain reasonably consistent results, given care in their installation and prudent interpretation of data.

Groundwater samples were collected from wells on a monthly basis throughout the course of this study (Figure 13). Samples of soil percolate were collected on a weekly basis during the spring and fall periods of recharge and monthly during other periods when accessible. Sampling of soil percolate from ceramic cup suction lysimeters consisted of sample extraction using a vacuum pump and resetting the tension in the soil water sampler to 33 cm of mercury (Figure 14).

Water samples collected from both wells and lysimeters were placed into plastic collection bottles, preserved with 40 mg/L $HgCl_2$ and placed in cold storage at 4°C. Sample analysis was conducted by the Research Analytical Laboratory at the University of Minnesota at St. Paul. Analysis for nitrite plus nitrate, ammonia, total kjeldahl nitrogen and total phosphorus was conducted using a Technicon Autoanalyzer II. Inductively coupled plasma atomic emission spectrophotometry (Applied Research Laboratories ICP) was used to determine zinc, cadmium, copper and nickel levels in water samples collected from porous cup lysimeters.

Figure 13. Groundwater sampling from galvanized steel well.

Figure 14. Soil percolate sampling from ceramic cup suction lysimeter.



Soil Evaluation

In late August of 1976 and 1977 soils on both sites were sampled to determine changes in soil chemistry and surface soil physical properties. A bulk density soil sampler was used to obtain undisturbed cores at the 0-5 cm and 5-10 cm soil depths (Figures 15 and 16). Ten sampling points were systematically selected in each plot on the Udell site and each white pine plot on the Pine River site and five sampling points were systematically selected in each red pine plot on the Pine River site. A bucket auger was used to sample deeper soil layers: 15-30 cm, 45-60 cm and 105-120 cm. Four sample points per plot were systematically selected on the Udell site and two sample points per plot were systematically selected on the Pine River site.

Soil samples from the 0-5 cm and 5-10 cm soil layers were weighed "fresh," dried at 105°C for 24 hours and weighed "dry" to gravimetrically determine surface soil moisture content and bulk density. All soil samples were combined into a plot composite sample for each of the 5 soil layers examined. Soil sampled from 15 cm to 120 cm was air dried. All soil was passed through a 2 mm screen prior to chemical analysis.

Chemical analysis was conducted by the Research Analytical Laboratory at the University of Minnesota at St. Paul and by the U.S. Forest Service Research Laboratory at East Lansing, Michigan. Nitrite plus nitrate and ammonia was extracted with 1 N KCl and analyzed using a Technicon Autoanalyzer II. Total nitrogen was measured using the macro-Kjeldahl method (Black 1965). Total

Figure 15. Undisturbed soil core sampler.

Figure 16. Undisturbed soil cores: 0-5 cm and 5-10 cm.

phosphorus was determined by nitric-perchloric acid digestion and inductively coupled plasma emission spectrophotometry. Extractable potassium, calcium, magnesium and sodium, were extracted with 1 N NH_4OAc and analyzed on an atomic absorption spectrophotometer (Jarrel-Ash Model 810). Iron, copper, zinc, manganese, cadmium, lead, chromium and nickel, were extracted using DPTA and TEA and analyzed on an inductively coupled plasma emission spectrophotometer (Applied Research Laboratories). Boron evaluation was conducted using hot water extraction and emission spectrophotometric analysis. Exchangeable acidity was accomplished with a 0.2 N TEA plus 0.5 N $BaCl_2$ extraction and titration with 0.1 N HCl. Specific conductivity of soil samples was determined using a conductivity meter and pH was measured with a glass electrode. Percentage of organic matter was determined by the loss on ignition technique.

Forest Floor and Understory

In early September of 1976 and 1977 understory plants and the forest floor (O horizons) were sampled on both sites to assess the influence of sludge applications upon the physical and chemical properties of these two ecosystem components. Eight sample locations per plot on the Udell site and four sample locations per plot on the Pine River site were systematically selected.

At each sample location all understory plants were cut at the groundline within a square meter area upon the forest floor and stored in paper bags (Figure 17). The understory plants consisted of small tree seedlings as well as herbaceous species. The forest floor under

Figure 17. Understory plant collection within a 1 m^2 sampling square.

Figure 18. Forest floor sampling within a 0.25 m^2 collection area.

these pine plantations could be described as a mor humus dominated by a litter layer of pine needles, deciduous plant leaves, pine cones and fallen tree branches generally less than 7 mm in diameter, in various stages of decomposition, lying upon a clearly defined mineral soil surface. Following understory sampling, all forest litter down to mineral soil was collected within a 0.25 m^2 area and stored in paper bags (Figure 18).

Understory and litter samples were dried in a forced draft oven at 75°C for 24 hours, weighed and ground in a Wiley mill with a 20 mesh screen. Samples were combined into one composite sample per plot for each component and chemically analyzed at the Research Analytical Laboratory of the University of Minnesota at St. Paul. Total nitrogen on these tissue samples was determined by the semi-micro Kjeldahl method and P, K, Ca, Mg, Al, Na, Fe, Mn, Zn, Cu, B, Co, Pb, Cr, Cd and Ni was measured using an inductively coupled plasma emission spectrophotometer (Applied Research Laboratories). Litter pH and specific conductivity was measured at the U.S. Forest Service Research Laboratory in East Lansing using, respectively, a glass electrode and a conductivity meter.

Slash

Following thinning operations on both sites in early 1976 trails of patterned slash were left upon the study plots. This slash consisted of tree branches, tops and needles, much of which became undiscernible from normal litter fall materials. Unless obviously traceable to harvest activity, all plant residues under 7 mm diameter were considered forest litter. All materials larger than 7 mm in diameter were regarded as slash unless their state of decay indicated that they were present on the forest floor prior to thinning. A more complete perspective of the long-term nutrient availability on the two sites was anticipated through sampling the slash residues present upon the study plots.

Slash sampling was conducted in September 1976 by two methods adopted from Howard and Ward (1972). Slash on the Udell site was oriented in a north-south manner. Four sample transects 1 m x 23 m were cut in an east-west orientation, perpendicular to the slash pattern, in control plots and all materials classified as slash were collected. Slash on the Pine River site was arranged in a somewhat less regular pattern depending on plot location. Four randomly oriented transects 1 m x 15 m were cut from plot center to plot perimeter, two in red pine and two in white pine control plots and all slash materials were collected. Sampled slash residues were weighed in the field and subsamples were collected, transported to the laboratory where they were oven dried at 75°C for 24 hours, weighed and ground in a Wiley mill with a 20 mesh screen. Chemical analysis was conducted as described above for litter and understory plant tissues.

Overstory

Evaluation of diameter, height, needle growth and foliar nutrient status were undertaken to document overstory responses to treatment. Following the 1976 and 1977 growing season DBH measurements were recorded on five sample trees per Udell plot and Pine River red pine plot and on 10 trees per Pine River white pine plot using a diameter tape. As Wright et al. (1972) have noted the lower genetic variability in the growth characteristics of red pine, a lower sampling intensity was used for this species than for white pine. Also following the 1977 growing season increment cores were taken at breast height on each of the same trees to assess the recent history of the stands' radial growth.

During late August of 1976 and 1977, subsequent to bud set and needle maturation (Benzie 1977), branch samples were collected from the uppermost sunlit crown of the codominant trees (Leaf 1973), 5 trees per red pine plot and 10 trees per white pine plot, and placed into a composite plot sample paper bag (Figure 19). From these, shoot, fasicle and needle samples from the current year's production were obtained (Hall 1966). Shoots were weighed before drying to determine their fresh weight. All tissues were then oven dried at 75°C in a forced draft oven and weighed. Needle lengths were recorded on 15 needles per plot. All needle samples were then ground in a Wiley mill with a 20 mesh screen (White 1958) and chemically analyzed as previously described for litter and understory plant tissues.

Figure 19. Collecting branch samples from the upper crown of codominant trees.

In April of 1978, during the dormant season, 5 trees per Udell plot and 2 trees per Pine River plot (20 trees/ha) were felled and their overall length and internodal growth along their mainstems recorded in the field for the 1973 to 1977 individual growing seasons. A cross-sectional disc at the base of each tree's live crown were then removed to assess radial growth occurring at this point during the previous four growing seasons.

CHAPTER V

RESULTS AND DISCUSSION

Sludge Treatment

A major concern of sewage sludge landspreading is adequate disposal of the nutrients contained in the applied waste. In evaluating each ecosystem's ability to capture and recycle supplementary nutrients, it was necessary to chemically define each sludge as a prerequisite to determining the ultimate fate of these elements.

Sludge Composition

The mean elemental concentrations of both sludges may be seen in Table 1. In examining the composition of these two sludges, it was noted that the most prominent difference between them was the presence of greater levels of trace elements and heavy metals in the municipal sludge. When compared with the data summarized by Kardos et al. (1977) for typical sludges produced in the United States, it was found that Zn, Cu, Pb, Ni and Cd were present in the municipal sludge in moderate to high concentrations while levels present in the industrial sludge were quite low. In the municipal sludge Cu, Ni and Cd were found to exceed their respective 800, 100 and 10 ppm levels of potentially hazardous rate of application. These elements were present at nonhazardous levels in the industrial sludge.

Table 1. Mean elemental concentrations in industrial and municipal sludges, 1976

Element	Pine River site: Municipal sludge Cadillac, Michigan	Udell site: Industrial sludge (paper mill) PCA, Filer City, Michigan
	---------------------ppm, dry wt.	----------------------
NH_4	16,600	4,442
NO_3	24	1,147
TKN	60,000	69,500
P	78,200	10,000
K	1,540	2,100
Na	--	88
Ca	14,000	17,400
Mg	7,760	4,900
Fe	1,420	2,400
Mn	1,540	1,060
Zn	1,648	542
Cu	1,040	48
B	2	43
Pb	960	49
Cr	780	27
Cd	440	5
Ni	192	17

Total Kjeldahl nitrogen and total phosphorus were relatively high in both sludges while potassium levels were low to moderate (Kardos et al. 1977). Calcium concentrations were moderate and magnesium levels were somewhat high in both the municipal and industrial sludge.

The sludge total solids content in each case was found to be 5.5%. Carbon to nitrogen ratios were determined to be 12.7:1 for the municipal sludge and 8.8:1 for the industrial sludge. Both values approximated the optimum 12:1 ratio considered ideal for humus mineralization in the forest environment. Zinc to cadmium ratios were computed to be 3.7:1 for the municipal sludge and 108:1 for the industrial sludge. Domestic Zn:Cd being normally 100:1, indicated the industrial sludge to be low in cadmium with respect to zinc; however, the municipal sludge was a high cadmium sludge.

Nutrient Loading

Because nitrogen has been shown to greatly influence vegetation growth, biological decay rates and soil water quality in forest ecosystems, it was selected as the index nutrient by which sludge application rates were determined. Nutrient loading with industrial sludge is shown in Table 2. Nitrogen application rates ranged from 140 kg/ha to 1,091 kg/ha. The higher rates were intended to test the limits of the site with regard to assimilation and retention of nutrients and enrichment of groundwater. Phosphorus application rates varied from 20 kg/ha to 157 kg/ha. Additions of other nutrients were low, even at the highest rate of sludge application.

Table 2. Nutrient loading by industrial sludge application on the Udell study site

Element	Sludge application rate (tonne/ha)			
	2.0	4.0	7.9	15.7
	kg/ha			
NH_4	9.0	17.8	35.1	69.7
NO_3	2.3	4.6	9.1	18.1
TKN	140.1	278.0	549.1	1,091.2
P	20.2	40.0	79.0	157.0
K	4.2	8.4	16.6	33.0
Na	0.18	0.35	0.70	1.4
Ca	37.6	69.6	137.5	273.2
Mg	10.6	19.6	38.7	76.9
Fe	5.2	9.6	19.0	37.7
Mn	2.3	4.3	8.4	16.6
Zn	1.2	2.2	4.3	8.5
Cu	0.10	0.19	0.38	0.75
B	0.09	0.17	0.34	0.68
Pb	0.11	0.20	0.39	0.77
Cr	0.06	0.11	0.21	0.42
Cd	0.01	0.02	0.04	0.08
Ni	0.04	0.07	0.13	0.27

In Table 3, nutrient loading with municipal sludge may be seen. Nitrogen application rates ranged from 322 kg/ha to 1,155 kg/ha. Most of the nitrogen applied in both sludges was present as organic-N, approximately 25% of which is available for plant uptake in any single growing season. The percentage of total-N present as ammonia varied from 6% in the industrial sludge to 28% in the municipal sludge. Ammonia gas volitalization potentials may be assumed to have been proportional for the two sludges. Nitrate additions are of minor significance, being less than 20 kg/ha in each case.

Total phosphorus additions with municipal sludge were relatively high ranging from 420 kg/ha to 1,506 kg/ha. These P loading rates were an order of magnitude greater than those supplied by industrial sludge at equivalent sludge application rates. Trace elements (Zn and Cu) and heavy metals (Pb, Cr, Cd and Ni) in the municipal sludge were applied in amounts one to two orders of magnitude greater than with the industrial sludge. Additions of other nutrients in the municipal sludge were moderately low.

Forest Litter and Logging Slash

Sludge applied to forest ecosystems was introduced onto the forest floor where, upon drying, it became a constituent of the litter layer. The initial impacts of sludge application were observed in the litter layer, primarily as a result of nutrient additions.

Table 3. Nutrient loading by municipal sludge application on the Pine River study site

	Sludge application rate (tonne/ha)		
Element	5.4	9.7	19.3
	kg/ha		
NH_4	89.3	160.0	319.8
NO_3	0.11	0.22	0.45
TKN	322.6	577.9	1,155.8
P	420.4	753.2	1,506.4
K	8.3	14.8	29.7
Na	--	--	--
Ca	75.3	134.8	270.0
Mg	41.7	74.7	149.5
Fe	7.6	13.7	27.3
Mn	8.3	14.8	29.7
Zn	8.8	15.9	31.7
Cu	5.6	10.0	20.0
B	0.01	0.02	0.03
Pb	5.2	9.3	18.5
Cr	4.1	7.5	15.0
Cd	2.4	4.3	8.5
Ni	1.0	1.9	3.7

Litter pH

Litter pH was seen to increase with increasing rates of sludge application on both sites (Table 4). Addition of basic cations elevated pH in the red pine litter on the Udell site as high as 6.1, nearly two pH units above the control in 1976. By late 1977 cation leaching, nutrient assimilation by plants and nitrification resulted in pH decreases at all treatment levels. Treated plot pH's nonetheless remained significantly greater than those in control plots.

Litter pH also demonstrated increases in sludge treated plots on the Pine River site in 1976 with a subsequent decline occurring in 1977. These pH values were in general significantly greater than those in controls. Worthy of note was the finding that white pine litters were of higher pH in both control and treated plots.

The trends established for litter specific conductivity were similar to those discussed for pH (Table 5). Sludge applications were found to significantly increase the total salts content of the litter upon both study sites.

Nutrient Enrichment

Nitrogen and phosphorus concentrations were significantly increased in the Udell study site litter (Table 6). Control nitrogen levels were surpassed in the initial season following treatment by levels exceeding 2% at the highest sludge application rate. Native phosphorus levels near 0.05% were increased nearly one order of magnitude to 0.41% at the highest sludge treatment rate. Other nutrients (K, Ca, Mg, Al, Na, Fe, Zn, Cu, B, Pb, Cr, Cd and Ni)

Table 4. Litter pH changes resulting from sludge treatment

Sludge treatment (tonne/ha)	pH 1976		pH 1977	
Udell study site				
15.7	6.1a*		4.9a	
7.9	5.9ab		5.0a	
4.0	5.8ab		4.8a	
2.0	5.4b		5.0a	
0.0	4.2c		4.1b	
	Red pine	White pine	Red pine	White pine
Pine River study site				
19.3	5.9a	6.3a	5.2a	5.6a
9.7	5.7a	6.1ab	5.4a	5.4a
5.4	5.3b	5.7b	4.8ab	5.2a
0.0	4.2c	4.6c	4.3b	4.7b

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 5. Specific conductivity of litter, 1977

Sludge treatment (tonne/ha)	Specific conductivity (µmhos/cm)	
Udell study site		
15.7	2,290a*	
7.9	2,043a	
4.0	1,340b	
2.0	817bc	
0.0	506c	
	Red pine	White pine
Pine River study site		
19.3	1,027a	793a
9.7	708ab	554ab
5.4	494ab	454b
0.0	340b	310b

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 6. Litter nitrogen and phosphorus concentration on the Udell site

Sludge treatment (tonne/ha)	TKN		Total P	
	1976	1977	1976	1977
	-------------------- % --------------------			
15.7	2.27a*	1.96a	0.41a	0.37a
7.9	1.50b	1.78a	0.29ab	0.34a
4.0	1.80ab	1.52b	0.24b	0.21b
2.0	1.41bc	1.32b	0.15bc	0.16b
0.0	0.90c	0.93c	0.05c	0.07b

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

in the forest litter were increased significantly by sludge application; however, their impact upon litter decay was minimal. These data may be seen in Table 32 in the appendix.

As with the litter on the Udell site, nitrogen was significantly increased in the red pine litter and the white pine litter on the Pine River site (Table 7). Red pine litter N increased from control levels of 0.85% to 1.33% at the highest sludge treatment rate in 1976 and remained relatively stable through 1977. Native N levels in white pine litter increased from 0.99% to 1.61% in 1976, declining somewhat by the end of the 1977 growing season. Phosphorus levels in these litters were correspondingly increased following treatment. Red pine litter P increased from control levels of 0.05% to 0.44% in 1976 and 1.25% in 1977 and white pine litter P increased from similar control

Table 7. Litter nitrogen and phosphorus concentrations on the Pine River site

Sludge treatment (tonne/ha)	TKN		Total P	
	1976	1977	1976	1977
	%			
Red pine				
19.3	1.33a*	1.34a	0.44a	1.25a
9.7	1.25a	1.21ab	0.34ab	1.15a
5.4	1.12ab	0.98b	0.30b	0.54b
0.0	0.85b	0.70c	0.05c	0.05c
White pine				
19.3	1.61a	1.32a	0.81a	1.45a
9.7	1.55ab	1.33a	0.66ab	1.12a
5.4	1.20bc	1.10ab	0.41b	0.59b
0.0	0.99c	0.76b	0.06c	0.05c

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

levels to 0.81% in 1976 and 1.45% in 1977, at the high sludge application rates. The apparent increase in P levels on treated plots from 1976 to 1977 could not be explained.

Zinc and cadmium were also seen to undergo significant elevation of their concentrations in the litter on the Pine River site (Table 8). Control Zn levels near 60 ppm in red pine litter were increased more than an order of magnitude and those near 80 ppm in white pine litter rose to over 1,300 ppm by 1977, at the highest sludge application rate. Cadmium in control plots averaged approximately 1.0 ppm. Sludge additions elevated Cd levels to over 100 ppm in both red pine and white pine litters, by 1977.

The control levels of N and P found in the litters on the Udell site and the Pine River site were comparable to those reported under western pines, Pinus ponderosa and P. monticola, by Daubermire and Prusso (1963), having very similar pH values. In the case of N and P, as with nearly all other measured nutrients, the increased levels of these elements in the forest litter was directly related to the nutrient application rates employed during sewage sludge disposal. On the Pine River site Cd levels in litter represented a potential hazard to plants exploiting the litter nutrient reservoir. Other nutrients (K, Ca, Mg, Al, Na, Fe, Mn, Cu, B, Pb, Cr and Ni) in the forest litter were also significantly increased via sludge application. These data are presented in Tables 33 and 34 in the appendix.

Table 8. Litter zinc and cadmium concentrations on the Pine River site

Sludge treatment (tonne/ha)	Zn 1976	Zn 1977	Cd 1976	Cd 1977
	ppm			
Red pine				
19.3	757a*	1,150a	63.2a	117.0a
9.7	634ab	1,058a	54.3ab	110.0a
5.4	520b	527b	40.7b	51.9b
0.0	62c	58c	1.0c	0.8b
White pine				
19.3	1,422a	1,330a	122.8a	136.2a
9.7	1,111ab	1,046a	85.1ab	107.5a
5.4	741b	558b	60.7b	53.2b
0.0	81c	79c	1.3c	1.1c

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Physical Changes

The most obvious physical change in the forest litter resulting from sludge application was an increase in litter dry weight per unit area (Table 9). Under the red pine on the Udell site a dry weight increase from 1,558 g/m^2 for controls to 4,386 g/m^2 for the highest dosage rate was effected. This represents an increase of 182% over the control. On the Pine River site the litter weight increased from 1,162 g/m^2 to 3,011 g/m^2 under the white pine (159%) and from 1,963 g/m^2 to 2,978 g/m^2 under the red pine (52%). The litter dry weights in controls, equivalent to 15.58, 11.62 and 19.63 tonne/ha, respectively, were comparable to those determined by Wollum and Schubert (1975) for thinned 43-year-old ponderosa pine in the Southwest and by Ffolliott et al. (1976) for ponderosa pine growing on sandy alluvium in Arizona.

The rates of litter decomposition may be inferred by comparing litter dry weights for 1976 and 1977. Although the nitrogen supplied with the sludge application narrowed the carbon to nitrogen ratio, it can be seen from the litter weight data that no appreciable acceleration in decay rate occurred. Variation in litter weight under a forest canopy is reportedly a result of species composition and basal area of the stand (Wooldridge 1970). As these factors were kept uniform on each study site, the variation in litter weights was most likely a function of the solids applied through the imposed treatments. Linear regression computations correlating sludge application rate with litter dry weight yielded r^2 values ranging from 0.83 to 0.99 (Table 68 in Appendix).

Table 9. Litter dry weights and carbon to nitrogen ratios, 1976 and 1977

	1976		1977	
Sludge treatment (tonne/ha)	Dry weight (g/m^2)	C:N	Dry weight (g/m^2)	C:N
Udell site				
15.7	4,386a*	24.2	4,982a	28.1
7.9	2,984b	30.6	4,077ab	30.9
4.0	2,520bc	36.7	2,995bc	36.2
2.0	1,989bc	39.0	2,495bc	41.7
0.0	1,558c	61.1	2,062c	59.1
Pine River site				
Red pine				
19.3	2,978a	41.4	3,292a	41.0
9.7	2,134a	44.0	3,116ab	45.5
5.4	2,004a	49.1	2,154ab	56.1
0.0	1,963a	64.7	1,898b	78.6
White pine				
19.3	3,011a	34.2	3,551a	41.7
9.7	2,649a	35.5	2,547a	41.4
5.4	1,917bc	45.8	2,484a	50.0
0.0	1,162c	55.6	2,079a	72.4

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Although the changes in carbon to nitrogen ratios failed to produce a reduction in the biomass of the total litter mass, locally within the litter layer decomposition of litter material was visible. In 1977 a second and third zone of fermentation was found in the litter between the pre-1976 and 1976 litterfall materials (Figure 20). This change in litter layer structure was best developed on high sludge dosage plots, occurring in the zones of locally favorable C:N at the sludge-litter interface. This characteristic L-F-S-F-L-F-H structure was not present on control plots.

Slash

Following the stand thinning in early 1976, a considerable mass of logging slash was present upon the sites. By the second growing season some of this material had begun to break up and become a part of the litter layer (Figure 21). At typical rates of slash decomposition, slash has not been implicated as a factor significantly influencing short-term nutrient cycling (R. E. Miller et al. 1976). Slash sampling, however, was conducted in the interest of gaining an improved perspective of longer term site nutrient dynamics.

Slash dry weights on the Udell site averaged 3.85 kg/m^2 (38.5 tonne/ha) while those on the Pine River site averaged 2.82 kg/m^2 (28.2 tonne/ha) under red pine and 3.67 kg/m^2 (36.7 tonne/ha) under white pine. The nutrient concentration and nutrient load of each slash is presented in Table 10. The slash materials contained respectable quantities of N, over 260 kg/ha; K, approximately 100 kg/ha; Ca, from 100 to 200 kg/ha; and Mn, ranging from near 20 to 30 kg/ha.

Figure 20. Sludge induced zone of fermentation in pine litter.

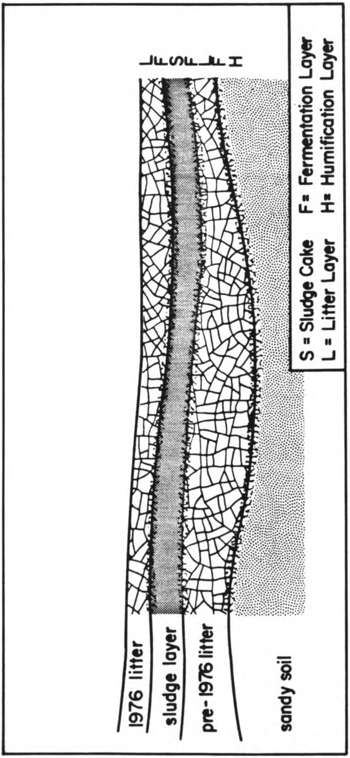

L
F
S
F
L
F
H
1976 litter
sludge layer
pre-1976 litter
sandy soil
S = Sludge Cake
L = Litter Layer
F = Fermentation Layer
H= Humification Layer

Figure 21. Logging slash on study plots.

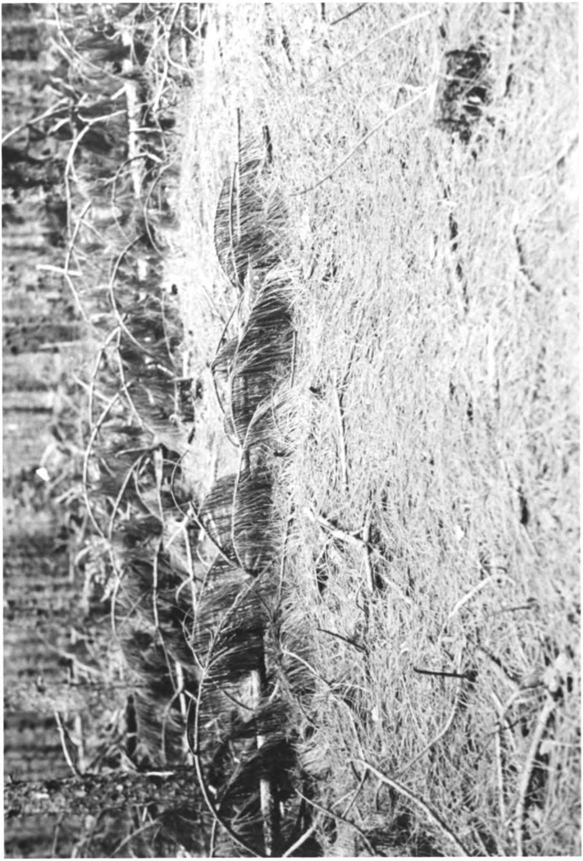


Table 10. Slash nutrient concentrations and nutrient loads

	Udell site		Pine River site			
	Red pine		Red pine		White pine	
Element	Conc. (ppm)	Load (kg/ha)	Conc. (ppm)	Load (kg/ha)	Conc. (ppm)	Load (kg/ha)
TKN	6,800	261.8	10,800	304.6	8,900	326.6
P	688	26.5	1,214	34.2	1,104	40.5
K	2,344	90.2	4,095	115.5	3,491	128.1
Ca	4,389	169.0	4,341	122.4	6,009	220.5
Mg	655	25.2	1,154	32.5	1,049	38.5
Al	276	10.6	445	12.5	341	12.5
Na	9	0.3	5	0.1	6	0.2
Fe	96.0	3.7	76.7	2.2	79.1	2.9
Mn	804.0	31.0	1,103.8	31.1	504.3	18.5
Zn	46.7	1.8	58.1	1.6	64.1	2.4
Cu	3.7	0.1	3.0	0.1	7.0	0.3
B	14.0	0.5	21.6	0.6	18.4	0.7
Pb	29.6	1.1	9.0	0.3	15.9	0.6
Cr	2.9	0.1	3.2	0.1	1.8	0.1
Cd	0.8	0.03	0.4	0.01	0.9	0.03
Ni	1.9	0.1	3.9	0.1	2.0	0.1

Other nutrients were present in the slash in low amounts. When the slow rate of slash decomposition is considered, the nutrients annually released from this material were of minor consequence when compared to those delivered to the site during sludge disposal.

Soil

Sludge nutrients applied to forest litter may be expected to enter the surface soil layers through the processes of litter decomposition and leaching resulting from percolating rainfall. The effect of this transfer was measured to ascertain the initial impact of treatment upon soil nutrient reserves and soil physical properties. As the surface soil layer is biologically the most active, measurements were most intensive in this region.

Soil Chemistry

The most dramatic effect of sludge treatment upon the 0-5 cm soil layer was the significant increase in NO_3-N and NH_4-N in the plots receiving the highest dosage rates (Table 11). Nitrogen delivery to these sites appeared not to increase soil TKN levels, implying that a majority of the N, applied as organic-N, remained in the litter layer above. The significant elevation in NH_4-N and NO_3-N soil levels were a function of their greater solubility as they were carried downward into the soil by percolating rainwater. From 1976 to 1977 NO_3-N levels increased in the soil of treated plots, an indication of nitrification activity in and above this layer.

Table 11. Soil nitrogen concentrations, 0-5 cm depth

Sludge treatment (tonne/ha)	NO_3		NH_4		TKN	
	1976	1977	1976	1977	1976	1977
	ppm					
Udell site						
15.7	2.9a*	19.6a	19.9a	29.6a	850a	683a
7.9	0.5b	4.6b	18.5ab	19.7ab	790a	703a
4.0	0.3b	1.5bc	13.6abc	15.3ab	763a	603a
2.0	0.2b	1.3bc	12.8bc	13.1b	873a	690a
0.0	0.2b	0.1c	10.8c	7.5b	847a	627a
Pine River site						
Red pine						
19.3	0.8a	1.5a	26.2a	19.0a	807a	623a
9.7	0.4a	0.3b	12.3b	10.8a	767a	623a
5.4	0.8a	0.4b	12.8b	21.4a	727a	667a
0.0	0.3a	0.1b	7.5b	14.1a	647a	613a
White pine						
19.3	4.1a	9.1a	26.7a	20.6a	720a	637a
9.7	2.5ab	2.4ab	15.3b	19.0a	700a	567a
5.4	0.7ab	1.1b	11.8bc	19.5a	883a	657a
0.0	0.3b	0.7b	9.1c	17.8a	757a	633a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Nitrification produces hydrogen ions which can displace cations on the exchange complex. This effect was in poor evidence on these sites, as neither a consistently significant increase nor decrease was observed for other cations in the soil (Appendix, Tables 35-37). Cation additions of minor magnitude were observed; however, their impact upon the total base reserves was minimal (Table 12). Significant increases in soil base saturation were sporadic and poorly related to sludge treatment levels. However, soil specific conductivity significantly increased on both sites in 1976 as a result of the leaching of soluble salts from the treated litter cover and the initial transfer of sludge supernatant at the time of treatment. This trend was seen to dissipate by 1977 as these soluble materials were assimilated by plants and leached from the soil profile.

The absence of major translocations of nutrients from the litter into the soil produced little change in soil pH and carbon to nitrogen ratio in the first two seasons following sludge treatment (Table 13). In 1976 pH did increase with sludge application under red pine but these trends were not significant on either side. Trends in pH were similar in 1977. Although soluble N entered the 0-5 cm soil layer, it was present in insufficient amounts to produce any meaningful narrowing in the C to N ratio there.

Soil phosphorus was significantly increased on the Udell site during 1976 and continued through the 1977 growing season. As liquid phosphoric acid was added to the industrial wastewater prior to its treatment, possibly the soluble phosphorus in the supernatant elevated

Table 12. Soil specific conductivity, base saturation and cation exchange capacity, 0-5 cm depth

Sludge treatment (tonne/ha)	Specific conductivity (μmhos/cm) 1976	Specific conductivity (μmhos/cm) 1977	Base saturation (%) 1976	Base saturation (%) 1977	Cation exchange capacity (meq./100 g) 1976	Cation exchange capacity (meq./100 g) 1977
Udell site						
15.7	266a*	312a	15.0a	14.2a	8.04aab	7.23ab
7.9	263a	225b	11.3ab	11.4a	8.06ab	5.55b
4.0	208ab	252ab	9.2b	10.1a	6.54b	6.45ab
2.0	244ab	207b	12.5a	9.8a	7.37ab	7.66ab
0.0	184b	187b	9.8b	9.3a	9.61a	7.00ab
Pine River site						
Red pine						
19.3	231a	206a	16.7a	12.5a	7.60a	6.73a
9.7	182ab	178a	19.2a	17.3a	7.79a	7.16a
5.4	157bc	234a	13.5a	11.0a	7.33a	6.74a
0.0	119c	164a	10.3a	9.7a	6.58a	5.79a
White pine						
19.3	244a	317a	20.7a	24.1a	7.41a	7.46a
9.7	177b	230b	16.6a	14.2b	7.00a	7.49a
5.4	177b	286ab	26.1a	20.6ab	7.83a	7.22a
0.0	144b	248ab	25.8a	18.6ab	6.61a	7.31a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 13. Soil pH and carbon to nitrogen ratio, 0-5 cm depth

Sludge treatment (tonne/ha)	pH		C:N	
	1976	1977	1976	1977
Udell site				
15.7	4.20a*	4.40a	36.6	22.1
7.9	3.97a	4.22a	30.4	19.3
4.0	4.13a	4.15a	30.4	28.0
2.0	4.20a	4.20a	32.9	24.4
0.0	3.90a	4.17a	43.8	24.6
Pine River site				
Red pine				
19.3	4.57a	4.46a	26.3	21.8
9.7	4.53a	4.51a	33.1	24.6
5.4	4.53a	4.26a	33.7	19.1
0.0	4.30a	4.30a	27.5	18.3
White pine				
19.3	4.63a	4.55a	30.5	23.1
9.7	4.47a	4.35a	26.5	21.2
5.4	4.53a	4.47a	42.6	24.2
0.0	4.80a	4.50a	26.1	22.9

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

total P in the soil of treated plots by the movement of this mobile P form into the surface soil during and shortly after sludge application. Soil P on the Pine River site was not significantly increased following sludge treatment in 1976. Higher native phosphorus levels and greater site variability diminished the impact of the supplemental phosphorus upon the soil (Table 14).

Soil zinc levels were moderate ranging from a low of 2.0 ppm on the Udell site to a high of 6.2 ppm on the Pine River site (Table 15). Soil cadmium concentrations were variable from less than 0.1 ppm to 0.4 ppm on the control and treated plots of both study sites, often exceeding the 0.1 ppm level described by Turner (1973) as causing root damage to growing vegetable crops. As Baker et al. (1977) pointed out, however, there was no indication of a toxic Cd buildup in grain crops until Cd levels in soil exceed 0.5 ppm. The zinc and cadmium applied in the sludge remained largely in the litter layer during both growing seasons, as significant increase trends in their soil levels were poorly developed. The only exception was the 1977 soil Cd levels under the white pine litter which did show a consistent increase with increasing sludge dosage.

In soil layers below the 5 cm depth fluctuations in soil nutrient concentrations were far less pronounced. On both study sites soil NO_3-N was elevated in 1976 and 1977 under the highest rates of sludge treatment (Tables 16 and 17). While soil NO_3-N concentrations generally ran less than 2.0 ppm, levels as high as 10.2 ppm were detected in the 5-10 cm soil layer on the Udell site.

Table 14. Soil phosphorus concentrations, 0-5 cm depth

Sludge treatment (tonne/ha)	Total P 1976	Total P 1977
	---------- ppm -----------	
Udell site		
15.7	171a*	141a
7.9	141ab	102b
4.0	125bc	99b
2.0	150ab	97b
0.0	101c	86b
Pine River site		
Red pine		
19.3	157a	146a
9.7	164a	137a
5.4	163a	111a
0.0	143a	109a
White pine		
19.3	164a	150a
9.7	174a	109ab
5.4	122a	132ab
0.0	170a	93b

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 15. Soil zinc and cadmium concentrations, 0-5 cm depth

Sludge treatment (tonne/ha)	Zn		Cd	
	1976	1977	1976	1977
	ppm			
Udell site				
15.7	2.7ab*	3.0a	<0.1b	0.4a
7.9	2.6ab	2.1a	0.1ab	0.2b
4.0	2.0b	2.4a	0.0b	0.3ab
2.0	2.5ab	3.1a	<0.1b	0.3ab
0.0	3.2a	2.6a	0.1a	0.3ab
Pine River site				
Red pine				
19.3	3.5ab	2.6a	0.3a	0.2a
9.7	6.2a	3.2a	0.3a	0.2a
5.4	3.5ab	2.7a	0.3a	0.2a
0.0	2.3b	2.3a	0.0a	0.2a
White pine				
19.3	3.0a	4.3a	0.0a	0.3a
9.7	4.1a	4.0a	0.3a	0.2ab
5.4	4.9a	5.2a	0.3a	0.2ab
0.0	4.0a	3.0a	0.3a	0.1b

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 16. Soil nitrate and ammonia in lower soil layers on the Udell site

Year	Sludge treatment (tonne/ha)	Soil depth (cm) 5-10	15-30	45-60	105-120
		NO_3 (ppm)			
1976	15.7	1.3	2.1	0.6	0.4
	7.9	0.3	0.7	0.6	0.4
	4.0	0.3	0.5	0.4	0.4
	2.0	0.3	0.5	0.6	0.4
	0.0	0.2	0.4	0.4	0.4
1977	15.7	10.2	8.2	2.8	1.0
	7.9	3.6	0.7	0.7	0.1
	4.0	0.9	0.7	0.4	0.2
	2.0	0.3	0.4	0.3	0.3
	0.0	0.3	0.3	0.3	0.1
		NH_3 (ppm)			
1976	15.7	13.8	7.5	4.1	3.9
	7.9	12.1	8.1	10.9	2.7
	4.0	8.8	6.4	5.2	1.7
	2.0	11.0	5.7	4.4	1.9
	0.0	6.6	6.2	3.2	1.7
1977	15.7	11.6	7.1	4.2	2.2
	7.9	10.8	3.2	2.6	1.5
	4.0	12.4	2.4	1.8	0.8
	2.0	10.5	5.0	2.5	3.2
	0.0	6.3	2.5	2.8	0.3

Table 17. Soil nitrate and ammonia in lower soil layers on the Pine River site

Year	Sludge treatment (tonne/ha)	Soil depth (cm) 5-10	15-30	45-60	105-120
Red pine		NO_3 (ppm)			
1976	19.3	1.7	0.5	0.4	--
	9.7	0.3	0.4	0.4	0.4
	5.4	0.8	0.4	0.4	0.4
	0.0	0.2	0.4	0.4	0.0
1977	19.3	1.5	0.5	0.3	0.2
	9.7	0.3	0.3	0.7	0.3
	5.4	0.3	0.1	0.3	0.2
	0.0	0.3	0.3	0.3	0.1
White pine					
1976	19.3	1.4	0.9	0.6	0.5
	9.7	0.3	0.4	--	0.4
	5.4	0.4	0.4	0.5	0.6
	0.0	0.3	0.4	0.4	0.4
1977	19.3	1.8	3.5	2.6	3.1
	9.7	1.0	0.5	0.4	0.2
	5.4	0.5	0.3	0.3	0.2
	0.0	0.6	0.3	0.1	0.1
Red pine		NH_4 (ppm)			
1976	19.3	18.9	9.6	4.8	--
	9.7	8.3	8.4	4.9	5.1
	5.4	9.8	7.4	3.9	1.1
	0.0	7.5	5.0	3.7	1.9
1977	19.3	15.2	2.9	1.6	1.6
	9.7	6.8	2.9	2.9	1.9
	5.4	18.1	3.0	1.4	0.6
	0.0	12.3	2.1	2.4	0.9
White pine					
1976	19.3	14.4	5.3	4.2	2.1
	9.7	6.8	6.0	--	3.0
	5.4	9.1	6.5	6.2	2.4
	0.0	7.1	6.2	5.5	2.9
1977	19.3	12.7	2.7	1.7	1.0
	9.7	13.1	3.9	3.3	1.2
	5.4	15.2	2.6	3.4	0.7
	0.0	16.8	2.6	1.6	1.3

Soil NH_3-N levels were also somewhat elevated in soils under the highest treatment rates. Maximum NH_3-N levels of 18.9 ppm were measured on the Pine River site in the 5-10 cm soil layer. TKN failed to increase in these deeper soil layers, indicating a lack of organic-N movement into these depths (Appendix, Tables 38 and 48). As indicated earlier, organic-N appears to have been immobilized in the litter layer while mobile N forms, NO_3 and NH_4, leached downward into the soil profile.

As with the case of total N, most other measured nutrients and soil chemistry parameters did not exhibit appreciable change below the 5 cm depth (Appendix, Tables 38-57). Minor elevations of Na and Mg were detected in the 5-10 cm and 15-30 cm soil layers on the Udell site and slight increases in the specific conductivity in the 5-10 cm soil layer were noted on both study sites. Generally, however, the influence of the sludge upon the chemistry of lower soil layers was minimal.

Soil Physical Properties

Soil bulk density and moisture content in the upper 10 cm, measured at a single point in time on both study sites, were unaffected by the sludge treatments (Appendix, Tables 58 and 59). This result was not unexpected, considering that few nutrients significantly increased in these soil layers. Without substantial modification of the nutrient equilibria, the action of proliferating microorganisms and plant roots could hardly be anticipated to significantly modify the soil bulk density or moisture content.

Water Quality

During the two years subsequent to sludge treatment, soil water on both sites was sampled using wells and suction lysimeters. Nitrate, NH_4, total P, TKN, Zn, Cd, Cu and Ni were monitored during this time. During the 1976 season all measured elements remained below 0.1 ppm. During snowmelt early in the 1977 season, however, elevated nitrate levels appeared in the water samples taken from both sites.

Groundwater Recharge

As nutrients in the pine ecosystem move into groundwater during periods of recharge, it was necessary to compute the groundwater recharge occurring on the two sites. The water budget method developed by Thornthwaite and Mather (1957) was employed, utilizing temperature and rainfall data collected at U.S. Forest Service field weather stations located near each study area. Groundwater recharge and other water budget parameters are presented in Table 18 for the Udell site and in Table 19 for the Pine River site. Most recharge of groundwater occurred in spring, following snowmelt, and in fall, when evapotranspiration potential declined.

Nitrate

Under the red pine plantation on the Udell site no groundwater nitrate levels were in excess of 0.1 ppm during 1976. However, with snowmelt in early April 1977, NO_3-N levels in excess of the 10 ppm standard set by the U.S. Public Health Service were detected in groundwater following melting of the snowpack under plots receiving

Table 18. Calculation of groundwater recharge on the Udell study site according to Thornthwaite's water budget method

Year	Month	$\overline{X}$ monthly temperature	Adjusted monthly PE	Monthly ppt	Net ppt	Soil moisture storage	Moisture surplus	Total runoff	Detention	Groundwater recharge
		---- °C ----	----------	----------	----------	---------- mm	----------	----------	----------	----------
1975	October	10.8	31.4	57.2	25.8	100.0	25.8	--	--	25.8
	November	6.1	9.6	70.4	60.8	100.0	60.8	--	--	60.8
	December	-5.3	0.0	107.7	107.7	207.7	0.0	--	--	0.0
1976	January	-9.0	0.0	102.1	102.1	309.8	0.0	--	--	0.0
	February	-7.9	0.0	80.8	80.8	390.6	0.0	--	--	0.0
	March	-0.5	0.0	128.5	128.5	100.0	128.5	94.1	322.6	419.1
	April	5.6	10.1	80.3	70.2	100.0	70.2	198.7	368.9	70.2
	May	8.0	22.9	108.0	85.1	100.0	85.1	142.0	327.1	85.1
	June	17.4	89.0	39.6	-49.4	60.0	0.0	70.9	130.9	0.0
	July	17.1	85.8	11.9	-73.9	28.0	0.0	35.3	63.3	0.0
	August	15.0	64.8	77.5	12.7	32.0	0.0	17.7	49.7	0.0
	September	13.1	46.8	40.4	-6.4	30.0	0.0	8.9	38.9	0.0
	October	5.6	14.3	53.3	39.0	69.0	0.0	4.3	73.3	0.0
	November	-0.6	0.0	54.9	54.9	123.9	0.0	2.3	126.2	0.0
	December	-7.4	0.0	56.1	56.1	180.0	0.0	1.2	181.2	0.0
1977	January	-13.9	0.0	134.4	134.4	314.4	0.0	0.7	315.1	0.0
	February	-10.6	0.0	56.1	56.1	370.5	0.0	0.2	370.7	0.0
	March	-1.2	0.0	60.5	60.5	100.0	60.5	57.4	222.9	331.0
	April	6.2	20.2	97.5	77.3	100.0	77.3	175.5	352.8	77.3
	May	13.8	68.6	4.6	-64.0	52.0	0.0	87.8	139.8	0.0
	June	13.3	65.8	31.0	-34.8	36.0	0.0	43.9	79.9	0.0
	July	22.7	140.4	122.4	-18.0	30.0	0.0	21.9	51.9	0.0
	August	17.8	90.0	106.7	16.7	46.7	0.0	10.9	57.6	0.0
	September	14.3	59.3	103.1	43.8	90.5	0.0	5.5	96.0	0.0
	October	9.5	31.4	75.9	44.5	100.0	35.0	20.2	155.2	35.0
	November	3.1	7.2	113.0	105.8	100.0	105.8	63.1	268.9	105.8
	December	-6.1	0.0	151.1	151.1	251.1	0.0	31.6	282.7	0.0
1978	January	-9.5	0.0	86.1	86.1	337.2	0.0	15.7	352.9	0.0
	February	-12.2	0.0	30.2	30.2	367.4	0.0	7.8	375.2	0.0
	March	-4.2	0.0	12.4	12.4	379.8	0.0	3.8	383.6	0.0
	April	3.0	10.1	38.1	28.0	100.0	28.0	44.0	172.0	307.8
	May	11.7	57.2	69.3	12.1	100.0	12.1	139.9	252.0	12.1
	June	11.1	54.2	141.7	87.5	100.0	87.5	113.7	301.2	87.5
	July	16.3	89.7	41.4	-48.3	61.0	0.0	56.9	117.9	0.0

Table 19. Calculation of groundwater recharge on the Pine River study site according to Thornthwaite's water budget method

Year	Month	$\bar{X}$ monthly temperature	Adjusted monthly PE	Monthly ppt	Net ppt	Soil moisture storage	Moisture surplus	Total runoff	Detention	Groundwater recharge
		°C	mm							
1975	October	12.8	31.4	61.5	30.1	100.0	30.1	--	--	30.1
	November	8.0	9.6	78.0	68.4	100.0	68.4	--	--	68.4
	December	-3.2	0.0	102.1	102.1	202.1	0.0	--	--	0.0
1976	January	-9.1	0.0	60.2	60.2	262.3	0.0	--	--	0.0
	February	-7.8	0.0	63.2	63.2	325.5	0.0	--	--	0.0
	March	-0.4	0.0	137.7	137.7	100.0	137.7	94.1	331.8	363.2
	April	7.1	10.1	73.2	63.1	100.0	63.1	168.8	331.9	63.1
	May	10.4	26.7	113.8	87.1	100.0	87.1	127.9	315.0	87.1
	June	20.2	100.6	31.0	-69.6	49.0	0.0	64.0	113.0	0.0
	July	20.8	109.2	26.4	-82.8	21.0	0.0	31.9	52.9	0.0
	August	18.6	79.2	64.3	-14.9	18.0	0.0	15.9	33.9	0.0
	September	13.9	37.4	39.6	2.2	20.2	0.0	8.0	28.2	0.0
	October	6.6	14.3	37.1	22.8	43.0	0.0	4.0	47.0	0.0
	November	-1.6	0.0	50.0	50.0	93.0	0.0	2.0	95.0	0.0
	December	-8.7	0.0	37.1	37.1	130.1	0.0	0.9	131.0	0.0
1977	January	-13.4	0.0	71.9	71.9	202.0	0.0	0.4	202.4	0.0
	February	-9.1	0.0	60.2	60.2	262.2	0.0	0.2	262.4	0.0
	March	0.4	0.0	62.2	62.2	100.0	62.2	47.3	209.5	224.4
	April	9.3	30.2	84.1	53.9	100.0	53.9	115.6	269.5	53.9
	May	17.8	91.4	3.8	-87.6	40.0	0.0	57.8	97.8	0.0
	June	16.1	81.3	33.5	-47.8	25.0	0.0	28.9	53.9	0.0
	July	20.8	120.9	103.4	-17.5	21.0	0.0	14.4	35.4	0.0
	August	15.1	68.4	143.8	75.4	96.4	0.0	7.3	103.7	0.0
	September	12.8	46.4	99.6	52.8	100.0	49.2	28.2	177.4	49.2
	October	7.2	17.1	70.1	53.0	100.0	53.0	40.6	193.6	53.0
	November	2.9	2.4	103.1	100.7	100.0	100.7	70.8	271.5	100.7
	December	-5.2	0.0	130.0	130.0	230.0	0.0	35.3	265.3	0.0
1978	January	-7.4	0.0	59.9	59.9	289.9	0.0	17.5	307.4	0.0
	February	-7.5	0.0	26.4	26.4	316.3	0.0	8.8	325.1	0.0
	March	-1.9	0.0	18.3	18.3	334.6	0.0	4.3	338.9	0.0
	April	4.1	6.7	38.1	31.4	100.0	31.4	41.4	172.8	266.0
	May	13.6	61.0	66.0	5.0	100.0	5.0	117.1	222.1	5.0
	June	11.9	54.2	100.3	46.1	100.0	46.1	81.6	227.7	46.1
	July	17.6	93.6	32.3	-61.3	53.0	0.0	40.7	93.7	0.0

15.7 tonne of industrial sludge per hectare (Figure 22). Nitrate-N levels declined until June and rose sharply again in July and September, at which time both the 15.7 and the 7.9 tonne/ha sludge treated plot groups exceeded the 10 ppm standard. By May of 1978, following snowmelt, these same treatment groups equaled or exceeded the USPHS nitrate standard again. Water samples taken from plots receiving lighter dosages of sludge were not seen to exceed 5.7 ppm nitrate at anytime.

Should groundwater containing nitrate levels in excess of the 10 ppm standard travel along the piezometric gradient and experience insufficient dilution before encountering receiving surface waters, a nitrate pollution hazard could develop as a result of sludge application. Water quality beyond the vicinity of the site was not measured, however.

Under the red pine and white pine plantation on the Pine River site soil water nitrate levels did not exceed 0.1 ppm during 1976. Following the spring snowmelt in 1977, however, nitrate levels under both red pine and white pine exceeded the 10 ppm standard where treated with 19.3 tonne of municipal sludge per hectare (Figure 23). Soil water nitrate concentrations under white pine plots remained above 10 ppm from spring through the end of 1977 while those under red pine plots experienced greater variation peaking in late spring and in early fall. In 1978, scant data indicated elevated nitrate levels under high treatment plots once again. Water samples from plots receiving lower sludge dosages did not exceed 2.8 ppm NO_3-N during the study period.

Figure 22. Nitrate concentrations in groundwater on the Udell study site.

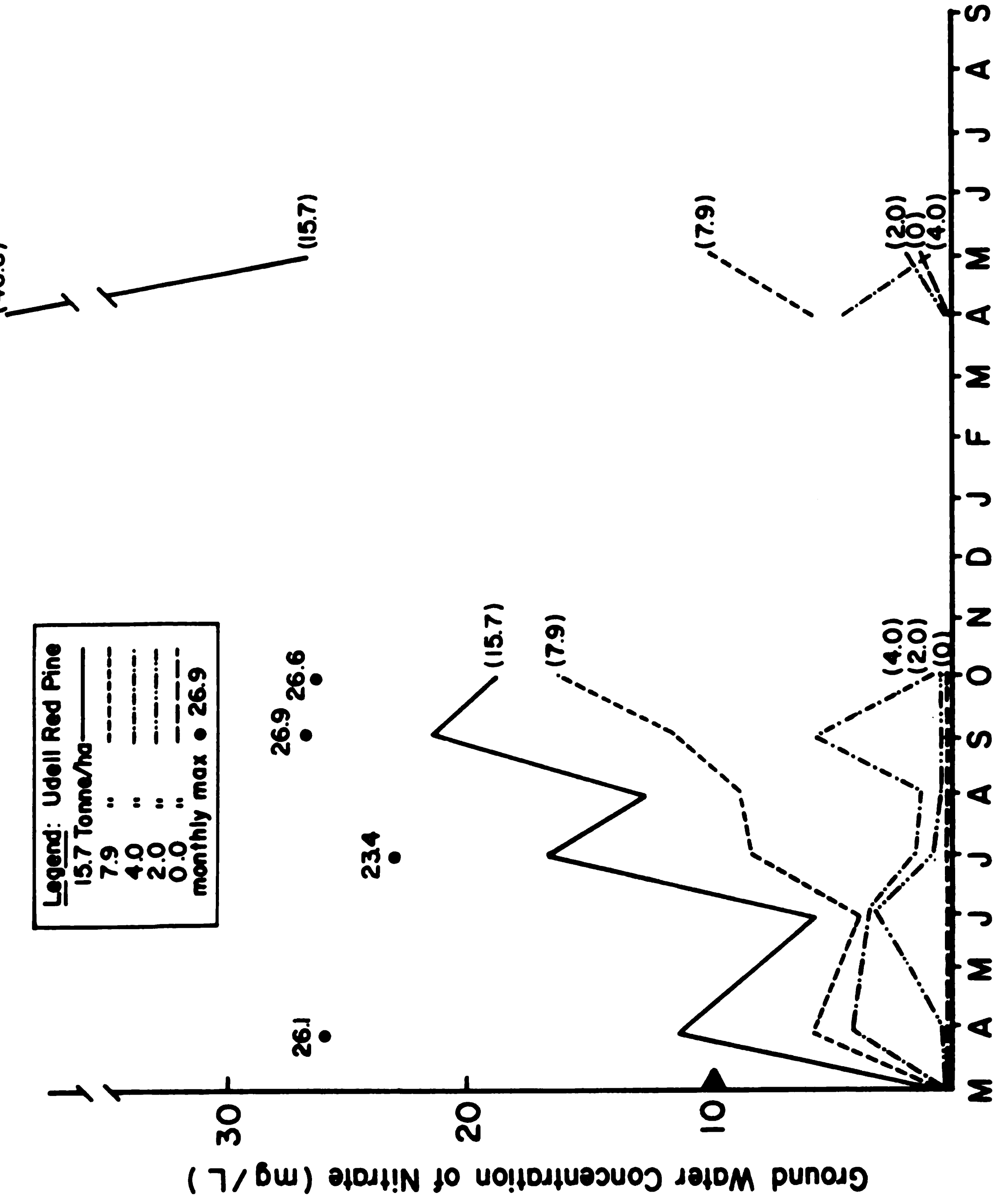
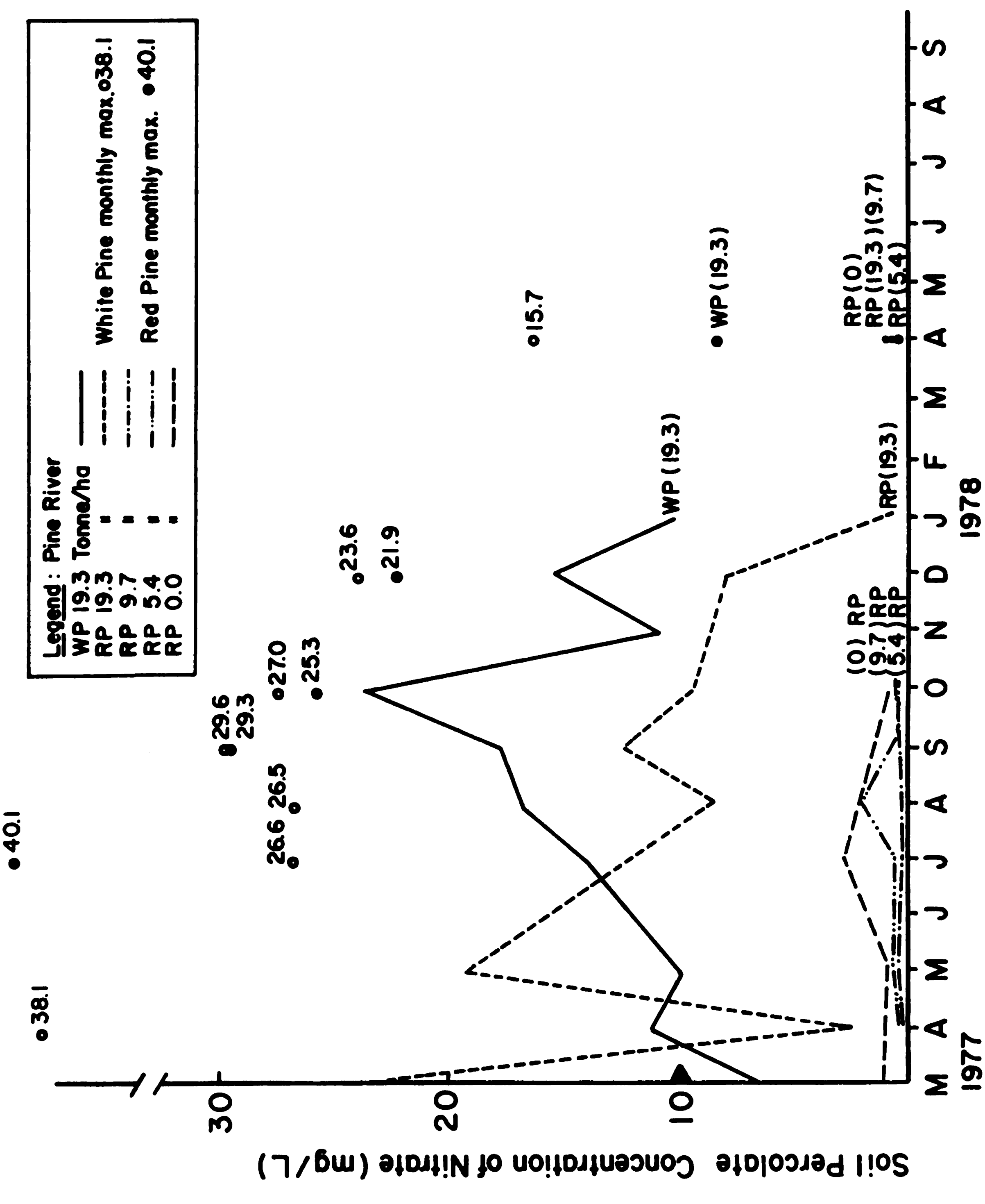

Legend: Udell Red Pine
15.7 Tonne/ha
7.9 "
4.0 "
2.0 "
0.0 "
monthly max • 26.9
Ground Water Concentration of Nitrate (mg/L)
10
20
30
M A M J J A S O N D J F M A M J J A S
1977
1978
26.1
23.4
26.9
26.6
(15.7)
(7.9)
(4.0)
(2.0)
(0)
(46.6)
(15.7)
(7.9)
(2.0)
(0)
(4.0)

Figure 23. Nitrate concentrations in soil water on the Pine River study site.


Legend: Pine River
WP 19.3 Tonne/ha
RP 19.3
RP 9.7
RP 5.4
RP 0.0
White Pine monthly max. o38.1
Red Pine monthly max. ●40.1
Soil Percolate Concentration of Nitrate (mg/L)
10
20
30
M A M J J A S O N D J F M A M J J A S
1977
1978
WP (19.3)
RP(19.3)
(0) RP
(9.7) RP
(5.4) RP
RP(0)
RP (19.3) (9.7)
RP(5.4)
38.1
40.1
26.6
26.5
29.6
29.3
27.0
25.3
23.6
21.9
15.7

In Table 20 nitrate losses from the rooting zone under the Pine River pines were calculated. It should be noted from this data that high nitrate levels in soil water produced no loss of nitrogen from the rooting zone during non-recharge months. The danger of groundwater enrichment is only posed during months when excessive nitrate levels coincide with recharge water volumes sufficient to transport the soluble nitrate anion into the surface aquifer. Under the highest treatment rate the annual NO_3-N loss during 1977 was 53.3 kg/ha under the white pine plots and 73.8 kg/ha under the red pine plots. These amounts were equivalent to 4.6% and 6.4%, respectively, of the 1,155 kg N/ha delivered to the plots during sludge treatment. Nitrate loss from the site on lower dosage rate plots was indistinguishable from background values in controls. During 1978 evidence of excessive nitrate levels was obtained only under white pine plots at maximum dosage rates (Figure 23).

Zinc

During the 1977 season some of the water samples obtained via suction lysimetry on the Pine River site indicated the presence of zinc in concentrations exceeding the 5 ppm USPHS standard under plots receiving the highest sludge dosage rate, 19.3 tonne/ha (Figure 24). Zinc levels were most elevated in water samples obtained under white pine plots. As with nitrate, zinc losses from the rooting zone were also computed (Table 21). Losses during 1977 amounted to 9.5 kg Zn/ha under white pine and 2.8 kg Zn/ha under red pine, or 30% and 9%, respectively, of the zinc applied with the sludge treatment. At lower dosage rates, no zinc increases were noted in the soil water samples.

Table 20. Soil water nitrate concentrations and nitrate escape from the rooting zone estimation for the Pine River site under red pine (r) and white pine (w)

			Concentration					Escape from rooting zone				
			Sludge treatment (tonne/ha)									
Year	Month	Recharge	19.3w	19.3r	9.7r	5.4r	0.0r	19.3w	19.3r	9.7r	5.4r	0.0r
		---mm---	------------ ppm ------------					------------ kg/ha ------------				
1976	June	0.0	--	--	--	--	--	0.0	0.0	0.0	0.0	0.0
	July	0.0	--	--	--	--	--	0.0	0.0	0.0	0.0	0.0
	August	0.0	--	--	--	--	--	0.0	0.0	0.0	0.0	0.0
	September	0.0	--	--	--	--	--	0.0	0.0	0.0	0.0	0.0
	October	0.0	--	--	--	--	--	0.0	0.0	0.0	0.0	0.0
	November	0.0	<0.1	<0.1	<0.1	<0.1	<0.1	0.0	0.0	0.0	0.0	0.0
	December	0.0	--	--	--	--	--	0.0	0.0	0.0	0.0	0.0
1977	January	0.0	--	--	--	--	--	0.0	0.0	0.0	0.0	0.0
	February	0.0	--	--	--	--	--	0.0	0.0	0.0	0.0	0.0
	March	224.4	6.6	23.6	--	--	1.1	14.8	53.0	--	--	2.5
	April	53.9	11.2	2.2	0.4	0.7	1.0	6.0	1.2	0.2	0.4	0.5
	May	0.0	9.9	19.2	0.5	0.8	1.0	0.0	0.0	0.0	0.0	0.0
	June	0.0	11.8	15.8	0.4	0.7	1.8	0.0	0.0	0.0	0.0	0.0
	July	0.0	13.8	12.2	0.2	0.6	2.8	0.0	0.0	0.0	0.0	0.0
	August	0.0	16.8	8.3	0.1	2.0	2.0	0.0	0.0	0.0	0.0	0.0
	September	49.2	17.4	12.4	0.1	0.6	1.2	8.6	6.1	0.1	0.3	0.6
	October	53.0	23.2	9.1	0.3	0.2	0.8	12.3	4.8	0.2	0.1	0.4
	November	100.7	11.5	8.6	--	--	--	11.6	8.7	--	--	--
	December	0.0	15.0	7.9	--	--	--	0.0	0.0	0.0	0.0	0.0
1978	January	0.0	9.9	0.6	--	--	--	0.0	0.0	0.0	0.0	0.0
	February	0.0	--	--	--	--	--	0.0	0.0	0.0	0.0	0.0
	March	0.0	--	--	--	--	--	0.0	0.0	0.0	0.0	0.0
	April	266.0	8.0	0.5	0.5	0.4	0.9	21.3	1.3	1.3	1.1	2.4
	May	5.0	--	--	--	--	--	--	--	--	--	--
	June	46.1	--	--	--	--	--	--	--	--	--	--
	July	0.0	--	--	--	--	--	0.0	0.0	0.0	0.0	0.0

Figure 24. Zinc concentrations in soil water on the Pine River study site.

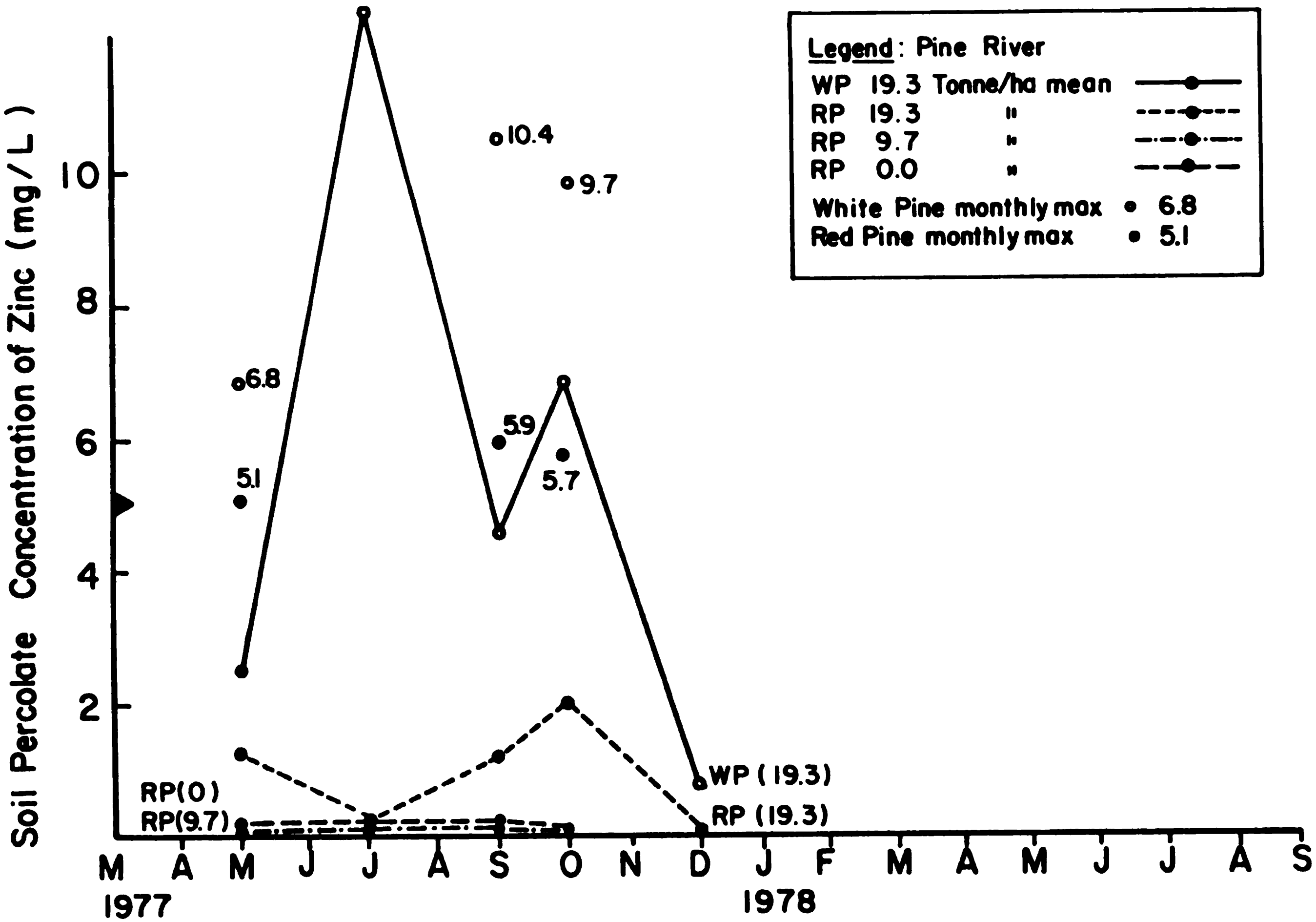

Legend: Pine River
WP 19.3 Tonne/ha mean
RP 19.3 "
RP 9.7 "
RP 0.0 "
White Pine monthly max • 6.8
Red Pine monthly max • 5.1
Soil Percolate Concentration of Zinc (mg/L)
10
8
6
4
2
6.8
5.1
10.4
9.7
5.9
5.7
WP (19.3)
RP (19.3)
RP(0)
RP(9.7)
M A M J J A S O N D J F M A M J J A S
1977
1978

Table 21. Soil water zinc concentrations and zinc escape from the rooting zone estimation for the Pine River site under red pine (r) and white pine (w)

			Concentration				Escape from rooting zone			
			Sludge treatment (tonne/ha)							
Year	Month	Recharge	19.3w	19.3r	5.4r	0.0r	19.3w	19.3r	5.4r	0.0r
		---mm---	------------ppm	-----------			-----------kg/ha-----------			
1977	May	0.0	2.3	1.2	0.1	0.2	0.0	0.0	0.0	0.0
	June	0.0	6.6	0.7	0.1	0.2	0.0	0.0	0.0	0.0
	July	0.0	11.8	0.3	0.1	0.2	0.0	0.0	0.0	0.0
	August	0.0	8.3	0.8	0.1	0.2	0.0	0.0	0.0	0.0
	September	49.2	4.5	1.2	0.1	0.2	2.2	0.6	0.1	0.1
	October	53.0	6.8	2.0	0.1	0.2	3.6	1.1	0.1	0.1
	November	100.7	3.7	1.1	0.1	0.1	3.7	1.1	0.1	0.1
	December	0.0	0.8	0.2	0.1	0.1	0.0	0.0	0.0	0.0

The disparity between zinc levels under red pine compared with those under white pine prompted a careful examination of the suction lysimeter water samplers. It was noted that in the white pine plots those yielding consistently elevated zinc concentrations were installed in the planting furrow where sludge ponded during application had concentrated. Further, slope of the microtopography surrounding these lysimeters was near zero percent resulting in the downward movement of zinc from pockets of excessive accumulation through sandy soil with high infiltration. The outcome of these circumstances was unrepresentative levels of Zn in soil water percolating near these lysimeters. The lower zinc levels in soil water measured from samplers placed between furrows, in all probability, yielded much more realistic data concerning zinc dynamics in the soil percolate beneath the Pine River pine plantation on the whole.

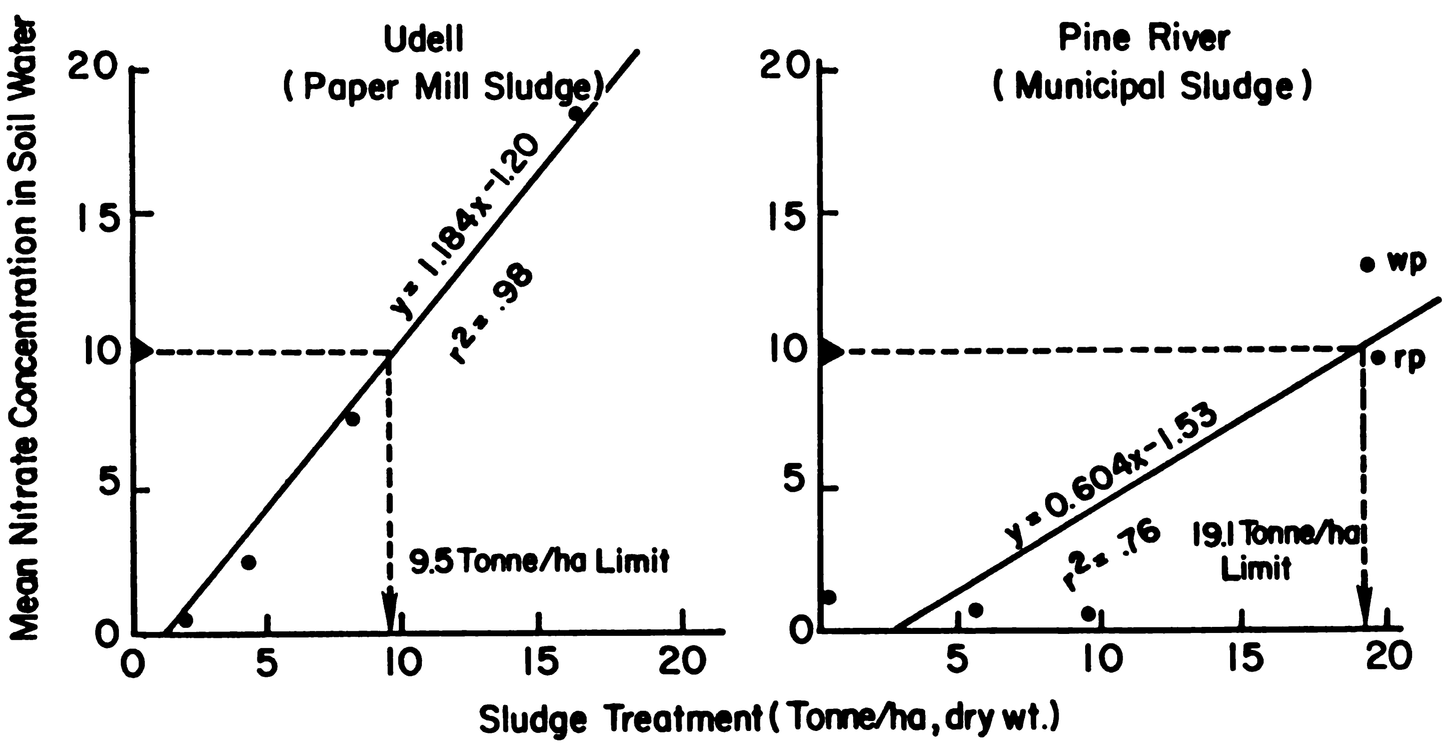
Sludge Dosage and Water Quality

A primary goal of this investigation was to determine the maximum sludge application rates usable on each site which would not endanger groundwater quality. To this end linear regression analysis was conducted, correlating soil water nitrate levels with sludge treatment rates (Figure 25).

On the Udell study site, analysis determined that sludge treatment rates should not exceed 9.5 tonne/ha in order to meet the 10 ppm NO_3-N health standard. Analysis of the Pine River site data indicated that maximum sludge dosages should not exceed 19.1 tonne/ha. The proportion of the variability in soil nitrate levels explained by

Figure 25. Estimation of the maximum sludge application rates allowable upon the Udell and Pine River sites which will also meet nitrate standards for groundwater.

Estimation of Safe Sludge Loading Rates Based on Nitrate Leaching



sludge treatment rates ranged from 0.76 on the Pine River site to 0.98 on the Udell site. The higher treatment maximum computed for the Pine River site may be attributed to its higher native fertility, providing greater soil nutrient retention. The higher water table under the Udell red pines diminished the treatment maximum on this site, as percolating soil water experienced a shorter residence time in the unsaturated zone.

The highest sludge dosage rates, 15.7 tonne/ha on the Udell site and 19.3 tonne/ha on the Pine River site, exceeded their respective computed application maximums, 9.5 and 19.1 tonne/ha. These rates and the 7.9 tonne/ha industrial sludge rate, were the only treatments to produce NO_3-N levels exceeding 10 ppm in soil water. At comparable N application rates, soil water NO_3-N was seen by Otchere-Boateng (1976) to exceed 10 ppm in coarse textured soil under pine. However, as Kreutzer and Weiger (1974) pointed out, soil water NO_3-N concentrations in excess of 10 ppm do not in every situation constitute a threat to the quality of groundwater, as dilution effects must be considered. In spite of the excessive soil water nitrate levels in the highest treatment rate plots on the Pine River site, no evidence of nitrate enrichment could be detected in groundwater flowing from this site. The absence of groundwater enrichment on this site was largely a function of the extremely small proportion of the watershed which was sludge treated and the uncertainty surrounding the actual direction of subsurface water flow from the study site.

The impact of other nutrients upon water quality was minimal on both study sites. As with the studies of Humphreys and Pritchett

(1971), little if any leaching of phosphorus occurred below the plots on either site. Regression analysis of zinc data from the Pine River plots indicated that only 28% of the variation in soil water Zn levels was explained by the sludge treatments and that a dosage rate of at least 31.8 tonne/ha, exceeding all rates employed, would be needed to produce soil water Zn concentrations exceeding the 5 ppm standard.

Understory Vegetation

The impact of sludge applied nutrients upon the vegetative component of pine ecosystems was investigated with regard to assessing nutritional benefits and detecting potentially hazardous elemental accumulations in understory and overstory plants. In the understory the total above-ground vegetation was harvested, chemically analyzed and compared with control plots and data published by Gerloff et al. (1964) for undisturbed understories of similar species composition. Because the understory maintains a high proportion of its total root biomass near the biologically active soil-litter interface, it was anticipated that understory nutrient concentrations would be diagnostic of initial vegetation nutrient assimilation trends. Representative understory types may be seen in Figures 26 through 29.

Nutrient Concentrations

Understory vegetation significantly benefited from nitrogen and phosphorus additions to both study areas (Table 22). While mean N concentrations in control plots ranged from 1.03% to 1.41%, N levels progressively increased in plots receiving increasing sludge dosages

Figure 26. Pteridium understory.

Figure 27. Vaccinium understory.

Figure 28. *Carex* understory.

Figure 29. Mixed understory including *Vaccinium*, *Pteridium*, *Gaultheria* and grasses.

Table 22. Understory nitrogen and phosphorus concentrations

Sludge treatment (tonne/ha)	TKN		Total P	
	1976	1977	1976	1977
	---------------------- % ----------------------			
Udell site				
15.7	2.35a*	2.28a	0.385a	0.219ab
7.9	2.34a	2.42a	0.190b	0.247a
4.0	1.63ab	1.94ab	0.154b	0.190abc
2.0	1.27ab	1.54bc	0.094b	0.142bc
0.0	1.03b	1.26c	0.082b	0.108c
Pine River site				
Red pine				
19.3	2.66a	2.96a	0.326a	0.374a
9.7	1.93ab	2.10b	0.276ab	0.272ab
5.4	1.81ab	1.74b	0.223b	0.266b
0.0	1.15b	1.21c	0.116c	0.130c
White pine				
19.3	2.41a	2.81a	0.338a	0.363a
9.7	2.12ab	2.17b	0.336a	0.294b
5.4	1.51b	1.71c	0.264a	0.242b
0.0	1.41b	1.36c	0.164b	0.167c

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

and exceeded 2% at the highest treatment rates. Control P levels did not exceed 0.167% while understories receiving the highest sludge dosages generally exceeded 0.3%. The significant increases in N and P were the result of understory plant roots exploiting the enriched litter and surface soil. Control levels of N, P and other macronutrients were comparable to those reported by Gerloff et al. (1964) for similar species assemblages. Other macronutrients examined, K, Ca, Mg, and Na, failed to produce consistently significant trends of uptake. These elements were generally present in low to moderate concentrations (Appendix, Tables 60-62).

Significant understory increases in cadmium were detected on the Pine River site in 1976 and again in 1977 (Table 23). Levels of Cd on treated plots ranged from 10.7 ppm to 22.7 ppm in 1976 while control plots registered less than 1 ppm. Although Cd levels declined in 1977, plots receiving the highest sludge dosages maintained significantly elevated Cd concentrations over controls. Noting the absence of increased soil Cd levels, the understory Cd increases were undoubtedly the result of direct exploitation of the enriched litter material by understory plant roots and/or plant surface absorption.

Allaway (1977) has indicated that Cd concentrates in foliage rather than in seeds and fruits. Baker et al. (1977) recommended maintaining foliar Cd levels below 1.0 ppm to avoid potential food chain buildup problems in the ecosystem. The understory Cd levels reported for the sludge treated plots on the Pine River site were values for all above-ground plant parts (stem + leaves + fruit and

Table 23. Understory cadmium and copper concentrations

Sludge treatment (tonne/ha)	Cd 1976	Cd 1977	Cu 1976	Cu 1977
	ppm			
Udell site				
15.7	1.0a*	0.6a	15.3a	5.8a
7.9	0.7b	0.5ab	13.2ab	5.7a
4.0	0.5bc	0.4abc	10.2b	5.1a
2.0	0.5bc	0.3bc	10.6b	5.0a
0.0	0.4c	0.2c	9.9b	4.5a
Pine River site				
Red pine				
19.3	13.8a	2.0a	37.7a	8.3a
9.7	16.4a	1.4ab	38.8a	6.2b
5.4	10.7ab	2.6a	26.4ab	7.2ab
0.0	0.7b	0.3b	10.3b	3.5c
White pine				
19.3	22.1a	2.8a	50.1a	9.5a
9.7	22.7a	1.0b	51.1a	5.2b
5.4	16.3ab	1.1ab	44.1a	6.0b
0.0	0.9b	0.6b	16.1a	4.8b

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

seeds) combined and as such represent a dilution of the higher foliar concentrations which would be most subject to wildlife grazing. Cadmium levels reported in understory plants on this site did constitute a potential food chain transfer hazard during the 1976 and 1977 growing seasons. Cadmium levels on the Udell site indicated no hazardous accumulation in the understory plants. Plant toxicity symptoms arising from cadmium accumulation were not apparent on either study site.

Understory copper levels in sludge treated plots on the Pine River site significantly exceed those in controls by 1977. In 1976 these levels were in excess of those reported by Gerloff et al (1964) and exceeded the 20 ppm toxic limit reported by Jones (1973). No copper toxicity symptoms were noted in the understory plants examined, however. Gagnon et al. (1958) concluded that differential accumulation of nutrients by different understory species was dependent upon inherent species properties and Waring and Youngberg (1972) noted that the nutritional needs of agronomic crops varied greatly from those of forest plants. The nutrient toxicity (and deficiency) limits established for domesticated plants which have been genetically modified through many generations lose their applicability among the wild plants in a forest setting. The Cu levels in understory plants on the Pine River site, although quite high by agronomic standards, appeared to be within the range acceptable to wild genotypes in this study area. Copper levels in understory plants on the Udell site were comparable to those reported by Gerloff et al. (1964).

Other micronutrients (Fe, Mn, Zn, and B) and heavy metals (Pb, Cr and Ni) remained variable in their uptake trends. Understory Fe was elevated on both sites as a result of treatment. Although foliar Mn commonly approached or exceeded 1,000 ppm on both sites, no definitive trends for its assimilation could be deduced. Increases in Zn, Pb, Cr and Ni concentrations were generally significant in 1976 and diminished by 1977 (Appendix, Tables 60-62).

Plant Growth

In the first year following treatment significant trends of increased understory biomass production resulting from sludge dosages were nonexistent (Table 24). By 1977, however, understory production increased on all plots, a result of overstory thinning in 1976 presumably, and the highest sludge treatment plots under the red pine produced biomasses significantly greater than their controls on both study sites. A nonsignificant trend in biomass increase with treatment increase was partially established in the understory under white pine. Regression analysis correlating understory biomass in 1977 with sludge dosage in 1976 accounted for 78% of the variability under the Pine River red pine and only 33% of the variability under the Udell red pine. Absence of a significant trend in the understory beneath white pine was thought to be a function of the greater native fertility of the soil there, noting the high biomass production in the control plots in 1977.

Table 24. Understory above-ground biomass

Sludge treatment (tonne/ha)	Biomass (g/m^2)	
	1976	1977
<u>Udell site</u>		
15.7	11.0b*	54.6a
7.9	11.4ab	28.6c
4.0	17.2ab	40.0ab
2.0	27.4a	40.9bc
0.0	24.8ab	28.5c
<u>Pine River site</u>		
Red pine		
19.3	16.9a	50.4a
9.7	12.8a	46.8ab
5.4	6.3a	22.4b
0.0	21.5a	21.7b
White pine		
19.3	9.7a	45.4a
9.7	11.3a	46.6a
5.4	16.9a	41.6a
0.0	14.9a	35.9a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

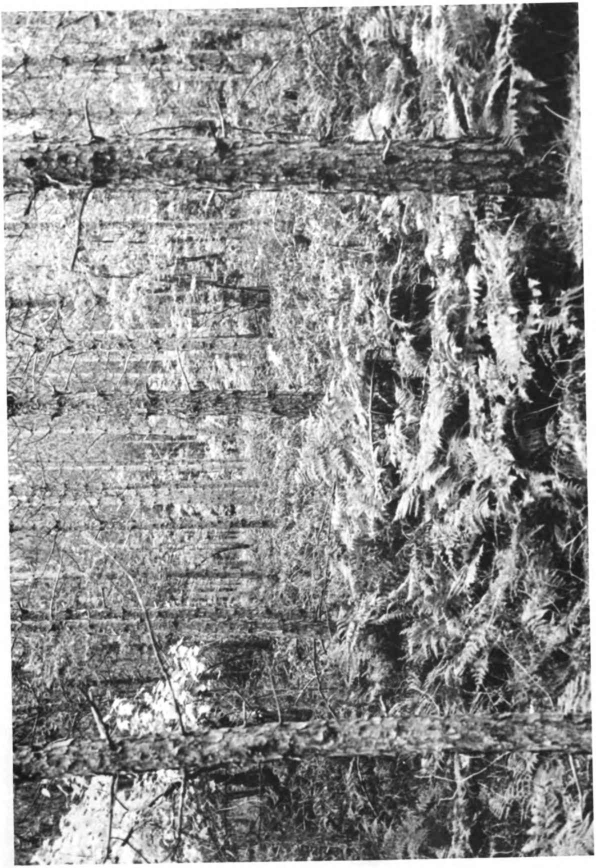
McConnel and Smith (1970) found that understory production increased from 8.4 g/m^2 to $46.8g/m^2$ under ponderosa pine in eastern Washington following stand thinning. Agee and Biswell (1970) reported that understory production increased from 2.0 g/m^2 to 25.5 g/m^2 under thinned and fertilized ponderosa pine in northern California. The low r^2 value determined for biomass production under the Udell red pine may have been a result of stand thinning effects upon the understory (Cochran 1975). Sludge treatment appeared to stimulate understory productivity, allowing the ground vegetation on both sites to out-produce the 37.8 g/m^2 found under sugar maple-basswood and birch forests on dry sites in northern Wisconsin (Zavitkovski 1972).

Visual inspection of the plots receiving the highest sludge treatment rates revealed the lush green growth of bracken fern in these plots during the late growing season when vegetation in the surrounding area had already begun to discolor and approach dormancy (Figure 30). This response was similar to that produced when luxury consumption of abundant nitrogen in the environment prolongs succulent growth.

Overstory Trees

Foliage samples were collected from codominant red pine and white pine trees to determine whether sludge treatments influenced foliar nutrient status and growth in the overstory. As nutrient content of the various tree parts (leaves, bark, branches, stem and roots) has been seen to be quite variable, current year's foliage produced in the upper tree crown was sampled in late August as being

Figure 30. Lush late season growth of bracken fern on plot receiving highest sludge treatment rate.



most indicative of the nutrient economy of recently matured, metabolically active overstory tissues (van den Driessche 1974). Although tree stems contain greater total nutrient amounts, tree leaves remain the most sensitive indicators of mineral nutrient change.

Nutrient Status

Pines growing on plots treated with sludge experienced significant foliar N concentration elevation over those found on controls (Table 25). By 1977 foliar N levels from plots receiving the highest sludge dosages ranged from 1.59% to 2.03%, while those from controls ranged from 1.09% to 1.30%. On the Udell site an increase of 62% in foliar N was observed and on the Pine River site increases of 46% for red pine and 29% for white pine foliar N were seen during 1977.

Foliar P levels were not significantly increased by the sludge nutrient applications on either site. However, by 1977 increases in the N to P ratio had occurred among the trees receiving the highest treatment rates.

Mallonee (1975) reported foliar N increases in pines as the result of comparable N additions to the forest environment. Wollum and Davey (1975) point out that although the greatest N needs in pines occur prior to age 30, N additions are of benefit to older pines, such as were present on these study sites. The pines on the control plots of both sites fell into the lower portion of the tolerable N:P for pines, 5:1 to 16:1. Additions of N to sludge treated plots improved this ratio, allowing it to approach to optimum for pines of 10:1 (van den Driessche 1974).

Table 25. Overstory needle nitrogen and phosphorus concentrations and ratios

Sludge treatment (tonne/ha)	TKN		P		N:P	
	1976	1977	1976	1977	1976	1977
	---------------------- % ----------------------					
Udell site						
15.7	1.24a*	2.03a	0.168a	0.184a	7.4	11.0
7.9	1.17ab	1.57b	0.166a	0.170a	7.0	9.2
4.0	1.13b	1.39c	0.168a	0.171a	6.7	8.1
2.0	1.09b	1.29c	0.164a	0.176a	6.6	7.3
0.0	1.09b	1.25c	0.165a	0.171a	6.6	7.3
Pine River site						
Red pine						
19.3	1.28a	1.59a	0.157b	0.155a	8.2	10.3
9.7	1.17b	1.36b	0.151b	0.179a	7.7	7.6
5.4	1.14bc	1.17bc	0.176a	0.169a	6.5	6.9
0.0	1.10c	1.09c	0.158b	0.174a	7.0	6.3
White pine						
19.3	1.36a	1.68a	0.168a	0.165b	8.1	10.2
9.7	1.24b	1.47b	0.171a	0.183a	7.3	8.0
5.4	1.16bc	1.36bc	0.167a	0.177ab	6.9	7.7
0.0	1.09c	1.30c	0.164a	0.183a	6.6	7.1

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

The assimilation of elements by different plant species is a function of their inherent morphological and physiological properties. In considering the differential nutrient content of red pine and white pine foliage, it is not only prudent to consider differences in the native fertility of the soil in which each was growing, but also the way in which each species selectively exploits that soil. Garin (1942) reported that white pine fine roots, which are feeder roots, were found primarily in the A soil horizon with far fewer occurring in the B horizon. Red pine, on the other hand, had, in general, fewer total fine roots and concentrated them in the A and B1 horizons.

Nitrogen was readily assimilated from the soil under both tree species. No significant trend of increased P uptake developed for either pine or either site. However, a different pattern of K assimilation developed for the red pine growing on the Udell site as compared to that on the Pine River site.

Foliar K was significantly increased with sludge treatment in the red pine growing on the Udell site in 1976 and 1977 (Table 26), as were litter K and soil K. On the Pine River site foliar K levels did not increase with treatment, as was the case with soil K levels. However, under the red pine on the Pine River site litter K levels were significantly elevated by 1977, indicating that K assimilation by the pines was occurring via the soil and that the feeder roots had failed to directly tap the nutrient reservoir in the forest litter.

Table 26. Overstory needle potassium concentrations

Sludge treatment (tonne/ha)	K 1976	K 1977
	----------- % -----------	
Udell site		
15.7	0.707a*	0.924a
7.9	0.691a	0.848b
4.0	0.685a	0.817b
2.0	0.652ab	0.731c
0.0	0.620b	0.771c
Pine River site		
Red pine		
19.3	0.697a	0.698a
9.7	0.698a	0.671a
5.4	0.697a	0.728a
0.0	0.699a	0.733a
White pine		
19.3	0.728a	0.725a
9.7	0.751a	0.772a
5.4	0.740a	0.769a
0.0	0.714a	0.764a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Neary (1974), in a municipal wastewater irrigation study, noted needle necrosis, a symptom of boron toxicity, with foliar B levels exceeding 75 ppm in red pine. As Stone and Baird (1956) indicated, B toxicity in pine foliage is likely to occur in pines when B concentrations exceed 45 ppm. No significant increases in foliar B were noted in the overstory foliage sampled (Table 27). All levels of B were well below those reported to be toxic. Considering the low amounts added with land treatment, 0.03 to 0.68 kg/ha, B was not seen as a major hazard in sludges. Minroe (1975) found that forest plants of the genus *Vaccinium* are less tolerant to B additions than pines. Should B eventually become troublesome, species of this genus could be used as indicators of potentially toxic conditions before pine trees could be endangered.

Other analyzed elements (Ca, Mg, Al, Na, Fe, Mn, Zn, Cu, Pb, Cr, Cd and Ni) failed to exhibit consistent trends of significant increase with increasing sludge applications (Appendix, Tables 63-65). Foliar nutrient concentrations were generally found to be low to moderate when compared to levels reported by Gerloff et al. (1964) and Young and Carpenter (1967). Foliar Fe was identified as possibly deficient in red pine on both sites, as levels below the 40 ppm critical value determined for pines by Ingestad (1960) were consistently obtained from analysis.

Table 27. Overstory needle boron concentrations

Sludge treatment (tonne/ha)	B 1976	B 1977
	ppm	
Udell site		
15.7	17.5a*	16.0a
7.9	20.5a	15.4a
4.0	19.2a	17.5a
2.0	17.4a	17.0a
0.0	17.6a	17.6a
Pine River site		
Red pine		
19.3	17.7a	15.4b
9.7	17.4a	16.1ab
5.4	17.9a	15.9ab
0.0	18.7a	18.5a
White pine		
19.3	20.5a	16.4b
9.7	21.3a	18.0ab
5.4	21.7a	17.3b
0.0	20.5a	20.3a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Growth Responses

The initial overstory growth responses which could be related to sludge treatment appeared as increases in fasicle dry weight and needle length (Table 28). Fasicle weight was significantly increased on treated red pine plots on both study sites by 1977; however, the weights for treated white pine fasicles were not significantly greater than those in controls. The dry weight increases represented a 47% increase over controls (r^2 = .71) in the Udell site red pine and a 50% increase over controls (r^2 = .997) in the Pine River site red pine, each at their respective highest sludge dosage. Needle length for red pine growing on the Udell site exhibited a significant increase, amounting to as much as a 30% increase over controls (Figure 31), with increasing sludge treatement rates (r^2 = .86). The trends of needle length increase of red pine and white pine on the Pine River site were not significant, however (Figures 32 and 33). Apparently, the greater variability among trees sampled on the Pine River site contributed to the lack of significance in these trends. Needles obtained from treated plots, upon visual inspection, appeared to have a darker green color than those from control plots.

In Table 29 data concerning annual radial increment at breast height and biennial radial growth at the base of the live crown are presented. Significant increases in annual radial growth with treatment were seen in white pine in 1976 and 1977. These growth increases represented 39% in 1976 (r^2 = .99) and 47% in 1977 (r^2 = .94) at the highest treatment rates over those in controls. Radial growth trends failed to develop with treatment for red pine on either site.

Table 28. Overstory fasicle dry weight and needle length, 1977

Sludge treatment (tonne/ha)	Fasicle dry weight (g)	Needle length (mm)
Udell site		
15.7	0.072a*	122.1a
7.9	0.066a	113.7ab
4.0	0.067a	110.3b
2.0	0.051b	96.4c
0.0	0.049b	93.6c
Pine River site		
Red pine		
19.3	0.066a	109.7a
9.7	0.054ab	95.9a
5.4	0.050ab	93.6a
0.0	0.044b	86.9a
White pine		
19.3	0.032a	67.5a
9.7	0.029ab	64.9a
5.4	0.025b	65.0a
0.0	0.028ab	59.7a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Figure 31. Average red pine needle length on the Udell site.

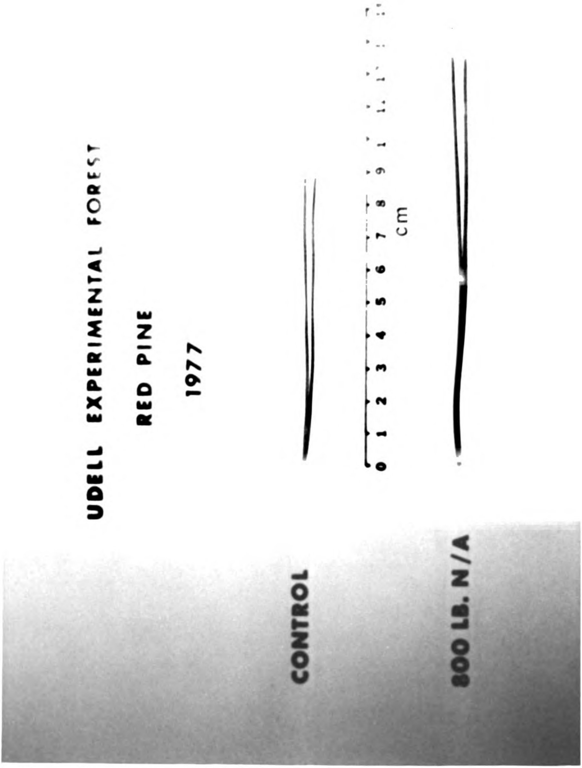
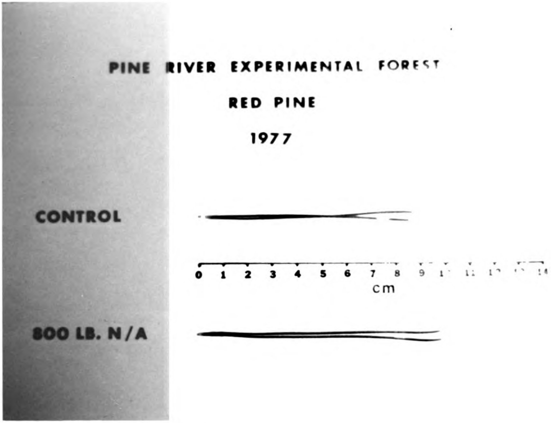

UDELL EXPERIMENTAL FOREST
RED PINE
1977
CONTROL
0 1 2 3 4 5 6 7 8 9 1
cm
800 LB. N/A

Figure 32. Average red pine needle length on the Pine River site.

Figure 33. Average white pine needle length on the Pine River site.


PINE RIVER EXPERIMENTAL FOREST
RED PINE
1977
CONTROL
0 1 2 3 4 5 6 7 8
cm
800 LB. N/A

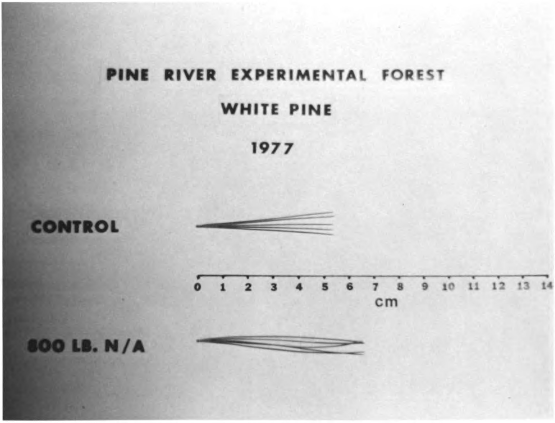

PINE RIVER EXPERIMENTAL FOREST
WHITE PINE
1977
CONTROL
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
cm
800 LB. N/A

Table 29. Radial growth in overstory pines

Sludge treatment (tonne/ha)	Annual radial increment		Radial growth at base of live crown	
	1976	1977	1974 + 1975	1976 + 1977
	mm			
Udell site				
15.7	1.8a*	1.5a	6.4c	6.0b
7.9	1.9a	1.6a	6.7abc	6.3ab
4.0	1.7a	1.6a	7.1a	6.9a
2.0	1.7a	1.5a	6.5bc	6.4ab
0.0	1.7a	1.6a	7.0a	6.5ab
Pine River site				
Red pine				
19.3	1.7a	1.7a	6.9a	6.9a
9.7	2.4a	2.0a	6.5a	4.7a
5.4	2.0a	1.8a	7.9a	7.1a
0.0	2.0a	1.8a	6.7a	6.2a
White pine				
19.3	2.5a	2.2a	6.8b	4.9b
9.7	2.2ab	2.0ab	8.8ab	5.8ab
5.4	2.0ab	1.8ab	9.0a	6.7a
0.0	1.8b	1.5b	8.2ab	6.9a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Increases in radial growth at the base of the live crown failed to develop with treatment for either species on either site. A significant decrease of 29% was observed in the radial growth at the base of the live crown of white pine receiving 19.3 tonne of sludge per hectare (r^2 = .96). All other silvicultural growth parameters examined failed to produce significant trends of increase with sludge treatment (Appendix, Tables 66 and 67).

These results were similar to those of Miller and Miller (1976) and Tolle (1976) who found increases in foliar biomass, needle length and stem radial growth in pines subject to nutrient additions, particularly nitrogen. Mader and Howarth (1970) have demonstrated that growth in red pine in Massachusetts was significantly related to foliar nutrient levels and Miller and Cooper (1973) have determined that volume growth was maximized when foliar nitrogen exceeded 2%. The across-the-board improvement of nitrogen nutrition with sludge treatment and increasing trends in fasicle dry weight and needle length were indicative of slow buildup in overstory photosynthetic capacity. Other growth parameters, i.e., radial increment and height, have generally not yet responded to treatment, because as Leaf et al. (1970) pointed out, a lapse time of 2 to 5 years from the date of treatment is needed to remedy nutrient deficiencies and build up an increased photosynthetic mechanism capability thereby permitting the trees to demonstrate a growth response to nutrient additions in their environment. This lag time is of particular importance in trees which experience predeterminant growth patterns, as do pines. Subsequent growing seasons on these study plots should find increasing growth responses to treatment among the overstory trees.

Comparison of Site Dynamics

The major intent of this study has been to evaluate the suitability of thinned, pole-sized red pine and white pine plantations growing in coarse textured soils for sewage sludge landspreading. Up to this point sludge properties, litter, soil chemistry, water quality and understory and overstory vegetation growth and nutrition have been considered on a largely individual basis. Figures 34 and 35 summarize the major individual changes and provide an integrated perspective of growth and nutrient dynamics for each site.

Sludge treatment resulted in nutrient enrichment of forest litter and the upper soil layers on both sites. Nitrogen, as NH_4-N and NO_3-N, exhibited considerable increases in its movement from litter to soil, understory and overstory, including significant losses as NO_3-N below the rooting zone at the highest treatment rates. The Udell site, with its shallower water table, appeared to be a less desirable site for sludge disposal, in that percolating soil water, rich in NO_3, underwent a shorter retention period in the unsaturated soil zone allowing less opportunity for nutrient reduction prior to entering the groundwater aquifer.

Increased transfer of P and K from litter to the surface soil layers occurred only on the Udell site to any significant degree. On this site N and P assimilation by the understory from the litter and soil was significantly elevated, while increased N and K uptake by the

Figure 34. Udell site dynamics following industrial sludge application.

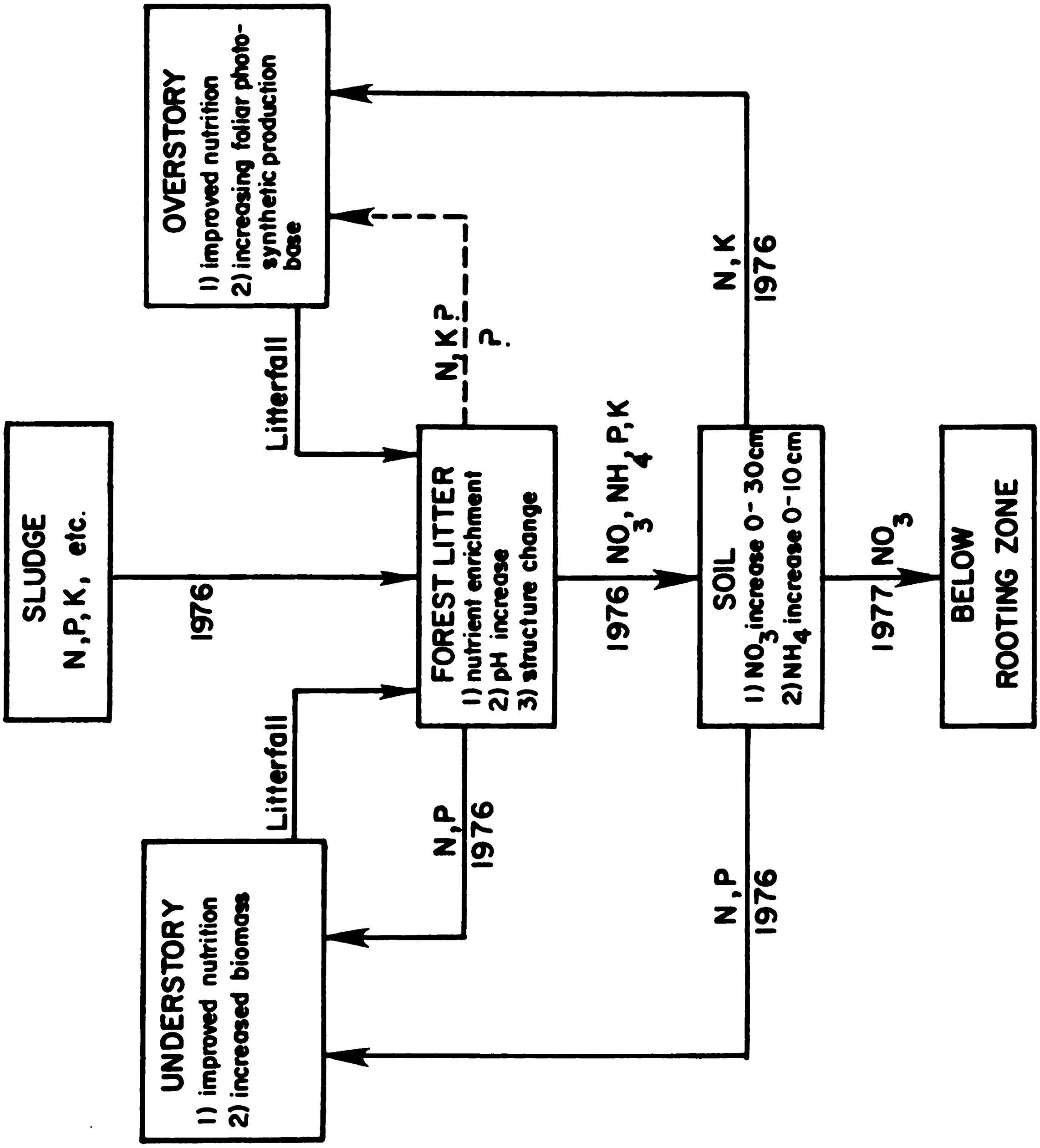
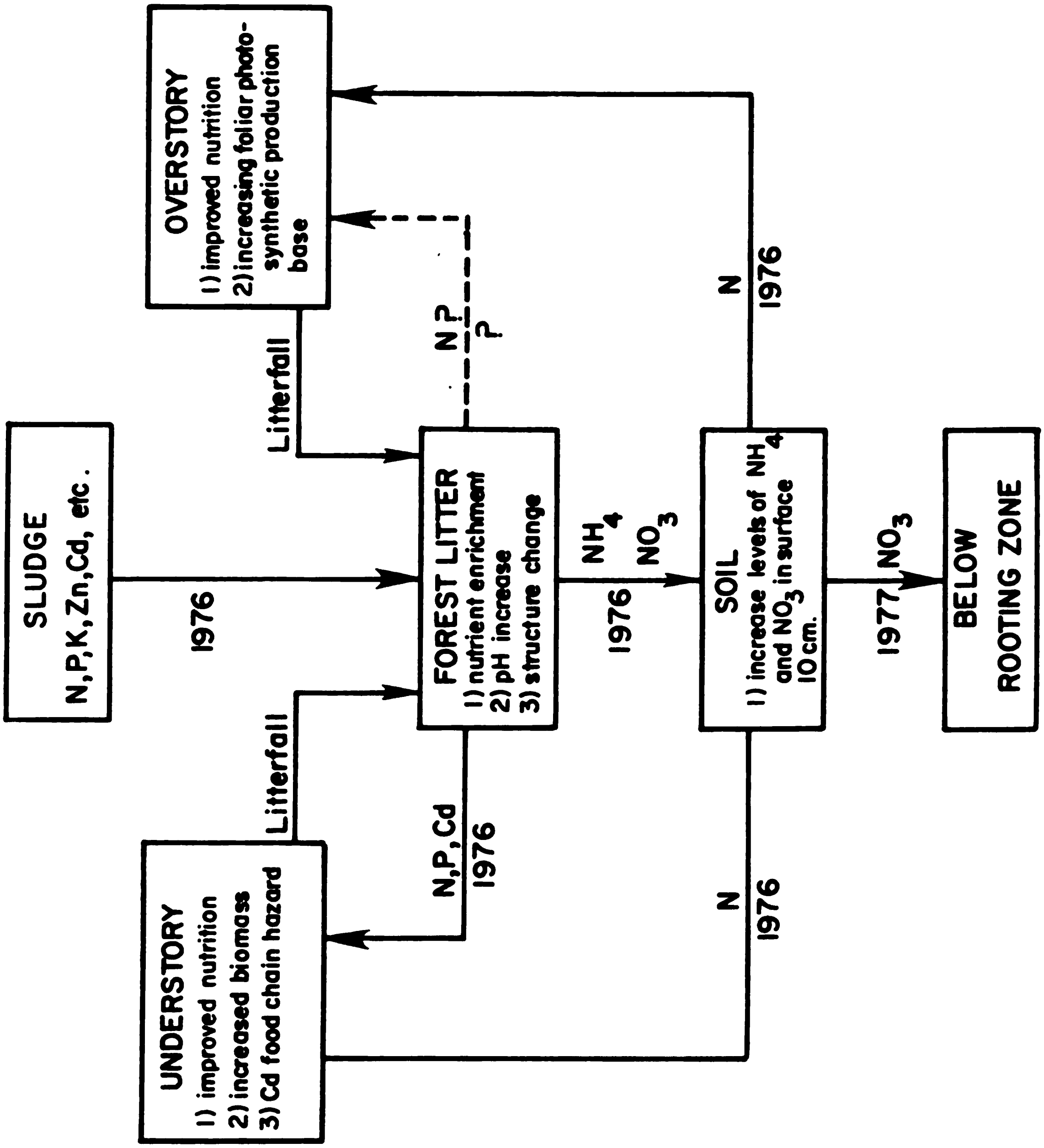

SLUDGE
N,P,K, etc.
1976
OVERSTORY
1) improved nutrition
2) increasing foliar photo-synthetic production base
Litterfall
N,K,P
P.
FOREST LITTER
1) nutrient enrichment
2) pH increase
3) structure change
Litterfall
N,P
1976
UNDERSTORY
1) improved nutrition
2) increased biomass
1976 NO3, NH4, P,K
N,K
1976
SOIL
1) NO3 increase 0-30cm
2) NH4 increase 0-10cm
N,P
1976
1977 NO3
BELOW
ROOTING ZONE

Figure 35. Pine River site dynamics following municipal sludge application.


SLUDGE
N,P,K,Zn,Cd, etc.
1976
OVERSTORY
1) improved nutrition
2) increasing foliar photo-synthetic production base
Litterfall
N,P
P
N
1976
FOREST LITTER
1) nutrient enrichment
2) pH increase
3) structure change
NH4
NO3
1976
SOIL
1) increase levels of NH4 and NO3 in surface 10 cm.
NO3
1977
BELOW
ROOTING ZONE
UNDERSTORY
1) improved nutrition
2) increased biomass
3) Cd food chain hazard
Litterfall
N,P,Cd
1976
N
1976

overstory from the soil was demonstrated. On the Pine River site increased amounts of N were assimilated by the overstory from the soil, while those assimilated by the understory appeared to originate from the soil and litter. The understory here also obtained significantly increased amounts of P and Cd from the forest litter. It was questionable whether overstory roots on either site had responded in any significant way to nutrient additions in the forest litter, as the pines demonstrated the ability to significantly elevate their uptake of nutrients increased only in the soil.

The overall response of the vegetation components on each site was similar. The nutrients applied with sludge treatment, particularly nitrogen, improved the nutritional status of the species, precipitating an increase in foliar tissue growth, thereby expanding the photosynthetic production base. Although volume growth increases in the overstories were not well expressed, biomass increases resulting from treatment in the understories were in good evidence. The cadmium levels discovered in the understory vegetation on the Pine River site, however, represented a possible food chain transfer hazard to wildlife and presented another limitation to municipal sludge disposal in forests, in addition to that already posed by NO_3-N losses below the rooting zone.

Thinned, pole-sized red pine and white pine plantations appear to be capable of accommodating sewage sludges and usefully incorporating the supplementary nutrients into ecosystem components. The nitrogen application rates, however, should be adjusted so as not to exceed 448 kg N/ha, to minimize the possibility of enriching the underlying groundwater with NO_3-N produced during nitrification. Furthermore, Youngberg (1975) and Wells et al. (1976) reported that maximum growth benefit to pines is derived from N application rates near 448 kg/ha. The litter layer was paramount in effecting capture of the applied nutrients and the soil, with the exception of NO_3-N at the highest treatment levels, served as an effective filter for percolate nutrient solutions. The most outstanding, unresolved problem identified by this study was the food chain hazard presented by excessive Cd in the understory plants growing on the Pine River site. Future research should determine the actual severity of this hazard and offer possible abatement alternatives.

CHAPTER VI

SUMMARY AND RECOMMENDATIONS

Summary

Industrial sewage sludge from a paper mill was applied via an all-terrain tanker to a previously thinned 40-year-old red pine plantation located on the Udell Experimental Forest during June of 1976 at rates of 2.0, 4.0, 7.9 and 15.7 tonne per hectare. Municipal sewage sludge from the city of Cadillac, Michigan was applied using portable pipelines and a fire hose sprayer to a previously thinned 36-year-old red pine and white pine plantation located on the Pine River Experimental Forest during July of 1976 at rates of 5.4, 9.7 and 19.3 tonne per hectare. These sludge application rates were equivalent to total nitrogen rates of 140, 278, 549 and 1,091 kg/ha and 323, 578 and 1,156 kg/ha, respectively. The municipal sludge was a high cadmium sludge with a Zn:Cd ratio of 3.7:1.

Upon drying the sludge became a part of the forest litter layer, significantly increasing the nutrient levels found in this ecosystem component on both study sites. Litter cadmium levels as high as 136 ppm were measured on the Pine River site. Within the forest litter, pH and specific conductivity significantly increased with treatment and C to N ratios were narrowed to as low as 24.2:1. The addition of nitrogen to the litter precipitated a structural change wherein a second and third zone of fermentation could be discerned along the margins of the sludge layer in the litter profile. As of 1977, however, no appreciable increase was observed in the rate of litter decomposition on either site.

Increases in nutrient transfer from the litter layer to the underlying soil occurred only to a limited degree. On both sites the 0-5 cm soil layer experienced significant increases in NH_4-N and NO_3-N but not total N, indicating that the largest N fraction, organic-N, was mostly retained in the litter layer above. Total P increased in the Rubicon and Croswell sands of the Udell site but not in the Grayling and Menominee sands of the Pine River site. On both sites soil specific conductivity temporarily increased; however, no significant soil pH, C to N ratio or other nutrient or physical changes in the 0-5 cm layer were observed. Soil cadmium level increase trends were generally poorly developed with a range of values from 0.1 to 0.4 ppm, indicating little Cd movement from the litter into the surface soil.

The soil below the 5 cm depth experienced minimal influence from sludge treatment. On the Udell site NO_3-N increases were seen down to 30 cm while the Pine River soils exhibited NO_3-N increases only down to 10 cm. On both sites NH_4-N increased down to the 10 cm soil depth. No other evidence of chemical or physical change was found in the lower soil depths.

The quality of water moving from the treated plots was monitored using wells inserted into the surface of the water table aquifer and porous cup soil water samplers. During 1976 all measured elements remained below 0.1 ppm. With snowmelt early in the 1977 season, however, elevated nitrate levels appeared in the water under both sites. Although NO_3-N levels in soil water under the highest sludge treatment plots exceeded the 10 ppm USPHS standard throughout much of the year, significant losses from the rooting zone occurred only during months of groundwater recharge in spring and fall. Maximum allowable sludge dosage rates which would meet the 10 ppm NO_3-N standard were computed to be 19.1 tonne per hectare for the Pine River site and 9.5 tonne per hectare for the Udell site. These limits indicated the inherent superiority of the Pine River site as a sludge disposal area, with its deeper water table, over the Udell site, with its shallower water table and hence shorter percolate retention time in the unsaturated zone.

Understory plants on the Udell site significantly improved their nutritional status and growth by increasing their N and P assimilation from the enriched soil and litter layers. Increases as great as 128% in total N, 370% in total P and 92% in total above ground biomass production resulting from treatment were measured on this site.

Understory plants on the Pine River site also improved their nutritional status and growth with treatment. Significantly increased levels of N, from soil and litter, and P and Cd, from litter, were assimilated. Increases as high as 144% in total N, 188% in total P and 132% in total above-ground biomass were seen here. However, understory cadmium concentrations, as great as 22.7 ppm, exceeded the desired 1.0 ppm foliar recommendation for avoiding food chain buildup problems in the ecosystem.

The red pine growing on the Udell site benefited nutritionally from the N and K supplied in the sludge treatment while the red pine and white pine growing on the Pine River site underwent an improvement in their N status. On both sites there was little evidence that the roots of the overstory had begun to exploit the enriched forest litter nutrient reservoir to any significant degree. Growth benefits to the trees were primarily expressed in terms of increased needle length and dry weight. Both stands appeared, at this point, to be expanding their photosynthetic production base as a prelude to future volume growth responses.

Recommendations

Data compiled in the course of this study have indicated that thinned, pole-sized red pine and white pine plantations growing in coarse textured soils derived from glacial outwash are capable of usefully incorporating into their various ecosystem components the nutrients delivered to them by sewage sludge landspreading. Within the limits imposed by these terrestrial ecosystems groundwater quality can be ensured and vegetation growth and nutrition can be improved in conjunction with sludge disposal. The following recommendations are offered as guidelines for meeting the environmental limitations inherent in these conifer systems.

1. To ensure that soil percolate and groundwater nitrate levels meet the 10 ppm USPHS standard, sludge application rates should not exceed 9.5 tonnes per hectare on sites with high water tables, i.e., within 3 m of the surface as on the Udell site, and 19.1 tonnes per hectare on sites with deep water tables, i.e., greater than 25 m from the surface as on the Pine River site. These limits correspond to 660 kg N/ha and 1,144 kg N/ha, respectively.
2. To optimally benefit overstory growth in these conifer ecosystems, sludge dosages should be adjusted so that approximately 448 kg N/ha is applied to either type of setting.
3. Diminishing the food chain transfer hazard posed by excessive cadmium accumulation in understory plants should be achieved by lowering sludge Cd levels prior to landspreading, as even the lowest sludge application rate employed produced understories with Cd exceeding 1 ppm. Using wildlife populations as a means of terrestrial dispersal for this element would be a practice accompanied by some risk.

Sewage sludge landspreading in northern coniferous forests should not be conducted with the notion of disposing the maximum sludge volume upon the smallest possible land area. Rather, sludge recycling is best conducted from the perspective of insuring long-term ecosystem integrity, by maintaining a groundwater recharge of high quality and vigorous production of vegetation while minimizing the opportunity for toxic element accumulation in the environment.

APPENDIX

APPENDIX

Table 30. Udell site species list of vascular plants

Common name	Scientific name	Family
Red pine	Pinus resinosa, Ait.	Pinaceae
Jack pine	Pinus banksiana, Lamb.	Pinaceae
White oak	Quercus alba, L.	Fagaceae
Black oak	Quercus velutina, Lamb.	Fagaceae
Cherry	Prunus spp., L.	Rosaceae
Hawthorne	Crataegus spp., L.	Rosaceae
Red maple	Acer rubrum, L.	Aceraceae
Serviceberry	Amelanchier spp., Med.	Rosaceae
Brambles	Rubus spp., L.	Rosaceae
Gooseberries, currants	Ribes spp., L.	Saxifragaceae
Sweet fern	Comptonia peregrina, (L.) Coult.	Myricaceae
Mapleleaf viburnum	Viburnum acerifolium, L.	Caprifoliaceae
Blueberry	Vaccinium spp., L.	Ericaceae
Bracken fern	Pteridium aquilinum, (L.) Kuhn.	Polypodiaceae
Dogbane	Apocynum androsaemifolium, L.	Apocynaceae
False Solomon's seal	Smilacina stellata, (L.) Desf.	Liliaceae
Wintergreen	Gaultheria procumbens, L.	Ericaceae
Goldenrod	Solidago spp., L.	Compositae
Red sorrel	Rumex Acetosella, L.	Polygonaceae
Wild lily of the valley	Maianthemum canadense, Desf.	Liliaceae
Cow wheat	Melampyrum lineare, Desr.	Scrophulariaceae
Schizachne	Schizachne purpurascens (Torr.) Swallen	Gramineae
Poverty oat grass	Danthonia spicata, (L.) Beauv.	Gramineae
Big bluestem	Andropogon Gerardi, Vitm.	Gramineae
Panic grass	Panicum depauperatum, Muhl.	Gramineae
Sedge	Carex spp., L.	Cyperaceae

Table 31. Pine River site species list of vascular plants ("a" occurs in red pine plots; "b" occurs in white pine plots)

Common name		Scientific name	Family
Eastern white pine	b	Pinus strobus, L.	Pinaceae
Red pine	a	Pinus resinosa, Ait.	Pinaceae
Quaking aspen	ab	Populus tremuloides, Michx.	Salicaceae
Bigtooth aspen	b	Populus grandidentata, Michx.	Salicaceae
White oak	ab	Quercus alba, L.	Fagaceae
Northern red oak	ab	Quercus rubra, L.	Fagaceae
Black oak	ab	Quercus velutina, Lamb	Fagaceae
Sassafras	b	Sassafras albidum, (Nutt.) Nées.	Lauraceae
Cherry	ab	Prunus spp., L.	Rosaceae
Red maple	ab	Acer rubrum, L.	Aceraceae
Mountain maple	b	Acer spicatum, Lam.	Aceraceae
White ash	b	Fraxinus americana, L.	Oleaceae
Sweet fern	ab	Comptonia peregrina, (L.) Coult.	Myricaceae
Speckled alder	b	Alnus rugosa (Du Roi) Spreng.	Betulaceae
Gooseberries, currants	a	Ribes spp., L.	Saxifragaceae
Brambles	ab	Rubus spp., L.	Rosaceae
Serviceberry	ab	Amelanchier spp., Med.	Rosaceae
Blueberry	ab	Vaccinium spp., L.	Ericaceae
Mapleleaf viburnum	ab	Viburnum acerifolium, L.	Caprifoliaceae
Bracken fern	ab	Pteridium aquilinum, (L.) Kuhn	Polypodiaceae
Schizachne	ab	Schizachne purpurascens, (Torr.) Swallen	Gramineae
Poverty oat grass	ab	Danthonia spicata, (L.) Beauv.	Gramineae
Panic grass	ab	Panicum depauperatum, Muhl.	Gramineae
Big bluestem	b	Andropogon Gerardi, Vitm.	Gramineae
Sedge	ab	Carex spp., L.	Cyperaceae
False Solomon's seal	ab	Smilacina stellata, (L.) Desf.	Liliaceae
Wild lily of the valley	ab	Maianthemum canadense, Desf.	Liliaceae
Red sorrel	ab	Rumex Acetosella, L.	Polygonaceae
Dogbane	ab	Apocynum androsaemifolium, L.	Apocynaceae
Goldenrod	ab	Solidago spp., L.	Compositae
Pussy toes	ab	Antennaria neglecta, Greene.	Compositae
Hawkweed	ab	Hieracium spp., L.	Compositae
Arrow aster	a	Aster sagittofolius, Willd.	Compositae
Butterfly-weed	a	Asclepias tuberosa, L.	Asclepiadaceae
Tumble mustard	a	Sisymbrium altissimum, L.	Cruciferae
St. John's wort	a	Hypericum perforatum, L.	Hypericaceae

Table 32. Litter nutrient concentrations on the Udell site

Sludge treatment (tonne/ha)	Year	K	Ca	Mg	Al	Na	Fe	Mn
		------- % -------		------------ ppm ------------				
15.7	1976	0.101a*	1.11a	2,085a	1,613a	642.4a	1,448a	850ab
7.9		0.084ab	1.01a	1,686ab	1,426ab	382.2b	1,223a	967ab
4.0		0.075bc	0.90ab	1,553ab	1,223ab	296.0bc	1,067ab	825b
2.0		0.062bc	0.79ab	1,132bc	1,002bc	127.3cd	768bc	760b
0.0		0.056c	0.64b	499c	768c	12.5d	420c	1,070a
15.7	1977	0.070a	1.34a	2,578a	2,368a	107.2a	2,241a	1,222b
7.9		0.067ab	1.34a	2,337a	2,212a	119.0a	2,385a	1,302ab
4.0		0.069a	1.17ab	1,804b	1,822b	86.3ab	1,559b	1,547a
2.0		0.059bc	0.98b	1,437c	1,581b	71.2b	1,403b	1,245b
0.0		0.058c	0.60c	635d	1,103c	56.2b	926c	1,188b
		Zn	**Cu**	**B**	**Pb**	**Cr**	**Cd**	**Ni**
		------------ ppm ------------						
15.7	1976	98.3a	14.3a	16.6a	61.2a	13.5a	2.5a	4.3a
7.9		86.2ab	11.5ab	14.1ab	62.5a	11.2ab	2.0ab	3.8ab
4.0		77.9abc	10.2ab	12.4abc	63.2a	10.2ab	1.8bc	2.9abc
2.0		68.6bc	7.5bc	9.8bc	59.9a	7.5bc	1.4cd	2.6bc
0.0		58.8c	4.0c	7.9c	63.7a	4.9c	0.9d	1.7c
15.7	1977	121.9ab	14.2b	23.1a	78.9a	9.1b	2.4a	8.4a
7.9		137.2a	16.6a	21.4a	82.0a	12.5a	2.7a	7.9a
4.0		107.5bc	11.3c	17.2b	77.1ab	6.8bc	1.7a	5.5b
2.0		95.3c	9.1c	13.7c	77.0ab	5.4c	1.5a	4.7b
0.0		70.7c	4.9d	9.1d	69.5b	2.4d	0.8a	2.9c

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 33. Red pine litter nutrient concentrations on the Pine River site

Sludge treatment (tonne/ha)	Year	K	Ca	Mg	Al	Na	Fe
		------- % -------		----------------- ppm -----------------			
19.3	1976	0.042a*	1.37a	951a	990a	48.4a	16,792a
9.7		0.058a	1.01ab	717ab	715b	39.7a	16,102a
5.4		0.055a	1.12a	827a	842ab	36.5a	6,380ab
0.0		0.051a	0.62b	451b	751b	12.3b	451b
19.3	1977	0.060a	1.78a	2,241a	1,798a	72.3	22,191a
9.7		0.057ab	1.57a	2,007a	1,747a	60.5	21,238a
5.4		0.051bc	0.90b	1,058b	1,230b	48.4	10,850b
0.0		0.048c	0.56b	410b	1,055b	30.5	1,101c
		Mn	Cu	B	Pb	Cr	Ni
		ppm					
19.3	1976	958a	123.4a	43.5a	214.0a	183.3a	24.6a
9.7		929a	97.7ab	40.5ab	169.5a	138.3ab	17.2ab
5.4		900a	83.9b	10.3ab	163.0a	113.0b	15.6b
0.0		817a	4.3c	6.7b	64.3b	4.3c	1.3c
19.3	1977	991a	229.6a	55.2a	296.9a	190.1a	37.3a
9.7		1,279a	210.0a	50.8a	283.1a	173.3a	33.4a
5.4		1,083a	96.5a	25.9b	164.8b	78.4b	17.0b
0.0		920a	4.1b	7.0b	68.4b	2.0b	2.7c

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 34. White pine litter nutrient concentrations on the Pine River site

Sludge treatment (tonne/ha)	Year	K	Ca	Mg	Al	Na	Fe
		------- % -------		------------------ ppm ------------------			
19.3	1976	0.056a*	1.92a	1,424a	1,286a	58.1a	27,586a
9.7		0.062a	1.67ab	1,275a	1,168a	56.5a	21,800ab
5.4		0.061a	1.22bc	901b	1,253a	35.7b	16,538b
0.0		0.053a	0.72c	519c	826a	10.9c	521c
19.3	1977	0.057ab	1.95a	2,402a	2,026a	55.5a	26,078a
9.7		0.069a	1.67a	2,041a	1,668ab	53.3a	20,813a
5.4		0.059ab	1.08b	1,260b	1,627b	35.1b	12,374b
0.0		0.048b	0.50c	447c	1,254c	24.7b	1,324c
		Mn	Cu	B	Pb	Cr	Ni
		------------------ ppm ------------------					
19.3	1976	1,302a	228.2a	68.6a	355.8a	330.5a	40.9a
9.7		1,077ab	178.9ab	53.8ab	295.2ab	260.8ab	33.1ab
5.4		1,060ab	114.7b	40.7b	216.0b	171.6b	21.6b
0.0		817b	4.3c	7.3c	73.5c	4.4c	1.8c
19.3	1977	1,075	286.0a	62.9a	344.2a	233.6a	45.1a
9.7		951a	216.9a	49.0a	292.7a	179.0a	35.0a
5.4		848a	105.3b	28.4b	194.3b	91.5b	18.6b
0.0		981a	4.0c	7.3c	69.7c	2.6c	3.3c

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 35. Soil nutrient concentrations on the Udell site, 0-5 cm depth

Sludge treatment (tonne/ha)	Year	K	Ca	Mg	Na	H	OM
		meq/100 g					--%--
15.7	1976	0.10ab*	0.76a	0.14a	0.16a	6.88a	5.68a
7.9		0.10a	0.59ab	0.12ab	0.09ab	7.15a	4.37a
4.0		0.07b	0.43b	0.08c	0.03bc	5.93a	4.22a
2.0		0.07ab	0.69a	0.11bc	0.04bc	6.47a	5.23a
0.0		0.07b	0.77a	0.11abc	0.00c	8.67a	6.75a
15.7	1977	0.09a	0.73a	0.17a	0.05a	6.19ab	2.82a
7.9		0.05b	0.43a	0.10ab	0.03b	4.93b	2.49a
4.0		0.06b	0.48a	0.09b	0.02b	5.81ab	3.08a
2.0		0.05b	0.60a	0.09b	0.02b	6.89a	3.07a
0.0		0.05b	0.48a	0.09b	0.02b	6.37ab	2.80a
		Fe	**Cu**	**Mn**	**Pb**	**Cr**	**Ni**
		ppm					
15.7	1976	172a	0.3a	47.9a	3.7a	0.1a	0.1b
7.9		178a	0.2a	44.8a	4.1a	0.1a	0.1b
4.0		203a	0.3a	54.9a	3.6a	0.1a	0.0c
2.0		186a	0.2a	46.4a	4.4a	0.1a	<0.1c
0.0		194a	0.2a	70.3a	4.9a	0.1a	0.2a
15.7	1977	152ab	0.4a	46.1a	3.2a	0.1a	0.2a
7.9		149b	0.2a	38.4a	2.9a	0.1a	0.1b
4.0		164ab	0.3a	41.4a	3.0a	0.1a	0.2a
2.0		182a	0.3a	38.6a	3.3a	0.1a	0.2a
0.0		181a	0.4a	43.8a	3.1a	0.1a	0.2a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 36. Soil nutrient concentrations on the Pine River site under red pine, 0-5 cm depth

Sludge treatment (tonne/ha)	Year	K	Ca	Mg	Na	H	OM
		meq/100 g					--%--
19.3	1976	0.06a*	1.01a	0.15a	0.03a	6.36a	3.86a
9.7		0.06a	1.27a	0.15a	0.03a	6.29a	4.61a
5.4		0.05a	0.79a	0.11a	0.02ab	6.36a	4.46a
0.0		0.04a	0.57a	0.09a	0.01b	5.88a	3.24a
19.3	1977	0.04a	0.69a	0.07a	0.03a	5.91a	2.48ab
9.7		0.05a	1.10a	0.12a	0.02a	5.87a	2.79a
5.4		0.04a	0.61a	0.06a	0.01a	6.01a	2.32ab
0.0		0.04a	0.45a	0.06a	0.01a	5.23a	2.04b
		Fe	Cu	Mn	Pb	Cr	Ni
		ppm					
19.3	1976	165a	0.1a	93.8a	2.5a	0.1a	<0.1a
9.7		161a	0.2a	76.7ab	2.7a	0.1a	0.1a
5.4		149a	0.1a	61.9ab	3.3a	0.1a	0.1a
0.0		153a	0.1a	41.6b	2.9a	0.1a	<0.1a
19.3	1977	156a	0.3a	73.8a	2.1a	0.1a	0.2a
9.7		147a	0.4a	47.1a	2.5a	0.1a	0.2ab
5.4		147a	0.2a	69.1a	2.6a	0.1a	0.1ab
0.0		140a	0.3a	50.8a	3.1a	0.1a	0.1b

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 37. Soil nutrient concentrations on the Pine River site under white pine, 0-5 cm depth

Sludge treatment (tonne/ha)	Year	K	Ca	Mg	Na	H	OM
		------------- meq/100 g					--%--
19.3	1976	0.08a*	1.64	0.20a	0.01a	5.81a	4.02a
9.7		0.08a	0.93a	0.16a	0.02a	5.81a	3.36a
5.4		0.08a	1.76a	0.24a	<0.01a	5.74a	6.85a
0.0		0.09a	1.36a	0.23a	0.01a	4.92a	3.59a
19.3	1977	0.05a	1.64a	0.16a	0.01a	5.60a	2.71a
9.7		0.05a	0.92a	0.09a	0.01a	6.43a	2.19a
5.4		0.05a	1.30a	0.13a	0.01a	5.74a	2.89a
0.0		0.05a	1.15a	0.13a	0.01a	5.98a	2.37a
		Fe	Cu	Mn	Pb	Cr	Ni
		------------------- ppm					
19.3	1976	142a	0.1a	59.5ab	2.4a	0.1a	0.0a
9.7		155a	0.2a	52.0b	2.9a	0.1a	0.0a
5.4		161a	0.1a	82.6a	3.6a	0.1a	0.1a
0.0		128a	0.1a	51.7b	2.3a	0.1a	0.0a
19.3	1977	124ab	0.7a	52.1ab	2.8a	0.0b	0.2a
9.7		145a	0.4ab	37.5b	2.3a	0.1a	0.2a
5.4		117b	0.5ab	67.4a	2.7a	0.0b	0.2a
0.0		113b	0.3b	66.1ab	1.9a	0.1a	0.2a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 38. Soil TKN and total P on the Udell site

Year	Sludge treatment (tonne/ha)	Soil depth (cm)			
		5-10	15-30	45-60	105-120
		TKN (ppm)			
1976	15.7	620	320	150	150
	7.9	720	300	170	60
	4.0	590	330	170	90
	2.0	660	300	170	90
	0.0	530	320	200	50
1977	15.7	490	290	100	40
	7.9	520	250	90	40
	4.0	620	260	90	40
	2.0	590	250	110	50
	0.0	490	340	110	60
		Total P (ppm)			
1976	15.7	141	195	133	66
	7.9	157	139	156	71
	4.0	181	144	139	54
	2.0	157	167	128	60
	0.0	116	167	122	60
1977	15.7	100	137	93	52
	7.9	84	107	81	49
	4.0	103	129	90	49
	2.0	85	139	100	49
	0.0	79	104	100	49

Table 39. Soil K and Na on the Udell site

Year	Sludge treatment (tonne/ha)	Soil depth (cm) 5-10	15-30	45-60	105-120
		K (meq/100 g)			
1976	15.7	0.05	0.01	0.00	0.00
	7.9	0.04	0.01	0.00	0.00
	4.0	0.05	0.01	0.00	0.00
	2.0	0.04	0.00	0.00	0.00
	0.0	0.04	0.01	0.00	0.00
1977	15.7	0.04	0.04	0.02	0.01
	7.9	0.04	0.02	0.01	0.01
	4.0	0.04	0.02	0.01	0.01
	2.0	0.03	0.03	0.01	0.01
	0.0	0.03	0.02	0.01	0.01
		Na (meq/100 g)			
1976	15.7	0.10	0.01	0.01	0.00
	7.9	0.04	0.00	0.00	0.00
	4.0	0.03	0.00	0.00	0.00
	2.0	0.03	0.00	0.00	0.00
	0.0	0.00	0.00	0.00	0.00
1977	15.7	0.06	0.06	0.03	0.02
	7.9	0.04	0.03	0.02	0.01
	4.0	0.02	0.03	0.02	0.01
	2.0	0.02	0.04	0.01	0.02
	0.0	0.02	0.02	0.02	0.01

Table 40. Soil Ca and Mg on the Udell site

Year	Sludge treatment (tonne/ha)	Soil depth (cm) 5-10	15-30	45-60	105-120
		Ca (meq/100 g)			
1976	15.7	0.30	0.12	0.06	0.04
	7.9	0.21	0.07	0.03	0.01
	4.0	0.24	0.08	0.04	0.01
	2.0	0.30	0.13	0.05	0.02
	0.0	0.23	0.08	0.01	0.01
1977	15.7	0.27	0.12	0.03	0.03
	7.9	0.25	0.08	0.07	0.04
	4.0	0.22	0.15	0.05	0.03
	2.0	0.29	0.07	0.05	0.02
	0.0	0.16	0.05	0.06	0.02
		Mg (meq/100 g)			
1976	15.7	0.07	0.01	0.00	0.00
	7.9	0.04	0.00	0.00	0.00
	4.0	0.06	0.05	0.00	0.00
	2.0	0.05	0.01	0.00	0.00
	0.0	0.03	0.00	0.00	0.00
1977	15.7	0.07	0.03	0.02	0.01
	7.9	0.05	0.01	0.01	0.01
	4.0	0.03	0.01	0.01	0.01
	2.0	0.05	0.02	0.01	0.01
	0.0	0.03	0.01	0.01	0.01

Table 41. Soil Fe and Mn on the Udell site

Year	Sludge treatment (tonne/ha)	Soil depth (cm) 5-10	15-30	45-60	105-120
		Fe (ppm)			
1976	15.7	164.4	38.3	10.4	14.1
	7.9	179.5	41.6	13.1	6.4
	4.0	183.5	36.6	10.3	5.0
	2.0	185.6	53.1	12.6	6.1
	0.0	172.1	50.2	13.0	6.0
1977	15.7	111.5	25.9	9.3	6.9
	7.9	133.2	21.8	10.5	5.9
	4.0	139.4	24.8	8.1	6.0
	2.0	137.5	23.4	10.4	6.1
	0.0	123.8	26.6	10.2	5.2
		Mn (ppm)			
1976	15.7	38.6	4.1	1.0	1.8
	7.9	36.9	5.9	1.6	0.9
	4.0	32.8	4.6	1.1	0.8
	2.0	35.1	5.7	0.6	--
	0.0	43.1	8.2	1.4	0.8
1977	15.7	27.9	2.2	0.5	0.4
	7.9	26.1	1.5	0.8	0.4
	4.0	34.6	1.9	0.4	0.6
	2.0	23.2	1.3	1.2	0.5
	0.0	31.9	2.1	1.0	0.5

Table 42. Soil Zn and Cu on the Udell site

Year	Sludge treatment (tonne/ha)	Soil depth (cm) 5-10	15-30	45-60	105-120
		Zn (ppm)			
1976	15.7	1.3	0.4	0.8	0.3
	7.9	1.0	1.0	0.8	0.0
	4.0	2.1	0.4	0.1	0.0
	2.0	1.5	0.4	0.0	0.3
	0.0	2.8	0.3	0.0	0.8
1977	15.7	1.1	0.3	0.1	0.1
	7.9	1.4	0.3	0.1	0.1
	4.0	1.6	0.4	0.3	0.7
	2.0	2.1	0.3	0.7	0.2
	0.0	1.7	0.4	0.1	0.1
		Cu (ppm)			
1976	15.7	0.2	0.1	0.0	0.0
	7.9	0.2	0.1	0.0	0.0
	4.0	0.3	0.0	0.0	0.0
	2.0	0.3	0.0	0.0	0.0
	0.0	0.1	0.1	0.1	0.0
1977	15.7	1.1	0.3	0.1	0.1
	7.9	1.4	0.3	0.1	0.1
	4.0	1.6	0.4	0.3	0.7
	2.0	2.1	0.3	0.7	0.2
	0.0	1.7	0.4	0.1	0.1

Table 43. Soil Cd and Pb on the Udell site

Year	Sludge treatment (tonne/ha)	Soil depth (cm) 5-10	15-30	45-60	105-120
		Cd (ppm)			
1976	15.7	0.0	0.0	0.0	0.0
	7.9	0.0	0.0	0.0	0.0
	4.0	0.0	0.0	0.0	0.0
	2.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
1977	15.7	0.2	0.02	0.0	0.0
	7.9	0.2	0.0	0.0	0.0
	4.0	0.2	0.0	0.0	0.0
	2.0	0.2	0.01	0.0	0.01
	0.0	0.2	0.02	0.0	0.0
		Pb (ppm)			
1976	15.7	1.5	0.5	0.3	0.3
	7.9	1.6	0.5	0.2	0.1
	4.0	1.7	0.5	0.2	0.1
	2.0	1.9	0.5	0.3	0.2
	0.0	1.4	0.6	0.4	0.2
1977	15.7	1.2	0.5	0.2	0.1
	7.9	1.5	0.4	0.2	0.1
	4.0	1.6	0.5	0.1	0.2
	2.0	1.5	0.5	0.2	0.3
	0.0	1.4	0.4	0.2	0.2

Table 44. Soil Cr and Ni on the Udell site

Year	Sludge treatment (tonne/ha)	Soil depth (cm) 5-10	15-30	45-60	105-120
		Cr (ppm)			
1976	15.7	0.1	0.0	0.0	0.0
	7.9	0.1	0.0	0.0	0.0
	4.0	0.1	0.0	0.0	0.0
	2.0	0.1	0.0	0.0	0.0
	0.0	0.1	0.0	0.0	0.0
1977	15.7	0.1	0.0	0.0	0.0
	7.9	0.1	0.0	0.0	0.0
	4.0	0.1	0.0	0.0	0.0
	2.0	0.1	0.0	0.0	0.0
	0.0	0.1	0.0	0.0	0.0
		Ni (ppm)			
1976	15.7	0.2	0.1	0.2	0.0
	7.9	0.0	0.1	0.0	0.0
	4.0	0.1	0.2	0.1	0.0
	2.0	0.1	0.2	0.2	0.1
	0.0	0.1	0.3	0.1	0.0
1977	15.7	0.1	0.1	0.0	0.0
	7.9	0.1	0.1	0.04	0.0
	4.0	0.1	0.1	0.0	0.0
	2.0	0.1	0.0	0.0	0.1
	0.0	0.1	0.1	0.1	0.0

Table 45. Soil pH and specific conductivity on the Udell site

Year	Sludge treatment (tonne/ha)	Soil depth (cm) 5-10	15-30	45-60	105-120
		------------------pH-------------------			
1976	15.7	4.2	4.9	5.1	5.2
	7.9	4.2	4.8	5.2	5.1
	4.0	4.1	4.9	5.0	5.1
	2.0	4.2	4.9	5.0	5.1
	0.0	4.1	4.8	5.0	5.1
1977	15.7	4.2	4.9	5.0	5.1
	7.9	4.1	4.9	5.0	5.1
	4.0	4.1	5.1	5.1	5.1
	2.0	4.1	5.1	5.0	5.1
	0.0	4.2	5.0	5.0	5.1
		---Specific conductivity (μmhos/cm)---			
1976	15.7	201	--	--	--
	7.9	157	--	--	--
	4.0	148	--	--	--
	2.0	160	--	--	--
	0.0	157	--	--	--
1977	15.7	215	139	79	69
	7.9	197	88	69	71
	4.0	201	79	53	62
	2.0	188	71	74	76
	0.0	147	71	69	53

Table 46. Soil exchange acidity and cation exchange capacity on the Udell site

Year	Sludge treatment (tonne/ha)	Soil depth (cm)			
		5-10	15-30	45-60	105-120
		H (meq/100 g)			
1976	15.7	4.75	5.78	2.89	1.65
	7.9	4.95	5.57	3.71	1.44
	4.0	5.57	5.37	3.10	1.65
	2.0	5.37	5.57	3.51	1.44
	0.0	4.33	5.16	2.89	1.44
1977	15.7	5.66	5.12	2.86	1.98
	7.9	5.54	4.62	2.04	0.62
	4.0	5.69	4.76	2.72	2.12
	2.0	7.05	5.98	1.58	0.82
	0.0	5.04	4.54	2.14	1.82
		CEC (meq/100 g)			
1976	15.7	5.27	5.93	2.96	1.69
	7.9	5.28	5.65	3.74	1.45
	4.0	5.94	5.46	3.14	1.66
	2.0	5.79	5.71	3.56	1.46
	0.0	4.63	5.25	2.90	1.45
1977	15.7	6.11	5.37	2.95	2.04
	7.9	5.92	4.76	2.15	0.68
	4.0	6.00	4.98	2.80	2.17
	2.0	7.45	6.13	1.66	0.87
	0.0	5.28	4.64	2.23	1.86

Table 47. Soil base saturation and organic matter on the Udell site

Year	Sludge treatment (tonne/ha)	Soil depth (cm) 5-10	15-30	45-60	105-120
		Base saturation (%)			
1976	15.7	9.9	2.5	2.4	2.4
	7.9	6.2	1.4	0.8	0.7
	4.0	6.2	1.6	1.3	0.6
	2.0	7.3	2.5	1.4	1.4
	0.0	6.5	1.7	0.3	0.7
1977	15.7	7.3	4.7	3.1	3.0
	7.9	6.3	2.9	5.1	8.8
	4.0	5.3	4.4	2.9	2.3
	2.0	5.3	2.4	4.8	5.7
	0.0	4.8	2.2	4.0	2.2
		Organic matter (%)			
1976	15.7	3.11	--	2.87	--
	7.9	2.98	--	2.67	--
	4.0	3.36	--	2.78	--
	2.0	3.72	--	2.98	--
	0.0	3.42	--	2.93	--
1977	15.7	2.08	1.51	0.62	0.22
	7.9	2.27	1.34	0.65	0.17
	4.0	2.27	1.47	0.58	0.22
	2.0	2.46	1.61	0.60	0.20
	0.0	2.10	1.34	0.62	0.19

Table 48. Soil TKN and total P on the Pine River site

Year	Sludge treatment (tonne/ha)	Red pine				White pine			
		Soil depth (cm)							
		5-10	15-30	45-60	105-120	5-10	15-30	45-60	105-120
		TKN (ppm)							
1976	19.3	530	220	220	0	530	220	220	0
	9.7	570	270	200	60	570	270	200	60
	5.4	540	300	170	40	540	300	170	40
	0.0	590	250	210	80	590	250	210	80
1977	19.3	490	270	100	90	370	270	130	40
	9.7	490	250	110	70	380	320	110	40
	5.4	460	260	110	40	520	240	140	40
	0.0	530	270	130	50	530	290	170	50
		Total P (ppm)							
1976	19.3	147	198	328	92	147	198	328	92
	9.7	118	238	198	76	118	238	198	76
	5.4	147	245	159	66	147	245	159	66
	0.0	130	222	193	141	130	222	193	141
1977	19.3	127	185	100	58	112	148	103	56
	9.7	111	179	112	70	103	170	124	40
	5.4	111	122	87	47	84	198	116	66
	0.0	103	223	119	76	98	132	108	50

Table 49. Soil K and Na on the Pine River site

Year	Sludge treatment (tonne/ha)	Red pine				White pine			
		Soil depth (cm)							
		5-10	15-30	45-60	105-120	5-10	15-30	45-60	105-120
		K (meq/100 g)							
1976	19.3	0.06	0.03	0.02	0.01	0.06	0.03	0.02	0.01
	9.7	0.06	0.02	0.02	0.00	0.06	0.02	0.02	0.00
	5.4	0.05	0.02	0.01	0.00	0.05	0.02	0.01	0.00
	0.0	0.05	0.02	0.03	0.03	0.05	0.02	0.03	0.03
1977	19.3	0.03	0.02	0.01	0.01	0.03	0.03	0.02	0.01
	9.7	0.03	0.02	0.02	0.01	0.03	0.03	0.02	0.01
	5.4	0.03	0.02	0.02	0.01	0.04	0.03	0.02	0.01
	0.0	0.03	0.02	0.01	0.01	0.03	0.02	0.02	0.01
		Na (meq/100 g)							
1976	19.3	0.01	0.04	0.04	0.00	0.01	0.04	0.04	0.00
	9.7	0.03	0.01	0.01	0.00	0.03	0.01	0.01	0.00
	5.4	0.00	0.02	0.01	0.01	0.00	0.02	0.01	0.01
	0.0	0.00	0.02	0.03	0.03	0.00	0.02	0.03	0.03
1977	19.3	0.02	0.03	0.02	0.02	0.01	0.02	0.01	0.01
	9.7	0.01	0.03	0.02	0.01	0.01	0.01	0.01	0.01
	5.4	0.02	0.03	0.02	0.02	0.01	0.02	0.01	0.01
	0.0	0.01	0.03	0.02	0.02	0.01	0.02	0.01	0.01

Table 50. Soil Ca and Mg on the Pine River site

Year	Sludge treatment (tonne/ha)	Red pine				White pine			
		Soil depth (cm)							
		5-10	15-30	45-60	105-120	5-10	15-30	45-60	105-120
		Ca (meq/100 g)							
1976	19.3	0.70	0.13	0.15	0.04	0.70	0.13	0.15	0.04
	9.7	0.63	0.18	0.12	0.02	0.63	0.18	0.12	0.02
	5.4	0.72	0.19	0.08	0.02	0.72	0.19	0.08	0.02
	0.0	0.52	0.17	0.13	0.06	0.52	0.17	0.13	0.06
1977	19.3	0.47	0.11	0.06	0.24	0.81	0.19	0.12	0.07
	9.7	0.36	0.15	0.09	1.10	0.38	0.15	0.08	0.03
	5.4	0.54	0.18	0.07	0.03	0.71	0.39	0.37	0.12
	0.0	0.47	0.16	0.08	0.04	0.55	0.33	0.10	0.07
		Mg (meq/100 g)							
1976	19.3	0.12	0.03	0.03	0.00	0.12	0.03	0.03	0.00
	9.7	0.10	0.03	0.01	0.00	0.10	0.03	0.01	0.00
	5.4	0.11	0.03	0.01	0.00	0.11	0.03	0.01	0.00
	0.0	0.08	0.02	0.01	0.01	0.08	0.02	0.01	0.01
1977	19.3	0.05	0.01	0.01	0.07	0.07	0.03	0.02	0.01
	9.7	0.04	0.02	0.02	0.37	0.04	0.02	0.01	0.01
	5.4	0.04	0.02	0.02	0.01	0.09	0.07	0.03	0.02
	0.0	0.05	0.02	0.01	0.01	0.07	0.04	0.01	0.01

Table 51. Soil Fe and Mn on the Pine River site

Year	Sludge treatment (tonne/ha)	Red pine				White pine			
		Soil depth (cm)							
		5-10	15-30	45-60	105-120	5-10	15-30	45-60	105-120
		Fe (ppm)							
1976	19.3	119.3	59.5	20.6	--	113.3	35.1	22.4	7.4
	9.7	165.5	93.5	26.0	13.6	122.8	104.4	--	8.1
	5.4	177.8	71.6	17.0	8.1	145.3	88.2	31.8	7.8
	0.0	115.6	48.5	17.2	6.0	83.5	40.2	17.4	9.2
1977	19.3	99.5	28.2	9.2	9.0	111.8	33.2	19.1	8.1
	9.7	118.5	79.6	14.7	9.8	138.6	124.1	12.9	8.9
	5.4	149.1	31.1	12.7	5.9	136.2	79.9	12.4	8.2
	0.0	118.1	27.5	12.4	6.2	145.0	38.6	14.5	10.2
		Mn (ppm)							
1976	19.3	60.2	8.8	2.5	--	62.0	8.9	3.7	1.4
	9.7	75.0	16.5	3.9	2.5	43.4	6.0	--	1.2
	5.4	32.6	9.4	1.7	1.4	47.4	12.0	4.1	1.4
	0.0	35.3	5.4	2.3	0.8	32.7	8.9	3.6	2.1
1977	19.3	86.3	2.1	0.4	2.0	33.4	3.8	3.4	1.1
	9.7	33.4	3.7	0.9	1.4	35.9	2.5	0.4	0.8
	5.4	58.5	3.1	0.8	0.7	50.4	3.6	1.6	1.1
	0.0	71.0	10.1	2.1	0.9	71.0	2.4	1.9	1.9

Table 52. Soil Zn and Cu on the Pine River site

Year	Sludge treatment (tonne/ha)	Red pine				White pine			
		Soil depth (cm)							
		5-10	15-30	45-60	105-120	5-10	15-30	45-60	105-120
		Zn (ppm)							
1976	19.3	2.1	0.5	0.7	0.4	2.1	0.5	0.7	0.4
	9.7	2.0	0.5	0.3	0.1	2.0	0.5	0.3	0.1
	5.4	1.7	0.5	1.5	0.1	1.7	0.5	1.5	0.1
	0.0	1.6	0.3	1.0	0.0	1.6	0.3	1.0	0.0
1977	19.3	1.5	0.8	0.1	0.2	1.0	0.6	0.4	0.3
	9.7	1.2	0.8	0.7	0.3	1.0	1.0	0.2	0.1
	5.4	1.7	0.4	0.6	0.2	1.9	0.5	0.2	0.2
	0.0	1.8	0.8	0.2	0.2	1.7	0.4	1.1	0.2
		Cu (ppm)							
1976	19.3	0.1	0.2	0.0	0.0	0.1	0.2	0.0	0.0
	9.7	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.1
	5.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	0.0	0.1	0.3	0.0	0.0	0.1	0.3	0.0	0.0
1977	19.3	0.2	0.1	0.1	0.1	0.4	0.1	0.1	0.1
	9.7	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.04
	5.4	0.2	0.1	0.1	0.03	0.3	0.1	0.1	0.03
	0.0	0.2	0.1	0.1	0.04	0.2	0.1	0.1	0.1

Table 53. Soil Cd and Pb on the Pine River site

Year	Sludge treatment (tonne/ha)	Red pine				White pine			
		Soil depth (cm)							
		5-10	15-30	45-60	105-120	5-10	15-30	45-60	105-120
		Cd (ppm)							
1976	19.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	9.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1977	19.3	0.1	0.02	0.0	0.0	0.1	0.02	0.0	0.0
	9.7	0.1	0.03	0.01	0.0	0.1	0.01	0.0	0.0
	5.4	0.1	0.02	0.0	0.0	0.1	0.02	0.0	0.0
	0.0	0.1	0.02	0.0	0.0	0.1	0.01	0.0	0.0
		Pb (ppm)							
1976	19.3	1.0	0.7	0.5	--	1.6	0.3	0.4	0.2
	9.7	1.5	0.6	0.2	0.2	1.6	0.6	--	0.1
	5.4	1.8	0.5	0.3	0.1	1.9	0.6	0.3	0.1
	0.0	1.3	0.5	0.5	0.3	1.1	0.3	0.3	0.1
1977	19.3	1.0	0.5	0.2	0.0	0.9	0.6	0.4	0.1
	9.7	1.2	0.6	0.3	0.1	1.2	0.8	0.2	0.2
	5.4	1.1	0.5	0.2	0.1	1.7	0.7	0.3	0.2
	0.0	1.6	0.4	0.2	0.0	1.7	0.5	0.3	0.2

Table 54. Soil Cr and Ni on the Pine River site

Year	Sludge treatment (tonne/ha)	Red pine				White pine			
		Soil depth (cm)							
		5-10	15-30	45-60	105-120	5-10	15-30	45-60	105-120
		Cr (ppm)							
1976	19.3	0.1	0.0	0.0	--	0.0	0.0	0.0	0.0
	9.7	0.1	0.0	0.0	0.0	0.0	0.0	--	0.0
	5.4	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0
	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1977	19.3	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0
	9.7	0.1	0.1	0.0	0.0	0.1	0.1	0.0	0.0
	5.4	0.1	0.0	0.0	0.0	0.1	0.03	0.0	0.0
	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0
		Ni (ppm)							
1976	19.3	0.0	0.2	0.0	0.1	0.0	0.2	0.0	0.1
	9.7	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0
	5.4	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0
	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0
1977	19.3	0.2	0.1	0.1	0.04	0.1	0.1	0.04	0.0
	9.7	0.1	0.1	0.04	0.04	0.1	0.1	0.0	0.0
	5.4	0.1	0.1	0.04	0.1	0.1	0.1	0.0	0.0
	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.1

Table 55. Soil pH and specific conductivity on the Pine River site

Year	Sludge treatment (tonne/ha)	Red pine				White pine			
		Soil depth (cm)							
		5-10	15-30	45-60	105-120	5-10	15-30	45-60	105-120
		pH							
1976	19.3	4.5	--	--	--	4.5	--	--	--
	9.7	4.5	--	--	--	4.4	--	--	--
	5.4	4.4	--	--	--	4.4	--	--	--
	0.0	4.4	--	--	--	4.6	--	--	--
1977	19.3	4.4	5.3	5.2	5.7	4.6	4.9	5.0	5.7
	9.7	4.4	4.3	5.2	7.0	4.2	4.9	5.0	5.3
	5.4	4.4	5.1	5.2	5.6	4.4	5.2	5.5	5.8
	0.0	4.4	5.2	5.1	5.1	4.3	5.2	5.5	5.2
		Specific conductivity (µmhos/cm)							
1976	19.3	160	--	--	--	187	--	--	--
	9.7	152	--	--	--	152	--	--	--
	5.4	129	--	--	--	142	--	--	--
	0.0	103	--	--	--	116	--	--	--
1977	19.3	181	67	45	57	216	72	72	74
	9.7	179	84	52	158	195	71	60	53
	5.4	245	69	53	55	243	71	69	67
	0.0	178	72	55	54	211	65	57	57

Table 56. Soil exchange acidity and cation exchange capacity on the Pine River site

Year	Sludge treatment (tonne/ha)	Red pine				White pine			
		Soil depth (cm)							
		5-10	15-30	45-60	105-120	5-10	15-30	45-60	105-120
		H (meq/100 g)							
1976	19.3	6.15	3.69	2.87	0.41	6.15	3.69	2.87	0.41
	9.7	6.77	--	2.46	0.82	6.77	--	2.46	0.82
	5.4	6.15	4.10	1.44	0.41	6.15	4.10	1.44	0.41
	0.0	5.13	3.90	2.67	1.23	5.13	3.90	2.67	1.23
1977	19.3	6.45	5.68	1.68	1.52	5.52	5.62	2.08	0.84
	9.7	4.52	3.98	1.84	1.72	5.45	5.30	3.04	0.36
	5.4	4.48	4.40	2.92	1.12	5.09	4.08	1.66	2.90
	0.0	5.71	4.18	3.66	0.88	4.55	6.28	1.90	0.08
		CEC (meq/100 g)							
1976	19.3	7.04	3.92	3.11	0.46	7.04	3.92	3.11	0.46
	9.7	7.59	--	2.62	0.84	7.59	--	2.62	0.84
	5.4	7.03	4.36	1.55	0.44	7.03	4.36	1.55	0.44
	0.0	5.78	4.13	2.87	1.36	5.78	4.13	2.87	1.36
1977	19.3	7.02	5.85	1.71	1.86	6.44	5.88	1.86	0.94
	9.7	4.96	4.21	2.00	3.22	5.92	5.51	3.15	0.41
	5.4	5.11	4.64	3.04	1.18	5.94	4.58	2.09	3.06
	0.0	6.26	4.41	3.78	0.95	5.22	6.68	2.04	0.17

Table 57. Soil base saturation and organic matter on the Pine River site

Year	Sludge treatment (tonne/ha)	Red pine				White pine			
		Soil depth (cm)							
		5-10	15-30	45-60	105-120	5-10	15-30	45-60	105-120
		Base saturation (%)							
1976	19.3	12.6	5.9	7.7	10.9	12.6	5.9	7.7	10.9
	9.7	10.8	--	6.1	2.4	10.8	10.0	6.1	2.4
	5.4	12.5	6.0	7.1	6.8	12.5	6.0	7.1	6.8
	0.0	11.2	5.6	7.0	9.6	11.2	5.6	7.0	9.6
1977	19.3	8.7	2.9	5.3	18.3	15.4	4.4	9.7	10.6
	9.7	8.6	5.5	0.1	46.6	8.5	3.8	3.5	12.2
	5.4	12.2	5.2	3.9	5.1	16.2	10.9	20.6	5.2
	0.0	8.4	5.2	3.2	7.4	12.5	6.0	6.9	52.9
		Organic matter (%)							
1976	19.3	3.51	1.44	1.10	0.40	3.03	1.44	1.10	0.40
	9.7	2.92	1.58	1.12	0.36	2.99	1.58	1.12	0.36
	5.4	3.23	1.39	0.94	0.37	4.00	1.39	0.94	0.37
	0.0	2.39	1.17	0.89	0.37	2.80	1.17	0.89	0.37
1977	19.3	2.37	1.48	0.66	0.20	2.09	1.49	0.88	0.27
	9.7	1.64	1.42	0.68	0.31	2.17	1.49	0.84	0.22
	5.4	2.15	1.36	0.72	0.22	1.99	1.44	0.78	0.28
	0.0	2.26	1.39	0.76	0.24	1.93	1.53	0.81	0.37

Table 58. Soil bulk density

Sludge treatment (tonne/ha)	Soil depth (cm) 0-5 1976	0-5 1977	5-10 1976	5-10 1977
	g/cm^3			
Udell site				
15.7	1.10a*	1.11a	1.24a	1.24a
7.9	1.09a	1.17a	1.21a	1.22a
4.0	1.14a	1.12a	1.24a	1.23a
2.0	1.08a	1.16a	1.21a	1.23a
0.0	1.05a	1.14a	1.21a	1.26a
Pine River site				
Red pine				
19.3	1.18a	1.18a	1.26a	1.22a
9.7	1.09a	1.03a	1.23a	1.13a
5.4	1.16a	1.19a	1.25a	1.25a
0.0	1.19a	1.15a	1.28a	1.21a
White pine				
19.3	1.13a	1.18a	1.25a	1.32a
9.7	1.11a	1.17a	1.26a	1.26a
5.4	1.06a	1.17a	1.19a	1.30a
0.0	1.08a	1.16a	1.23a	1.26a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 59. Soil moisture

Sludge treatment (tonne/ha)	Soil depth (cm) 0-5 1976	0-5 1977	5-10 1976	5-10 1977
	%			
Udell site				
15.7	9.2a*	11.1a	6.7a	9.1a
7.9	6.5a	9.4a	6.0a	9.1a
4.0	6.4a	10.9a	6.2a	8.9a
2.0	7.9a	10.4a	9.0a	9.5a
0.0	9.6a	9.7a	8.0a	8.6a
Pine River site				
Red pine				
19.3	4.9a	10.3a	4.5a	11.1a
9.7	5.3a	11.1a	3.8a	8.0a
5.4	4.6a	9.5a	8.1a	8.9a
0.0	4.6a	9.1a	3.7a	8.6a
White pine				
19.3	5.0a	11.3a	6.0a	8.6a
9.7	4.8a	11.6a	4.5a	9.1a
5.4	5.4a	10.7a	5.8a	8.6a
0.0	4.1a	10.2a	4.4a	9.9a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 60. Understory nutrient concentrations on the Udell site

Sludge treatment (tonne/ha)	Year	K	Ca	Mg	Al	Na	Fe
		%	%	ppm	ppm	ppm	ppm
15.7	1976	1.350a*	0.826a	2,235a	525a	434.7a	454.3a
7.9		0.883a	0.801a	1,603a	292bc	169.6b	240.0b
4.0		0.758a	0.661a	1,556a	337ab	148.6bc	208.7bc
2.0		0.511a	0.630a	1,312a	195bc	56.1bc	135.0bc
0.0		0.871a	0.668a	1,283a	114c	11.4c	70.0c
15.7	1977	1.354a	0.576a	2,118a	138a	90.1a	127.7ab
7.9		1.335a	0.607a	2,400a	159a	57.8b	145.3a
4.0		1.163a	0.642a	2,406a	129a	33.6c	113.3ab
2.0		0.769a	0.628a	1,905a	173a	33.5c	138.7ab
0.0		0.968a	0.690a	2,068a	127a	21.5c	89.7b
		Mn	Zn	B	Pb	Cr	Ni
		ppm	ppm	ppm	ppm	ppm	ppm
15.7	1976	1,035a	74.8a	24.9a	13.7a	5.8a	2.5a
7.9		944a	55.2b	25.6a	10.2ab	4.5ab	1.8ab
4.0		850a	43.3b	23.8a	7.7b	3.7b	1.4b
2.0		946a	42.7b	24.6a	7.5b	3.4b	1.5b
0.0		1,049a	41.9b	25.2a	8.5b	3.0b	1.2b
15.7	1977	1,242a	61.3a	18.6a	7.8a	0.8a	3.1a
7.9		1,340a	56.2a	21.5a	8.3a	0.8a	2.7a
4.0		1,479a	54.8a	20.1a	6.7a	0.6a	2.1a
2.0		1,285a	52.5a	21.7a	9.4a	0.9a	2.4a
0.0		1,628a	50.4a	23.3a	7.9a	0.6a	2.8a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 61. Understory nutrient concentrations on the Pine River site under red pine

Sludge treatment (tonne/ha)	Year	K	Ca	Mg	Al	Na	Fe
		%	%	ppm	ppm	ppm	ppm
19.3	1976	1.567a*	0.898a	2,055a	196a	45.0ab	1,848a
9.7		1.076a	0.852a	1,743a	212a	39.0ab	1,884a
5.4		1.004a	0.790a	1,680a	184a	52.7a	1,319ab
0.0		0.850a	0.591a	1,711a	230a	15.3b	196b
19.3	1977	1.817a	0.715a	3,475a	82a	23.6a	370a
9.7		1.494a	0.753a	3,135a	70a	22.5a	215a
5.4		1.287a	0.801a	2,972a	105a	20.3a	310a
0.0		1.175a	0.676a	2,626a	113a	19.4a	109a
		Mn	Zn	B	Pb	Cr	Ni
		ppm	ppm	ppm	ppm	ppm	ppm
19.3	1976	773a	189.0a	17.9a	36.6ab	37.5a	4.8a
9.7		883a	230.9a	23.5a	43.2a	41.9a	4.8a
5.4		584a	154.5ab	18.7a	29.6ab	31.5a	3.4ab
0.0		755a	49.1b	24.8a	14.4b	3.6b	0.9b
19.3	1977	893a	80.4ab	19.3a	8.2a	2.7a	2.9a
9.7		982a	71.6ab	19.7a	6.4a	1.5a	2.3a
5.4		1,023a	110.8a	24.8a	9.9a	2.3a	2.0a
0.0		1,007a	56.7b	17.7a	8.8a	0.8a	1.8a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 62. Understory nutrient concentrations on the Pine River site under white pine

Sludge treatment (tonne/ha)	Year	K	Ca	Mg	Al	Na	Fe
		------- % -------		---------------- ppm	------------------		
19.3	1976	1.520a*	0.915a	1,965a	268a	53.1a	2,186a
9.7		1.072a	1.081a	1,907a	277a	43.1a	2,495a
5.4		0.882a	1.114a	1,793a	219a	40.0a	1,987a
0.0		1.140a	0.767a	2,026a	162a	15.8b	126b
19.3	1977	1.722a	0.965a	4,296a	115a	31.3a	534a
9.7		1.833a	0.831a	3,619a	69a	23.3a	175b
5.4		1.650ab	0.924a	3,662a	78a	22.5a	224ab
0.0		1.327b	0.908a	3,228a	162a	21.7a	154b
		Mn	Zn	B	Pb	Cr	Ni
		---------------------------- ppm	----------------------------				
19.3	1976	611a	286.4a	15.4a	57.6a	57.2a	7.4a
9.7		598a	291.6a	17.6a	57.6a	58.2a	7.1a
5.4		546a	220.7ab	20.6a	44.5a	42.7ab	5.4ab
0.0		670a	74.5b	25.0a	12.0b	2.7b	1.1b
19.3	1977	1,008a	78.5a	22.9ab	11.1a	2.2a	2.8a
9.7		869a	66.1a	19.9b	5.9b	1.2a	1.5b
5.4		850a	60.1a	20.2ab	8.6ab	1.6a	1.4b
0.0		847a	78.1a	24.6a	9.0ab	0.9a	1.8b

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 63. Nutrient concentrations in red pine needles on the Udell site

Sludge treatment (tonne/ha)	Year	Ca	Mg	Al	Na	Fe	Mn
		-- % --	ppm				
15.7	1976	0.182a*	870a	171a	1.3a	33.0a	620a
7.9		0.182a	847a	165a	0.8a	31.8a	622a
4.0		0.180ab	829a	165a	1.4a	33.6a	621a
2.0		0.180ab	837a	163a	1.5a	31.9a	568b
0.0		0.176b	865a	163a	1.8a	34.1a	562b
15.7	1977	0.181a	873a	113b	5.5ab	31.9ab	496b
7.9		0.162a	879a	124b	9.2ab	30.2b	481b
4.0		0.171a	859a	171a	4.9b	34.7ab	563ab
2.0		0.177a	930a	176a	6.0ab	35.8a	520b
0.0		0.187a	932a	183a	13.5a	35.7a	663a
		Zn	**Cu**	**Pb**	**Cr**	**Cd**	**Ni**
		ppm					
15.7	1976	42.5a	5.0a	2.3ab	0.4a	0.4a	4.6a
7.9		40.1a	4.9a	2.1b	0.4a	0.4a	5.0a
4.0		40.7a	5.0a	2.2b	0.4a	0.4a	4.8a
2.0		40.6a	4.9a	2.0b	0.4a	0.4a	4.9a
0.0		40.2a	4.9a	2.8a	0.3b	0.4a	4.8a
15.7	1977	46.8a	5.4a	1.8b	0.2a	0.5a	4.8b
7.9		41.3b	5.2a	2.0ab	0.3a	0.4a	5.3ab
4.0		40.9b	5.2a	1.8b	0.3a	0.4a	5.1ab
2.0		41.3b	5.4a	2.0ab	0.3a	0.4a	6.0a
0.0		42.3b	5.5a	2.3a	0.4a	0.5a	4.9b

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 64. Nutrient concentrations in red pine needles on the Pine River site

Sludge treatment (tonne/ha)	Year	Ca	Mg	Al	Na	Fe	Mn
		-- % --	ppm				
19.3	1976	0.188a*	885a	219a	1.1a	31.8a	605a
9.7		0.180a	780a	219a	0.9a	31.6a	533a
5.4		0.192a	893a	231a	0.8a	32.0a	528a
0.0		0.187a	839a	224a	1.0a	31.3a	607a
19.3	1977	0.164a	889a	135b	5.3a	31.2a	502a
9.7		0.172a	892a	218a	4.6a	34.9a	511a
5.4		0.156a	891a	154ab	6.2a	29.1a	458a
0.0		0.170a	996a	187ab	3.9a	36.1a	544a
		Zn	Cu	Pb	Cr	Cd	Ni
		ppm					
19.3	1976	37.6a	4.0ab	1.5a	0.0a	0.4a	4.3a
9.7		37.6a	4.1ab	1.5a	0.1a	0.4a	4.3a
5.4		35.6a	3.7b	1.5a	0.0a	0.4a	3.8a
0.0		38.5a	4.3a	1.5a	0.0a	0.4a	4.6a
19.3	1977	41.6a	4.3a	1.8a	0.1a	0.4a	5.4a
9.7		39.5a	5.2a	1.2a	0.2a	0.4a	5.8a
5.4		36.0a	5.0a	1.3a	0.1a	0.4a	5.0a
0.0		39.1a	4.7a	1.7a	0.2a	0.4a	6.0a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 65. Nutrient concentrations in white pine needles on the Pine River site

Sludge treatment (tonne/ha)	Year	Ca	Mg	Al	Na	Fe	Mn
		--%--	ppm				
19.3	1976	0.176a*	1,070a	176a	0.8a	90.3a	433a
9.7		0.177a	1,117a	184a	0.6a	41.9a	387a
5.4		0.171a	1,071a	194a	0.6a	39.0a	357a
0.0		0.174a	1,059a	181a	0.5a	36.4a	418a
19.3	1977	0.143b	1,022b	116b	11.2a	51.6ab	355a
9.7		0.160ab	1,113ab	156a	10.2a	60.0a	353a
5.4		0.149ab	1,108ab	157a	9.7a	53.1ab	308a
0.0		0.167a	1,166a	177a	8.1a	42.2b	372a
		Zn	Cu	Pb	Cr	Cd	Ni
		ppm					
19.3	1976	49.3a	5.6a	2.7a	0.4a	0.4a	2.8a
9.7		48.1a	5.0a	1.4b	0.3a	0.3b	2.8a
5.4		47.2a	5.0a	0.9b	0.3a	0.3b	2.7a
0.0		49.1a	4.9a	1.5ab	0.3a	0.3b	2.7a
19.3	1977	50.1a	5.5a	1.9ab	0.2ab	0.5a	3.0a
9.7		49.1a	6.0a	2.6a	0.3a	0.4a	3.6a
5.4		48.1a	5.8a	2.0ab	0.3a	0.3a	3.0a
0.0		47.9a	5.2a	1.7b	0.1b	0.3a	2.8a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 66. Height growth of overstory trees prior to and following treatment

Sludge treatment (tonne/ha)	Height growth				
	1973	1974	1975	1976	1979
	cm				
Udell site					
15.7	44.3ab*	49.4a	49.8a	46.1a	31.7a
7.9	44.5ab	45.0a	51.0a	46.6a	31.7a
4.0	50.8a	46.9a	52.2a	39.4b	34.4a
2.0	47.8ab	43.7a	50.2a	41.7ab	32.8a
0.0	42.8b	43.8a	52.4a	45.4a	32.9a
Pine River site					
Red pine					
19.3	45.2a	43.8a	50.2a	49.5a	29.8a
9.7	44.8a	47.3a	60.2a	55.0a	34.5a
5.4	38.0a	45.0a	57.7a	48.3a	40.3a
0.0	43.8a	43.2a	56.3a	49.5a	29.8a
White pine					
19.3	55.0a	58.8a	66.7ab	36.8b	23.5a
9.7	65.8a	61.7a	53.8b	61.5a	32.8a
5.4	62.3a	66.5a	82.2a	46.0ab	23.2a
0.0	49.0a	66.3a	56.2b	47.5ab	27.8a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 67. Growth parameters for overstory trees

Sludge treatment (tonne/ha)	Shoot dry wt. (g)		Shoot moisture (%)	Annual increment at breast height (mm)	D.B.H. (cm)		Total height (m)	D^2H (m^3)	Decrease in biennial radial growth at base of live crown (mm)
	1976	1977	1976	1975	1976	1977	1977	1977	1974 to 1977
<u>Udell site</u>									
15.7	3.6a*	6.2a	137.8a	1.7a	19.6a	19.9a	13.98a	0.553	0.4a
7.9	3.8a	5.3a	139.7a	1.8a	19.6a	19.7a	14.28a	0.554	0.5a
4.0	4.1a	6.1a	133.6a	1.7a	17.3a	20.7a	14.50a	0.621	0.3a
2.0	3.1a	4.8a	135.8a	1.6a	18.8a	20.3a	14.01a	0.577	0.3a
0.0	4.5a	4.5a	148.9a	1.8a	19.1a	20.3a	14.10a	0.581	0.5a
<u>Pine River site</u>									
Red pine									
19.3	6.9ab	4.7a	142.8a	1.9a	16.8a	17.9b	13.54a	0.434	0.1a
9.7	11.3a	5.9a	142.5a	2.3a	18.0a	22.1a	13.96a	0.682	1.8a
5.4	4.3b	4.9a	144.6a	2.0a	18.5a	20.8ab	14.08a	0.609	0.8a
0.0	6.0b	3.9a	146.8a	1.8a	16.5a	18.4ab	13.39a	0.453	0.5a
White pine									
19.3	1.2a	0.9a	146.3a	2.3a	16.0a	18.0a	12.13a	0.393	1.9a
9.7	1.3a	0.7a	145.9a	2.1a	15.8a	18.3a	12.03a	0.402	3.0a
5.4	1.3a	0.7a	135.9a	2.2a	15.8a	19.7a	12.25a	0.475	2.3a
0.0	1.4a	0.7a	146.0a	1.8a	16.8a	21.3a	11.80a	0.535	1.4a

*Numbers within the same column, study site and species group followed by different letters are significantly different at the .05 level (L.S.D.).

Table 68. Linear regression equations correlating physical parameters with sludge treatment rates

Parameter	Regression equation $y = mx + b$	Coefficient of determination r^2
Udell site		
Litter dry wt. (1976)	$y = 175.3x + 1,649$	.99
Litter dry wt. (1977)	$y = 186.2x + 2,153$	.99
Understory dry wt. (1977)	$y = 1.09x + 33.9$	.33
Fasicle dry wt. (1977)	$y = 0.0014x + 0.0527$	.71
Needle length (1977)	$y = 1.79x + 96.6$	.86
Pine River site		
Red pine		
Litter dry wt. (1977)	$y = 77.2x + 1,951$	.83
Understory dry wt. (1977)	$y = 1.66x + 21.0$	.78
Fasicle dry wt. (1977)	$y = 0.0011x + 0.044$	.997
White pine		
Litter dry wt. (1976)	$y = 95.1x + 1,367$	.90
Ann. radial increment, breast ht. (1976)	$y = 0.04x + 1.81$	.99
Ann. radial increment, breast ht. (1977)	$y = 0.04x + 1.57$	.94
Radial growth at base of live crown (1976-77)	$y = -0.11x + 7.02$	.96

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