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Sludge Fertilization of State Forest Land in Northern Michigan

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FOREWORD

The U.S. Environmental Protection Agency (USEPA) was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment.

The Great Lakes National Program Office (GLNPO) of the U.S. EPA was established in Chicago, Illinois to provide specific focus on the water quality concerns of the Great Lakes. The Section 108(a) Demonstration Grant Program of the Clean Water Act (PL 92-500) is specific to the Great Lakes drainage basin and thus is administered by the Great Lakes National Program Office.

Several demonstration projects within the Great Lakes drainage basin have been funded as a result of Section 108(a). This report describes one such project supported by this office to carry out our responsibility to improve water quality in the Great Lakes.

We hope the information and data contained herein will help planners and managers of pollution control agencies to make better decisions in carrying forward their pollution control responsibilities.

Director
Great Lakes National Program Office

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SLUDGE FERTILIZATION OF STATE FOREST LAND

IN NORTHERN MICHIGAN

by

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ABSTRACT

A five-year research-demonstration project to examine the logistic, economic, environmental and sociological aspects of municipal wastewater sludge application was conducted on State Forest land occupied by forest types of major commercial importance in northern Michigan. The procedures utilized for site preparation, sludge transportation and sludge application proved to be cost-effective and made possible uniform distribution of sludge upon the forest floor. Sludge applications averaging 9 Mg/ha (4 tons/acre) provided nitrogen additions of 531 kg/ha (473 lbs/acre) and phosphorus additions of 300 kg/ha (267 lbs/acre). Sludge applications resulted in increased levels of nutrients in forest floor and vegetation. Tree diameter, basal area and biomass growth increased as much as 78%, 56% and 57%, respectively. Leaching losses of nitrate-nitrogen and heavy metals were minor and did not degrade groundwater quality. Sludge nutrient additions increased the structural complexity of wildlife habitat and improved the nutritional quality of important wildlife food plants. Wildlife numbers and browse utilization increased on sludge fertilized areas. Food chain biomagnification studies found no significant risk of heavy metal transfer to wildlife or humans. Public preference among various sludge management alternatives is a direct result of the perceived level of protection each affords public health and environmental quality. While residents do not hold strong opinions concerning forest land application, it was their second most often preferred alternative, following incineration. As the public comes to recognize the environmental hazards and economic limitations inherent with incineration and the value of sludge as a byproduct resource, forest land application should receive increasing attention as a major sludge management alternative. State regulatory and resource management authorities are committed to use of this newly developed technology in addressing waste management and land management issues.

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ACKNOWLEDGEMENT

A multidisciplinary research-demonstration examining complex land management, environmental and sociological questions requires the cooperative interaction of numerous groups and individuals. While responsibility for achieving final objectives rests with the Project Manager, credit for success must be accorded those at the federal, state and local levels whose participation made the project possible. The author wishes to recognize and extend appreciation to the following who contributed their funding, ideas, time and labor.

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INTRODUCTION

Production of wastewater sludge has become a problem of growing proportion in the United States during recent decades. Expanding industrialization, population growth in urban and suburban areas and legislation requiring a higher standard of treatment for wastewater have resulted in increased generation of waste residuals which require periodic removal from treatment facilities. National sludge production near 3.6 million Mg (4 million dry tons) in 1970 (Walsh 1976) has increased to 6.4 million Mg (7 million dry tons) currently (Maness 1987) and is expected to double again by the year 2000 (Bastian 1988). Total discharge of domestic sewage in 1975 was 90.5 billion liters (24 billion gallons), a volume which contained approximately 733 million kg (1.6 billion lbs) of nitrogen, 674 million kg (1.5 billion lbs) of phosphorus and 428 million kg (942 million lbs) of potassium (Freshman 1977). The value of these nutrients amounted to 561 million dollars. Sludge is currently generated as a byproduct of wastewater treatment in 15,378 facilities nationwide (USEPA 1985).

Combined residential and industrial water use in Michigan has resulted in the annual production of 202,500 Mg (223,218 dry tons) of sludge by 199 municipal wastewater treatment plants (MDNR 1986). While traditional strategies for managing this residual waste have emphasized disposal options such as incineration and landfilling, sludge management programs developed since 1978 have increasingly identified nutrient utilization through the practice of land application. Approximately 57,200 Mg (63,000 dry tons) of wastewater sludge are presently used throughout the state as a soil amendment. Most of this residual byproduct is applied as a fertilizer of grain and forage crops grown on farm land; however, an increasing proportion is being recycled on forest land in northern regions of the state where suitable farm sites are less available.

To facilitate proper implementation of forest land application programs by communities and industries in northern Michigan, federally sponsored research studies conducted during the recent decade have aided in development of guidance criteria which provide for productive utilization of nutrients and organic matter contained in sludge and protection of the public health and environment. This report summarizes much of that research effort, documents conclusions which have been used as a basis for regulatory guidance and outlines a strategy for implementation of forest land application technology within existing environmental protection and resource management programs.

SUMMARY

In 1981, forest stands of aspen coppice, oak, pine and northern hardwoods growing on sandy soils in Montmorency County north of Atlanta, Michigan were selected in which to conduct a five year, $1.1 million U.S. Environmental Protection Agency (USEPA) sponsored research-demonstration project that examined the technological, environmental and sociological aspects of fertilizing forest land with wastewater sludge. This project was an extension of research initiated (and later discontinued) by the North Central Forest Experiment Station of the USDA Forest Service. The project was intended to serve as a bridge between the small plot studies of the Forest Service and the eventual large scale implementation of operational programs by local communities and industries.

Conduct of this multidisciplinary study required the participation of numerous individuals and groups at a variety of levels. Research studies were conducted by scientists from Michigan State University (MSU) in the Department of Forestry and Department of Fisheries and Wildlife. Research efforts were overseen by and coordinated through staff of the Michigan Department of Natural Resources (MDNR). Site selection was coordinated through local units of government and regional planning organizations. Site preparation and sludge application were performed by private contractors and coordinated through MDNR staff.

Following several years of study, we may conclude that forest land application has been shown to be a cost-effective, innovative management alternative for sludge generated as a byproduct of wastewater treatment. When appropriate quality control, application rates, site selection and program management are utilized, forest land application provides numerous benefits such as improving wildlife habitat and increasing forest productivity, while providing adequate protection for the environment and public health. Through these and related research studies, forest land application has been developed into an attractive silvicultural opportunity, especially when one recognizes that this byproduct resource is typically furnished to the land manager without charge.

TECHNOLOGICAL

During the fall of 1981 and early summer of 1982, 3,679,311 liters (972,077 gallons) of liquid (2.6 to 5.1% solids) anaerobically digested wastewater sludge were transported from Alpena and Rogers City a distance of 80 km (50 miles) by tank truck and applied to the forest floor of the four sites located on the Mackinaw State Forest. Prior to application, access trails at intervals of 20 m (66 feet) were created on each site by removal of existing trees, those of merchantable size being offered through the timber sale process. Sludge application was conducted using an all-terrain tanker vehicle equipped with high flotation tires, a standard pressure-vacuum pump and a series of nozzles designed to laterally disperse liquid sludge in a uniform pattern.

The sludge application rate received by the aspen site averaged 10 Mg/ha (4.5 tons/acre) resulting in respective nitrogen and phosphorus additions of 561 and 291 kg/ha (500 and 260 lbs/acre). The oak site was treated with a sludge rate of 8 Mg/ha (3.6 tons/acre) resulting in respective nitrogen and phosphorus additions of 401 and 272 kg/ha (358 and 243 lbs/acre). The sludge application rate delivered to the pine site averaged 8 Mg/ha (3.6 tons/acre) resulting in respective nitrogen and phosphorus additions of 379 and 253 kg/ha (338 and 226 lbs/acre). The northern hardwoods site received an application rate of 9 Mg/ha (4 tons/acre) resulting in respective nitrogen and phosphorus additions of 783 and 384 kg/ha (699 and 343 lbs/acre). Application rates of heavy metals were low on all sites.

The procedures developed for site preparation, sludge transportation and sludge application were highly effective in achieving the logistical aims of providing suitable site access for the application vehicle, prompt sludge delivery to the unloading area and uniform distribution of sludge upon the forest floor. These tasks were accomplished at costs that were comparable with those of other sludge management options. Unavoidable mechanical difficulties were not encountered in the process of applying sludge on these forest areas.

Costs for transportation and application of sludge totaled $48,576 ($303.52 per Mg or $275.94 per dry ton). This amount would be typically borne by the generator as an operational cost for sludge management. Costs normally incurred by the land manager would include those for site preparation. The land manager, however, would realize a net gain from sale of timber plus a value added to his site from sludge nutrients. The average value of the major macronutrients and trace elements contained in the sludges used in this study was \$46.07 per Mg (\$41.88 per ton), which provided a value addition of \$406.87 per ha (\$162.72 per acre). Benefit-cost ratios for full scale forest land application programs are anticipated to exceed the 1.47 value computed for this demonstration.

ENVIRONMENTAL

Nutrients delivered with sludge application to the forest floor were readily taken up by overstory trees and understory vegetation. The nutrient status of trees was improved as seen by increased levels of foliar nitrogen and phosphorus. Sludge treatment resulted in increased growth in tree diameter (aspen 23%, oak 78%, pine 25%, northern hardwoods 48%), basal area (aspen 48%, oak 56%, pine 36%, northern hardwoods 48%) and biomass (aspen 57%). An average 29% increase in long term tree volume growth (1.05 m^3/ha/yr) was predicted to continue as long as site nutrient levels are maintained by periodic reapplications of sludge.

Aspen mortality from infections of naturally occurring Armellaria, Fusarium and Cytospora fungi increased three fold following sludge application. This increase was not a direct result of sludge addition, but rather, a result of site preparation leading to increased sunscald on tree bark and increased breakage of stems which were heavily browsed by elk seeking foliage of higher nutrient value. These injuries predisposed young aspen to infection by fungi.

Compositional changes in understory vegetation did not result from sludge application. Sapling growth was improved on the aspen and oak sites but not on the pine or northern hardwoods sites. Seedling regeneration was increased on all treated sites, indicating that increases in groundcover vegetation (forbs, sedges, grasses) did not compete substantially with tree seedlings.

Fluctuations in forest floor weight, resulting from loading of sludge nutrients and organic matter, subsequent increases in microbial decomposition and recycling of plant parts in litterfall, were observed. Overall increases in forest floor weight and nutrient and trace element levels were proportional to sludge application rates. Significant increases for several elements in the 01 and 02 horizons were noted to persist throughout the study. The total amount of heavy metals present in the forest floor was quite small. The 02 horizon comprised 95% of the total forest floor mass and was the major repository for nutrients and trace elements. Very little change was noted in the chemical composition of surface and subsurface soils. Three years following sludge application, most nutrients and trace elements were either retained in the forest floor or had been taken up by vegetation.

Soil water and groundwater data indicated that small increases in nitrate-nitrogen movement below the plant rooting zone occurred within 6 to 18 months following sludge application. Nitrification of ammonia present in the sludge produced a modest surplus of nitrate which, when not assimilated by vegetation, was leached during periods of recharge. Average levels of nitrate leaching during these periods generally were well below the USEPA potable water standard of 10 mg/l and declined rapidly to near background in subsequent seasons. Minor leaching losses of calcium, magnesium, potassium and sodium cations occurred along with nitrate anion movement. However, leaching losses of zinc, manganese, cadmium, boron, copper, nickel and chromium to groundwater did not occur. The sludge application rates used in this study balanced element addition with ecosystem assimilation capacity and therefore posed no danger to the groundwater resource.

The structural and nutritional properties of wildlife habitat were significantly improved by sludge application. Vertical cover increased in 88% of the plant species present in the lower 2 m (6 feet) strata and horizontal cover (stem density) increased in 56% of the plant species. Increases up to 200% were measured in the annual primary production of herbaceous species. Deer and elk were observed to browse more heavily on sludge treated areas. Within one year following sludge application, significantly increased levels of protein (20 to 50%) and phosphorus were present in forage. Protein is a critical factor in the nutrition of deer and may typically limit fawn production in many areas. Population numbers of small mammals increased as much as 100% following sludge application. Similar improvements in habitat structure have been associated with increases in bird species diversity in temperate climates.

Food chain studies conducted in the field and laboratory indicated that forest land application of good quality sludges poses very little risk for biomagnification of heavy metals.

Tissue bioassays of free ranging small mammals in the field indicated that no accumulation of toxic metals was present. Small mammals confined to a laboratory diet of sludge grown forage showed very small, statistically nonsignificant accumulations of cadmium and zinc in liver and kidney tissue. Whitetail deer harvested from sludge treated field sites possessed slightly elevated levels of cadmium and zinc in liver and kidney tissue, but these were well below concentrations known to be hazardous to vertebrates. Woodcock confined to a laboratory diet of sludge-raised earthworms accumulated elevated levels of cadmium in liver and kidney tissue; however, these levels were below those hazardous to vertebrates. As sludge application is excluded by regulation from lowland forests where free ranging woodcock feed and liver and kidney tissues are discarded prior to consumption, the food chain risk to humans is minimal from forest land application.

SOCIOLOGICAL

A public opinion survey of forested counties in northern Michigan indicated that, while two-thirds of residents believe sludge generation to be a significant problem for cities and industries, a major portion were undecided about the practice of forest land application. The absence of strongly held opinions was attributed to very little technical information concerning the risks and benefits of various sludge management alternatives being available to the public. Developing effective public involvement on this issue may therefore be done through remediating deficient rather than inaccurate knowledge.

With current public knowledge, human health and environmental quality are of greatest concern and economics and esthetics of least concern to residents. Public preference among sludge management options is a direct result of the perceived impact each will have first on human health and second on environmental quality. Although forest land application is the second most preferred sludge management alternative, incineration is most preferred only because of the perceived human health protection it offers. When the public becomes aware of the major health, environmental and economic limitations inherent with incineration, forest land application will likely become their principal sludge management preference.

Forest land application of sludge is an emerging natural resource management issue which has not reached disruptive status with development of strongly polarized interest groups. To avoid its development to a disruptive level, forest land application proposals must not be introduced into the planning process as preformed alternatives to be accepted or rejected. Rather, the public must recognize that no decision will be made until they have had opportunity to learn about, participate in evaluation of and influence the final selection among the full range of options.

A booklet has been developed during this study, "The Sludge Solution: Comparing the Alternatives", which discusses in nontechnical terms the benefits and risks inherent in each sludge management option. This document will aid the public in gaining access to correct information concerning the issue. A second booklet, "A Manual for Public Involvement in Planning Sludge Management Programs", provides those groups planning sludge management programs with guidance on how to facilitate effective public input and makes available to the public background for providing effective input in the planning process.

Citizens are willing to take responsibility for management of sludge generated in their own communities, but most do not wish to have their locale become a dumping site for distant communities. Because of this prevailing view, forest land application programs should restrict sludge use to that from local sources. However, this attitude may change as education programs persuade the public to perceive sludge as a byproduct resource rather than waste.

REGULATORY SIGNIFICANCE

During the recent decade, MDNR Land Application Unit staff have developed a statewide program which has produced solutions for the effective management of residuals generated as byproducts of waste treatment. Initially the program focused upon agricultural land application of municipal wastewater sludges, but eventually gained responsibility for recycling numerous waste treatment byproducts on a variety of lands. With conclusion of this research study, unit staff have set in place systematic standards for the safe use of forest land as a waste management option. Criteria have been developed for sludge quality, site selection, sludge application rates and program management procedures. Public participation has been identified as essential to local program success.

Studies in the Pacific Northwest, Southeastern and Northeastern United States have demonstrated that sludge application can be successfully practiced in a variety of forest environments. However, characteristics of climate, topography, soil and vegetation unique to each region require that land application techniques and regulations be tailored to meet the needs of practitioners in a specific environment. Guidelines developed from research in Michigan should therefore be used with caution outside the Great Lakes Region and with special attention to environmental conditions prevailing in each specific locale.

Forest land application represents to the waste generator an additional sludge management alternative, but to the forest land owner and manager it is a land management opportunity to economically fertilize forest stands, increasing timber production and improving wildlife habitat. Practice of forest land application on public land will require the coordinated effort of staff in Forest Management Division, Wildlife Division and Environmental Protection Bureau with municipal or industrial generators and local elected officials. Despite circumstances which may complicate local program implementation, resource managers have expressed interest in adding forest land application to their array of land management tools.

Land Application Unit staff will continue their function in providing technical assistance to waste generators and disseminate information on forest land application to all segments of the interested public. Cooperative Extension workshops will continue as will agency training sessions and informational seminars. The technical and sociological data from local forest land application programs will be reviewed and used to refine the statewide program. Funding will also be sought to further research in the areas of long term site responses and environmental fate of organic chemicals.

BACKGROUND

HISTORICAL DEVELOPMENT

Traditional approaches to sewage disposal have primarily relied upon dilution via discharge into available surface waters. Since the beginning of the industrial revolution, growing populations have largely compounded the degree of water quality degradation. Section 13 of the Rivers and Harbors Act of 1899 represented the first attempt in the United States to prohibit discharge of waste into navigable waters; however, this law suffered from lack of enforcement (Sullivan 1973). The Water Pollution Act of 1948 gave states the primary enforcement responsibility in water pollution cases with assistance provided by the federal government. This law also lacked substance until passage of the Federal Water Pollution Control Act of 1956 which authorized large scale grants to assist states in planning and building wastewater treatment facilities.

Growing public awareness of the national environmental crisis resulted in passage of the National Environmental Policy Act of 1970, which sought to eliminate the practice of sludge discharge into surface waters (Sullivan 1973), and the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500), which focused attention on the need to develop waste management techniques that are cost-effective and environmentally sound (Morris and Jewell 1977). While section 301 of PL 92-500 required all wastewater to receive secondary stage treatment, thereby increasing sludge production, sections 402 and 403 discouraged sludge disposal in surface waters. Land application of wastewater sludge was cited as a major alternative for eliminating nutrient rich discharges into surface waters.

CURRENT ISSUE

Preliminary research and experience with sludge additions to farm sites have identified land application as an innovative, cost-effective technology for environmentally sound waste treatment (Forster et al. 1977). Increased crop production, improved soil fertility and a direct cost savings to farmers from decreased dependence on petroleum-based commercial fertilizers are nearly universal benefits of land application. As the popularity of agricultural land application has grown, it is likely that few individuals have not consumed foods produced on sludge fertilized soil.

Although farm land is most often selected for sludge application and has received more study in this regard, forest land offers several unique advantages in terms of site characteristics, ecological structure and mode of nutrient cycling (Smith and Evans 1977). Numerous industries and communities in northern Michigan have little farm land available for sludge recycling. In this locale are millions of hectares of forest land which could serve as sites where sludge nutrients and organic matter could be utilized to increase forest productivity and improve wildlife habitat (Brockway and Nguyen 1986).

Forest crops, ie., wood products, are generally nonedible, thereby diminishing the risk of human exposure to elements which may be hazardous in the food chain. The long term accumulation of biomass on a forest site provides substantial storage capacity for elements applied in sludge over the length of a crop rotation. The harvest of tree boles and whole trees offers a means of removing sludge-applied elements from the treated forest site. Forest soils are generally porous, resulting in minimal surface runoff of applied nutrients, and usually nutritionally impoverished, providing opportunity to substantially increase soil organic matter and nutrient levels through sludge additions. Native forest plants, though adapted to low ambient nutrient levels in forest soils, have demonstrated their ability to respond with nutrient and biomass increases following fertilization with sludge (Brockway 1983, Henry and Cole 1983, Zasoski et al. 1983, Wells et al. 1984). Forest sites are also typically remotely situated from large population centers and used for dispersed recreational activities, minimizing the opportunity for direct human contact with recently applied sludge.

Despite the apparent benefits of recycling nutrients through forest land application, numerous concerns have been raised about the potential hazards to public health and the environment. The possible presence of pathogens, heavy metals and toxic organic compounds in sludge are leading health concerns. Nutrient enrichment of groundwater and contamination of wildlife, soil and groundwater by toxic metals and organic chemicals are major environmental quality concerns. Prior to implementation of full scale operational programs, a research assessment of numerous forest types in Michigan was needed to establish suitable sludge application rates based upon corresponding sludge composition and evaluate application impacts upon wildlife, vegetation, soil and water resources.

MANAGEMENT OBJECTIVES

A major function of the Michigan Department of Natural Resources in carrying out its mission in environmental protection and resource management is to encourage wise resource utilization. When the two major components of that mission can be coordinated in beneficial fashion, there exists a special opportunity to serve the public interest. Sludge is generated as a potentially valuable byproduct of wastewater treatment, a process which clearly serves to promote water quality and enhance the environment. While wastewater sludge has in the past been routinely discarded in landfills as a supposedly useless waste, MDNR staff specialists have, in recent years, recognized the numerous benefits to be gained by recycling sludge on land.

As fossil fuel costs rise, incineration has become increasingly prohibitive technology for sludge treatment. Recognition that potentially toxic constituents are directly released as emissions to the atmosphere during incineration has warranted further caution, as concern increases about the hazards of cross media transfer. Landfill capacity for storage of incinerator ash and dewatered sludge is also diminishing as public agencies, local governments and residents have begun to appreciate the risks involved in concentrating wastes in structures built into geologic material which may be relatively unstable or quite permeable over the long term.

Where sludge has been utilized as a soil amendment, industrial and municipal wastewater treatment facility managers have realized immediate savings, from their perspective as being responsible for selecting least cost alternatives for residuals disposal. Land owners and managers applying sludge on their soils also receive a cost benefit in terms of dollars saved that would have otherwise gone for the purchase of expensive petroleum-based commercial fertilizers. The average nutrient value of each dry Mg of a typical sludge is approximately $26.31 ($23.92 per ton). At a 9 Mg/ha (4 tons per acre) application rate to the typical 40 ha (100 acre) farm an annual fertilizer savings of $9500 would be realized by the land owner. Crop productivity and soil fertility increases are additional benefits. As this nutrient rich byproduct is prevented from reaching surface waters and recycled on the land, the entire environment benefits.

Forest land application appears to hold a similar promise in completing the nutrient cycle for the economic and environmental benefit of society. It is also a special opportunity for MDNR to encourage utilization of a byproduct of an environmental protection program to the benefit of resource management programs in forestry and wildlife. In 1980, MDNR initiated a cooperative research-demonstration project with the U.S. Environmental Protection Agency and the Department of Forestry and Department of Fisheries and Wildlife at Michigan State University to further evaluate forest land application as a technology for operational use in Michigan. The major study objectives were to assess sludge constituent effects upon (1) plant productivity and nutrition, (2) soil fertility, (3) water quality and (4) wildlife habitat, nutrition and population dynamics. Additional objectives included (1) evaluation of forest land application methodology and equipment, (2) analysis of costs and (3) assessment of public acceptance and need for educational materials. Guidance criteria developed from this and related research would be incorporated into agency environmental and resource programs.

INVESTIGATIVE APPROACH

EARLY STUDIES

Advances in science and technology are typically built upon the foundation of work which has preceded. The current state of knowledge concerning forest land application is no exception. The first studies which used wastewater sludge applications in the forests of Michigan were conducted by the North Central Forest Experiment Station of the USDA Forest Service near Cadillac on the Manistee National Forest.

Beginning in 1975, aspen and pine forest types were fertilized with a range of sludge rates up to 46 Mg/ha (20 tons/acre) to determine maximum application rates which could be safely used in these ecosystems (Urie et al. 1978). Vegetation growth and chemical composition, soil fertility and leachate and groundwater chemistry were carefully monitored on these sites (Harris 1979, Brockway 1979). Regression analysis of soil leachate and groundwater data with USEPA water quality standards estimated safe maximum sludge application rates at 9.5 dry Mg/ha (4.2 tons/acre) to 19 dry Mg/ha (8.5 tons/acre) depending upon forest stand conditions and sludge chemical composition (Brockway and Urie 1983). Improved foliar nutrition and increased vegetation growth were noted in proportion to sludge application rate (Brockway 1983, Urie et al. 1984).

As encouraging as these preliminary studies were, they were conducted on small plots less than 0.2 ha (0.5 acre) in size and left unanswered questions related to mass effects from treatment of larger areas or entire watersheds as in the conduct of full scale operational sludge recycling projects. Also left unanswered were questions concerning the effects of repetitive sludge applications and their long term impact upon forest growth, wildlife and water quality. In the early 1980s, a rearrangement of funding priorities within the Forest Service led to termination of this valuable environmental research effort.

RECENT STUDIES

Interest in forest land application continued into the decade of the 1980s. However, numerous unanswered questions delayed implementation of full scale operational programs. Municipalities as well as industries (primarily involved in forest products) requested assistance in developing this sludge management alternative. In March 1980, MDNR applied to the Great Lakes National Program Office of USEPA for an assistance grant which would allow movement from small plot research to research-demonstration on larger operational scale plots in continuing development of forest land application technology. By mid-year, approximately one million dollars was committed to a cooperative research and development effort which was to span a period of at least five years. The terms of funding were 75 percent federal and 25 percent state awarded annually, based upon task accomplishment during the previous year and availability of federal funds. Michigan DNR staff from resource management as well as environmental protection programs contributed to completion of numerous project planning and design tasks. These included Forest Management Division, Wildlife Division, Land and Water Management Division and Water Quality Division. Several research scientists from Michigan State University were retained as principal investigators for their expertise in the disciplines of forest ecology, soils, hydrology, biometrics, pathology, wildlife ecology and citizen involvement in natural resource issues. The efforts of these researchers and their assistants and the use of the computer and laboratory facilities in the Department of Forestry and Department of Fisheries and Wildlife were crucial to completion of the research aspects of the project.

The comprehensive research-demonstration project sponsored by USEPA was the only vehicle by which forest land application technology could be further developed in Michigan. It represents a complex cooperative effort of many levels of government as well as educational institutions and citizen groups. Its findings are interesting, in some ways surprising and provide, in combination with other forest research, a solid basis for present regulatory guidance. This project will serve as the focus for discussion in subsequent sections of this report.

METHODS

SITE SELECTION

In addition to a thorough chemical analysis of the sludge, selection of suitable sites is of foremost importance to proper implementation of any forest land application project. Assessment of hydrology, physiography, soil physical and chemical properties and the vegetation present are all essential components of the site selection process. The proposed crop nutritional needs and soil fertility levels are also the primary factors determining sludge nutrient application rates. As this process is undertaken in the context of protection for the public health and environment, site selection must also be concerned with proximity to dwellings, public highways, surface waters and water supply wells.

Related Studies

As originally proposed, the research-demonstration was conceived as a means of assessing the effects of forest land application of a sludge which had previously received much study as an amendment to agricultural soils. The value of this approach would have been to diminish much of the variation inherent in using sludges from different sources, use an already established data base and facilitate comparisons between responses of farm and forest sites to application of a single sludge. The original candidate sludge source was the City of Jackson wastewater treatment facility.

Jackson, with a population of approximately 40,000, contains a moderate industrial base which results in production of a wastewater sludge containing moderately elevated levels of heavy metals. The City staff have for numerous years conducted a carefully monitored farm land application program which, despite the presence of heavy metals, was recognized for a record of productive achievements and protection of health and environment. Liquid sludge from the Jackson facility was to be transported by tank truck to application sites on State Forest land in northern Lower Michigan.

Technical Criteria

The principal project aims were to evaluate the wildlife, hydrological, soil and vegetation responses following sludge application in forest types of major commercial importance in Michigan. Application rates indicated as environmentally safe yet biologically productive in earlier Forest Service research were also to be tested on a larger scale in these forests. The forest types identified as being of major commercial value in this region were aspen, oak, pine and northern hardwoods.

Michigan DNR staff sought to locate an area of State Forest where these four forest types occurred in reasonably close proximity to one another to minimize planning and logistical problems. The types also needed to be located on sites meeting the criteria for physical environment which would ensure adequate protection for health and environment. In addition, the forest stands had to be of a condition where they were free of disease and insect infestation, fully stocked and competitively free to grow. Special attention was paid to access road system suitability and personal concerns of local residents.

By late 1980, MDNR staff completed an evaluation of State Forest land, screening candidate sites with reference to numerous technical criteria suiting them to the study objectives. This assessment included examination of maps, aerial photographs and actual field sites on four State Forests in consultation with Forest Management Division staff. At this time, sites in eastern Kalkaska County were identified as best meeting the biological, physical and logistical criteria. In January 1981, site preparation and the process of citizen involvement began.

Public Involvement

In early January 1981, MDNR staff brought before the Kalkaska County Board of Commissioners a proposal for fertilizing State Forest land in the eastern county with sludge from Jackson, Michigan. The proposal was well received by commission members and complimented as being visionary and sound in concept. Soon after that meeting, an article appearing in an area newspaper initiated a public reaction against the proposal.

In early February, MDNR staff presented the project proposal at a public meeting attended by residents of Garfield, Oliver and Bear Lake Townships in eastern Kalkaska County. Citizen reaction to the study was less than enthusiastic. Resident concerns ranged from fears about toxicant levels potentially present in the sludge to general indignation about not being personally consulted prior to tentative site selection. Eastern Kalkaska County had also been in the 1970s a burial site for PBB contaminated cattle, an activity conducted by MDNR over the objections of many area residents.

After weeks of attending numerous township meetings, it became clear that while many area residents favored or did not oppose the forest land application project, the political fallout from previous experience with MDNR programs was yet an overriding factor in the decision of most local elected officials. Township decision makers did not trust MDNR to act in their best interest. The northward transport of downstate sludge was also perceived as of no direct benefit to county residents. In keeping with our promise to conduct the research-demonstration only in consenting townships and counties, MDNR staff turned in late April to the process of selecting an alternative location for the project.

By early May, northern Montmorency County had been identified as an area which also contained forest stands meeting the technical criteria for the study. In addition, a decision was made to only utilize sludge generated at wastewater treatment facilities (Alpena and Rogers City) in the locale. Contacts were initiated through local MDNR offices with members of the Northeastern Michigan Council of Governments (NEMCOG), Huron Pines Resource Conservation and Development Council, Montmorency Township and Montmorency County Planning and Zoning Commission in seeking support for conduct of the research-demonstration project. Michigan DNR staff presented audio-visual discussions of previous land application research, conducted field trips to research sites where sludge had previously been applied to forests, engaged in numerous informal discussions with area leaders and sought local advice in specific site selection. By August, formal resolutions of support were obtained from local governments and citizen groups. The relationship of trust and confidence developed between local authorities and MDNR staff was largely responsible for acquisition of support for the project and assistance in final site selection in Montmorency Township. The circumspect approach of local groups and individuals to the germaine environmental and resource management issues resulted in prudent action and avoidance of devisive polarization.

SITE DESCRIPTION

Sites selected on which to conduct the forest land application research-demonstration project were located in northern Montmorency County on the Atlanta Forest Area (Figure 1) of the Mackinaw State Forest in northeastern lower Michigan (45^{o}N,84^{o}10'W). Site characteristics are summarized in Table 1. Vegetation on each site was representative of the upland forest types of major commercial importance in the northern portion of the state. Permeable glacial drift materials formed the parent material for the soils, which are low in native fertility and allow rapid infiltration of excess precipitation falling on all four of the forest sites. Annual precipitation in this area averages 766 mm (30 inches), with the equivalent of 160 mm (6.3 inches) incident as snow from late November to early April (NOAA 1982). The mean annual temperature is 5.8^{o}C (42.4^{o}F) with average extremes of -7.4^{o}C (18.7^{o}F) in January and 19.6^{o}C (67.3^{o}F) in July (NOAA 1981). The sites are underlain by a phreatic aquifer which is contiguous with the regional groundwater system. Elevation is approximately 300 m (985 ft) above sea level.

Aspen Site

The aspen site was occupied by a 10-year-old stand of coppice regeneration which was predominantly bigtooth aspen (*Populus grandidentata* Michx.) containing a secondary component of quaking aspen (*Populus tremuloides* Michx.), northern pin oak (*Quercus ellipsoidallis* L.), cherry (*Prunus spp.* L.) and other species. Soils on this site generally belonged to the Grayling series (Spodic Udipsammet) and the Rubicon series (Entic Haplorthod). Grayling soils are excessively drained and developed on deep glacial outwash sands (Table 2). Rubicon soils are deep, excessively drained and formed in sandy glacio-fluvial deposits. Surface runoff from the site does not occur as a result of high soil permeability. Surface emergence of groundwater occurs in the lowlands along Tomahawk Creek to the northwest of the site. Depth to groundwater at the study site was 5 to 8 m (16 to 26 feet).

Oak Site

The oak site was occupied by a 70-year-old stand that was a mixture of red oak (*Quercus rubra* L.) and white oak (*Quercus alba* L.) with red maple (*Acer rubrum* L.), scattered pines (*Pinus spp.* L.) and aspen. The stand (Table 3) contained 868 trees/ha

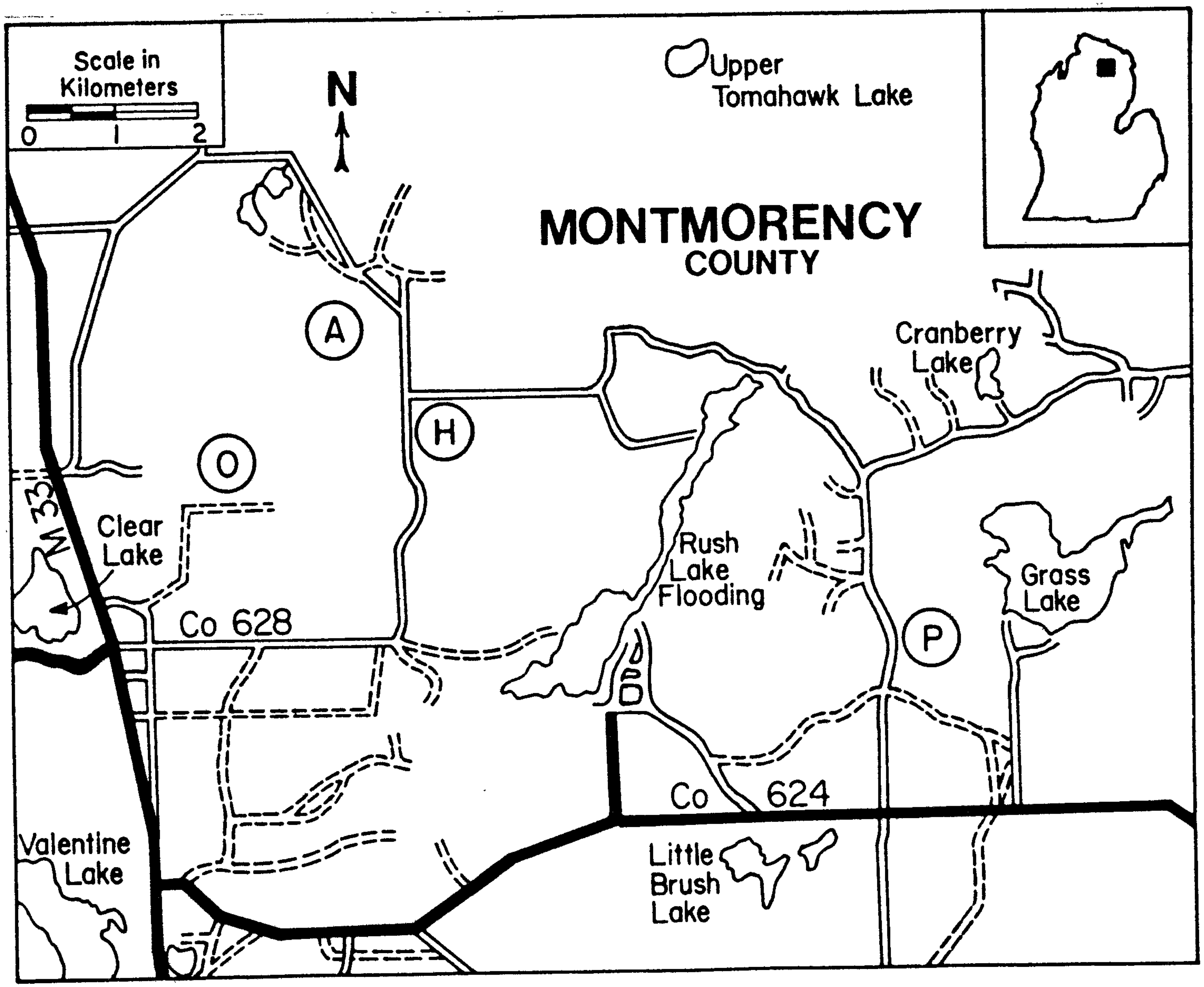

Figure 1. Sludge fertilization sites in northern Michigan.

Table 1. Characteristics of the aspen, oak, pine and northern hardwoods sites (Hart and Nguyen 1986).

Characteristic	Aspen	Oak	Pine	Northern Hardwoods
Physiography	Level to gently rolling	Gently rolling overwash moraine	Level plain	Gently rolling ground moraine
Geologic material	Sandy outwash over till	Sandy deposits over loamy till	Sandy outwash	Sandy and loamy till
Groundwater system	Groundwater at 5 to 8 m	Groundwater at over 25 m	Groundwater at 4 to 8 m	Groundwater at 1 to 16 m
Predominant soil series	Rubicon	Graycalm	Grayling	Mancelona and Melita
Soil group	sandy mixed, frigid entic Haplorthod	mixed, frigid alfic Udipsamment	mixed, frigid typic Udipsamment	sandy mixed, frigid alfic Haplorthod
Forest floor	Mull	Mull	Mor	Mull
Ground flora	Panic grass, brambles, sedge, sweetfern, bracken fern	Bracken fern, wintergreen, asters, Canada mayflower	Sedges, bearberry, lichens	Starflower, asters, violets, Canada mayflower
Overstory trees	Mixed bigtooth and quaking aspen	Mixed oak and red maple	Mixed red and jack pine	Red and sugar maple, yellow and white birch, beech and hemlock
Stand age	10 years	70 years	50 years	50 years, uneven age distribution

Table 2. Soil survey legend of sludge fertilization study area (Hart and Nguyen 1986).

Map Symbol	Soil Series	Soil Characteristics
Gy	Grayling	Excessively drained soil developed on deep glacial outwash sands
Gy-b	Grayling	Same as above, but with faint banding in the C horizon
Gr-b	Graycalm	Somewhat excessively drained soil formed in deep glacio-fluvial sands
Rb	Rubicon	Deep excessively drained soil formed in glacio-fluvial sands
Rb-s	Rubicon	Same as above, but with B_{hir} horizon
Rb-b	Rubicon	Same as above, but with sandy loam bands below 140 cm (55 inches)
Mt-w	Montcalm	Well drained soil formed in sandy and loamy glacio-fluvial upland deposits
Mt	Montcalm	Same as above, but with modal amounts of sand and loam in the C horizon
Ma	Mancelona	Deep excessively drained soil in sandy and gravelly glacio-fluvial uplands
Me	Melita	Deep somewhat excessively drained soil formed in sandy materials over loam
Mo	Menominee	Well to moderately well drained soils in sandy material overlying loam at 50 to 100 cm (20-40 inches)
Kw	Kawkawlin	Deep somewhat poorly drained soil formed in moderately fine textured glacial tills and ground moraines
Sm	Sims	Deep poorly and somewhat poorly drained soil formed in fine textured glacial tills and ground moraines

Table 3. Pretreatment tree stocking, diameter and density at the oak, pine and northern hardwood sites (Hart and Nguyen 1986).

Site and Species	Stocking (trees/ha)	DBH (cm)	Density (m^2/ha)
Oak site:			
All species	868	17.11	21.48
Red/black oak	287	18.88	9.32
White oak	228	14.33	5.83
Red maple	302	11.07	4.73
Other species	51	-	1.60
Pine site:			
All species	680	20.62	23.38
Jack pine	441	18.71	12.95
Red pine	225	19.13	10.07
Other species	14	-	0.36
Northern Hardwoods site:			
All species	720	19.06	22.23
Sugar maple	353	16.67	9.66
Red maple	161	10.14	4.53
Other species	206	-	8.04

(351/acre) and an average combined basal area of more than 21 m^2/ha (94 ft^2/acre). Soils were predominantly of the Graycalm series (Alfic Udipsamment) with smaller areas of the Rubicon series. Graycalm soils are somewhat excessively drained and formed in deep glacio-fluvial sands (Table 2). Surface runoff from the site does not occur as a result of high soil permeability. The site location on a high sandy morainal hill prevented successful drilling to the water table. Depth to groundwater at this study site was in excess of 30 m (97 ft).

Pine Site

The pine site was occupied by a 50-year-old plantation that was a mixture of jack pine (*Pinus banksiana* Lamb.) and red pine (*Pinus resinosa* Ait.). The stand (Table 3) contained 680 trees/ha (275/acre) and an average combined basal area of over 23 m^2/ha (102 ft^2/acre). Soils on the site were of the Grayling series with a smaller area of the Montcalm series (Eutric Glossoboralf). Montcalm soils are deep, well drained and formed in sandy and loamy glacio-fluvial deposits (Table 2). Surface runoff does not occur on this site because of its flat surface and highly permeable soils. The water table beneath this site slopes uniformly toward the east where groundwater emerges at Grass Lake 1 km (0.6 mile) away. Depth to groundwater at this study site was 6 to 7 m (20 to 23 feet).

Northern Hardwoods Site

The northern hardwoods site was occupied by a 50-year-old stand that was predominantly red maple and sugar maple (*Acer saccharum* Marsh.) with remnants of American beech (*Fagus grandifolia* Ehrh.), yellow birch (*Betula alleghaniensis* Britton) and white birch (*Betula papyrifera* Marsh.) and a minor number of red oak, American basswood (*Tilia americana* L.), white ash (*Fraxinus americana* L.) and eastern hemlock (*Tsuga canadensis* (L.) Carr.). The stand (Table 3) contained 720 trees/ha (291/acre) and an average combined basal area exceeding 22 m^2/ha (97 ft^2/acre). Soils were primarily Mancelona series, Melita series and Menominee series (Alfic Haplorthods) with minor areas of the Kawkawlin series (Aquic Eutroboralf) and Sims series (Mollic Haplaquept). Mancelona soils are deep, excessively drained and formed in sandy and gravelly glacio-fluvial upland deposits (Table 2). Melita soils are deep, somewhat excessively drained and formed in sandy materials overlying loamy deposits. Menominee soils are moderately well to well drained and formed in sandy material overlying loamy deposits at 50 to 100 cm (20 to 39 inches). Kawkawlin soils are deep, somewhat poorly drained and formed in moderately fine-textured glacial tills and ground moraines. Sims soils are deep, poorly to somewhat poorly drained and formed in fine-textured glacial tills and ground moraines. This study site is situated upon an area of relatively high elevation which is underlain by loamy sands and clay layers of low permeability. These materials cause periods of temporary flooding during spring snowmelt when the water table is at or near the soil surface and account for a groundwater gradient which slopes steeply to the west from the plots. Depth to groundwater at this study site ranged from 1 to 15 m (3 to 49 feet).

SITE PREPARATION

Prior to land application of wastewater sludge, each study site was prepared for treatment. The sequential steps in this process consisted of plot layout, baseline measurements and construction of access trails which would facilitate movement of application vehicles about each site.

Experimental Design

Three replications of three experimental treatments were assigned to completely randomized plots within each study site. The treatments consisted of (1) a control group of plots left undisturbed, (2) a group that underwent access trail development but received no sludge application and (3) a group that underwent access trail development and received a single application of liquid sludge. Experimental plots were each 1.5 ha (3.8 acres) in area and of a rectangular shape approximately 100 m by 150 m (328 by 492 feet). The study plots covered an area of 54 ha (132 acres), of which 18 ha (44 acres) were treated with nearly 4 million liters (1 million gallons) of wastewater sludge. The sludge application rate averaged 9 Mg of dry solids per ha (4 tons/acre). The design was suited to evaluate large scale operational procedures, equipment and costs while affording adequate area for a diverse array of environmental research studies (Brockway and Nguyen 1986).

Sampling and Measurements

Vegetation, forest floor and soil data collection was facilitated by use of a series of subplots designed in accordance with the ecological characteristics of each site (Hart and Nguyen 1986). Because of a lack of vegetation uniformity on the aspen site, twelve paired plots were installed across a range of tree heights and densities. Trees on each pair were assessed by species, diameter at breast height (DBH; 1.37m; 4.5 feet), crown class, condition, presence or absence of disease, total height, ground level diameter (GLD; 15 cm; 6 inches) and biomass. Sampling design for the oak, pine and northern hardwoods sites allowed evaluation of within plot thinning effects which might result from access trail construction. On subplots within each plot, trees greater than 10 cm (4 inches) DBH were assessed for species, DBH, crown class and condition. From these data, estimates of basal area, gross growth, mortality and net growth were calculated. Similar measurements were collected for saplings, defined as greater than 1.8 m (6 feet) tall and less than 10 cm (4 inches) DBH. Seedlings, defined as commercial species less than 1.8 m (6 feet) tall, were measured on 1 m^2 (11 ft^2) circular subplots. Ground vegetation, defined as grasses, forbs, shrubs or noncommercial tree seedlings, was measured as percent cover on 2 m^2 (43 ft^2) circular subplots. Foliar samples were collected from the upper sunlit crown of overstory trees during the fall season prior to leaf abscission to assess nutritional status and response to sludge nutrients. Forest floor samples partitioned into 01 (litter) and 02 (humus) layers were collected along with surface and subsurface soil samples on subplots in all stands. In 1981, 6300 trees were measured and tagged, 176 tree crown foliar samples collected, 1080 forest floor, surface and subsurface soil samples collected, 858 regeneration plots measured and 858 ground cover plots measured. Data from these analyses indicated that no significant differences existed among the study plots at each site prior to sludge application. Posttreatment sampling was continued annually.

Hydrological monitoring of the sites was accomplished through installation of a well network supplemented by pressure-vacuum lysimeters (Urie et al. 1986). Monitoring wells were inserted into the upper strata of the phreatic aquifer following drilling in unconsolidated glacial drift. The groundwater gradients were determined from static water table measurements. Lysimeters were installed at a depth of 120 cm (4 feet) in the soil. Water samples collected from the lysimeters represented dynamic changes in percolate as it moved through the plant rooting zone. Groundwater samples from the wells represented an integrated effect of all upgradient treatments. Samples were collected each week during spring and fall recharge periods and monthly during the summer and winter seasons.

Chemical analyses of water, soil, sludge and animal and plant tissues were conducted at the USDA Forest Service-Michigan State University Cooperative Analytical Laboratory in East Lansing. Concentrations of total Kjeldahl nitrogen, nitrate, ammonia, phosphorus, potassium, sodium, calcium, magnesium, sulfate, chloride, manganese, iron, boron, zinc, copper, nickel, chromium, cadmium, aluminum and other parameters were measured via Technicon autoanalyzer or plasma emission spectroscopy following various digestion and extraction procedures (Hart and Nguyen 1986, Urie et al. 1986, Haufler and Woodyard 1986, Haufler and Campa 1986). Data were unavailable for lead because of difficulty encountered with analytical equipment. However, previous work has shown lead to be strongly held in upland soils and less mobile than other heavy metals studied in these forest ecosystems. Laboratory participation in the USEPA quality assurance program ensured consistently high quality results from sample analysis.

Numeric analysis of data was performed using several data reduction software programs including Knowledgeman (Micro Data Base Systems 1984), Number Cruncher Statistical Systems (Hintze 1986) and Microstat (Ecosoft 1984). Analysis of variance and covariance, multiple regression analysis, non-parametric analysis and principal components analysis were among the data analysis techniques employed.

Wildlife studies were conducted both in the field and laboratory (Haufler and Woodyard 1986, Haufler and Campa 1986). Vegetation was examined to determine changes in habitat structure and species growth, composition and nutritive value. Nutritional properties of primary concern were fiber, crude protein and phosphorus levels. Small mammal (rodent) populations were monitored using baited live traps. Representative proportions of these populations were sacrified to allow chemical analysis of liver, kidney, humerus and leg muscle tissues. Three female whitetail deer (Odocoileus virginianus Zimmermann) were harvested from the sludge treated plots to allow chemical analysis of their liver, kidney, heart and skeletal muscle.

In the laboratory, two food chain studies were conducted. The first study grew rye grass (Lolium perenne) upon sludge treated soil and pressed the forage into food pellets which were fed to white-footed mice (Peromyscus leucopus) which were to be fed to great horned owls (Bubo virginianus) and red-tailed hawks (Buteo jamaicensis). The second study raised earthworms in sludge amended soil for 30 to 90 days then fed them to woodcock (Philohela minor) over a period of 30 days. Each bird consumed approximately 10,000 worms during this period. In the laboratory studies, unlike the field studies, sludge from the City of Detroit was substituted for the sludge from Rogers City. Sludge from the City of Alpena was used in the field and laboratory studies. Animals at all trophic levels of the food chain studies were sacrificed to allow chemical analysis of their liver, kidney, skeletal muscle and bone for accumulation of potential toxicants.

In addition to studies of the much emphasized physical environment, the social environment in relation to public acceptance of forest land application was also of prime importance to the success of this technology. Previous experience in the difficulties of siting land application projects underscored the need for a better understanding of citizen values, beliefs and attitudes. This effort was approached in two phases (Peyton and Gigliotti 1986). In phase I, public opinion surveys were developed and distributed to citizens selected at random within stratified groups residing in seven selected counties in northern Michigan. These survey instruments were accompanied by and followed up with correspondence explaining the purpose of the study, the importance of each individual's participation and use to be made of the information. Responses on returned questionnaires were tallied, interpreted and summarized. In phase II, the responses from the surveys were used to develop materials for public education and effective public participation in the forest land application planning process. The public education materials are factual summaries which provide the public with accurate information concerning land application and related sludge management alternatives. The public involvement manual will provide sludge generators and land managers with a clear understanding of their responsibilities in promoting constructive public participation and enlisting citizen support for local sludge management programs.

Access and Treatment

Prior to sludge application, a grid of parallel trails at 20 m (66 feet) intervals was prepared to facilitate application vehicle access and more uniform sludge distribution (Brockway and Nguyen 1986). The spacing interval for access trails was dictated by the maximum spray distance of the application vehicle and resulted in removal of 20 percent of the stand volume. Had equipment capable of discharging greater distances been available as in the Pacific Northwest studies (Henry and Cole 1983) and existing access used, little or no stand area would have been removed from production. Trees harvested from oak, pine and northern hardwoods sites were felled and removed as whole trees from the stand using a rubber-tired skidder. Because of their small unmerchantable size, trees on the aspen site were removed at the groundline with a bulldozer blade. Chenonquet Consulting Foresters of Hillman, Michigan worked in close cooperation with

MDNR staff to complete this task.

Anaerobically digested sludges from the municipal wastewater treatment facilities in Alpena and Rogers City were transported by tank truck to the demonstration sites, where single applications of liquid were sprayed on the forest floor. Applications were conducted in October and November 1981 on the oak and aspen sites and in June and July 1982 on the pine and northern hardwoods sites. An all-terrain vehicle, equipped with high flotation tires, a standard pressure-vacuum pump and a modified three nozzle spray system, was used for sludge application on each site (Figures 2, 3, 4, 5). Sludge Management Corporation of Washington, Michigan conducted both the transport and application of sludge on all sites.

LOGISTICS AND ECONOMICS

Site preparation to provide vehicle access in the stand is a major initial consideration in planning a forest land application program for wastewater sludge. If stands consist of young, unmerchantable age classes, site access may need be developed at a net cost to the land manager. Such was the case with the aspen coppice stand, in which trails were cleared at a cost of $1,485 ($163.91/ha or $66.36/acre) using a bulldozer. In contrast, a net income may be generated by harvest of timber growing in proposed access trails when trees are of sufficient size and quality. Following development of access trails on the pine, oak and northern hardwoods sites, net respective returns from sale of timber were $340 ($37.53/ha or $15.19/acre), $158 ($17.44/ha or $7.06/acre) and $140 ($15.45/ha or $6.26/acre). Where the services of consulting foresters were required in site preparation, a rate of $21 per hour resulted in a total fee of $3,973 ($109.63/ha or $44.38/acre) for the project.

Using one 32,000 liter (8,500 gallon) and two 23,000 liter (6,000 gallon) tank trucks, sludge was transported from the municipal wastewater treatment plants at Rogers City and Alpena, a distance of 80 km (50 miles) to each of the forest sites. Loading time at each treatment plant varied from 45 to 60 minutes for each truck and one-way transport time on the highway was approximately one hour. Onsite unloading for each truck ranged from 30 to 40 mimutes, resulting in a total delivery cycle of three to four hours per load. During a working day without mishap, each truck could complete three to four deliveries. More

Figure 2. Sludge application on aspen site.

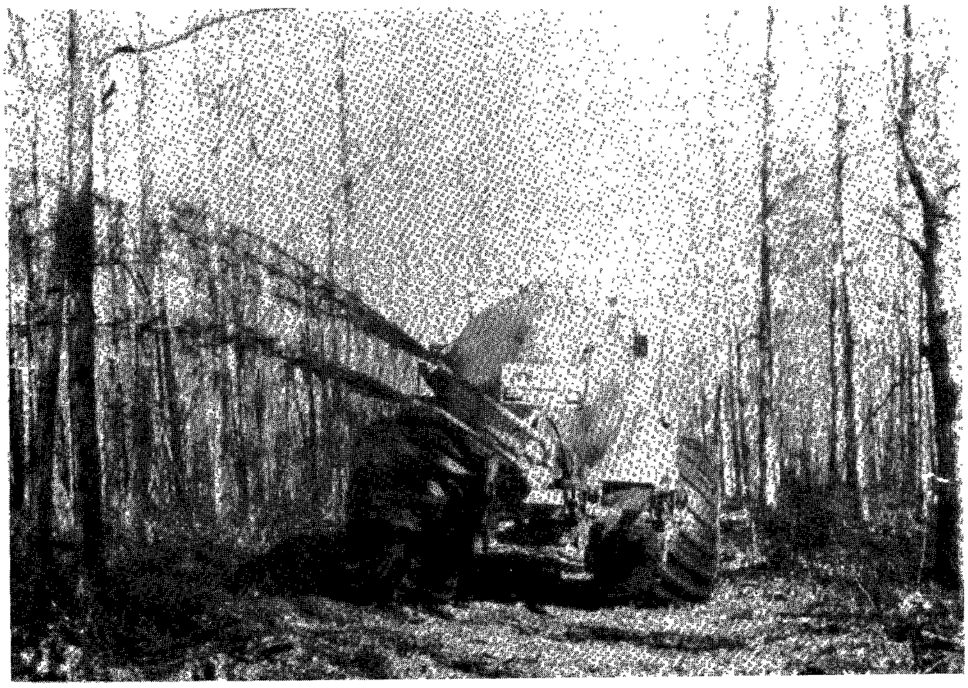

Figure 3. Sludge application on oak site.

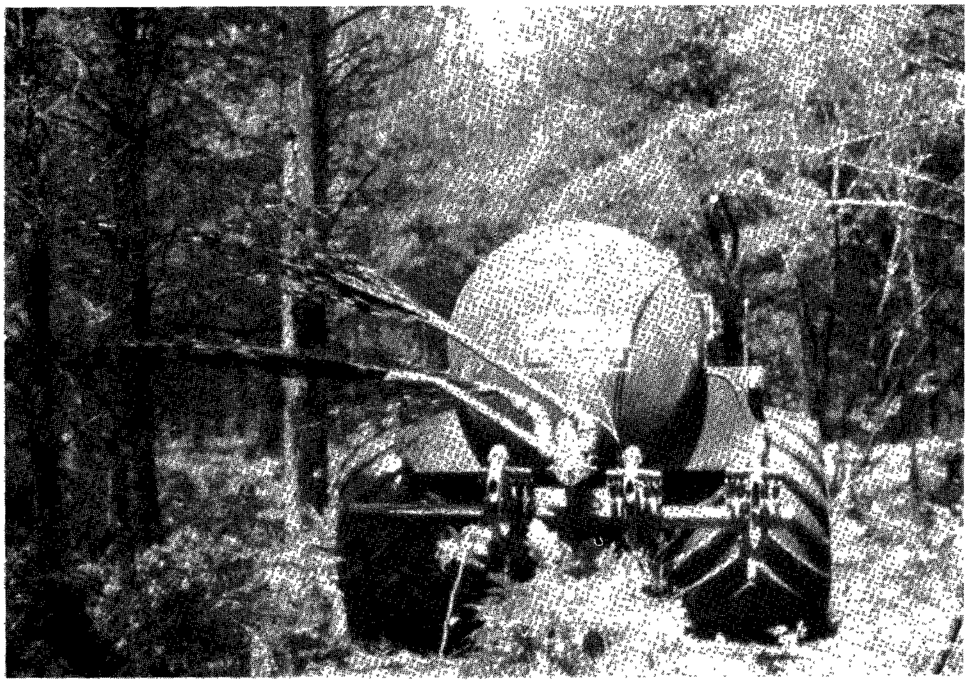

Figure 4. Sludge application on pine site.

Figure 5. Sludge application on northern hardwoods site.

typically, because of operational delays, daily sludge delivery rates averaged 147,615 liters (39,259 gallons) requiring a travel distance of 950 km (590 miles) and 18 man-hours during the 26 days on which sludge was transported.

Sludge application was conducted using an Ag-Gator 2004, manufactured by the Ag Chem Equipment Company of Minneapolis, Minnesota. This application vehicle was equipped with high flotation tires and a standard pressure-vacuum pump that was used to fill and empty its 8,300 liter (2,200 gallon) tank. Liquid sludge could be laterally discharged distances up to 10 m (33 feet) from one side of the vehicle through a modified spray system of three nozzles arranged to evenly cover near, intermediate and distant bands of the forest floor. This system can apply sludges approaching 12 percent solids, but was used here to apply liquids containing only 2.6 to 5.1 percent solids.

Contractual costs for transport and application of 3,679,311 liters (972,074 gallons) of liquid sludge totaled $48,576 ($303.52 per Mg or $275.94 per dry ton). This amount was equally apportioned by the contractor for transportation, application and administration (Table 4). Had this procedure been a sludge reapplication to a previously treated site, the contractor estimated a reapportionment of costs to 40% for transportation and 30% each for application and administration. The resultant lower total cost would be a product of less time needed in planning and greater efficiency in reapplication based on previous onsite experience.

While trafficability was satisfactory on most forest sites, pit and mound microtopography and high stumps remaining in trails at the completion of whole-tree skidding on the northern hardwoods site complicated application vehicle operation. Stumps caused the puncture of one high flotation tire and the generally rough terrain contributed to the eventual rupture of the hydraulic unit on the articulated steering mechanism of the application vehicle. Repair costs for these breakdowns totaled $4,070.

The cost of initial sludge transport and application to the four forest sites averaged 1.3 cents per liter (4.8 cents per gallon). If the expenditures for equipment repair are added, the total unit cost increases to 1.4 cents per liter (5.2 cents per gallon). When care in site selection, stand preparation and equipment operation are exercised, this cost increment for repairs can be minimized. If the expenditures for site preparation and service of consulting foresters are also added, the total unit

Table 4. Contractor cost breakdown for transportation and application (Brockway and Nguyen 1986).

	Initial Application	Subsequent Applications
Transportation	$16,515.84	$16,515.84
Labor	1,651.58	1,651.58
Equipment	11,561.09	11,561.09
Fuel	3,303.17	3,303.17
Application	16,030.08	12,144.00
Labor	1,603.01	1,214.40
Equipment	12,824.06	9,715.20
Fuel	1,603.01	1,214.40
Administration	16,030.08	12,144.00
Totals	$48,576.00	$40,803.84

cost increases to 1.5 cents per liter (5.6 cents per gallon) of sludge applied. When care is taken to select sites containing merchantable timber that will be harvested and sold in the course of developing access trails, this cost increase can also be abated. Had the procedure been a sludge reapplication to forest sites receiving periodic operational use, the total unit cost estimate would have approximated 1.1 cents per liter (4.1 cents per gallon).

These costs are comparable to those for sludge transport and application to farm land. Because the expenditures reported are for a research-demonstration project established to meet precise scientific criteria, the forest sites were located 80 km (50 miles) from the sludge source. Typical haul distances for operational sludge fertilization programs would more likely approximate 16 to 32 km (10 to 20 miles), proportionally reducing transportation costs. This decrease in program costs below those quoted above would make sludge application to forest land a highly attractive alternative.

Table 5. Assignment of cooperator benefits and costs.

Costs normally incurred by generator			$52,646.00
Sludge transportation	16,515.84		
Sludge application	16,030.08		
Equipment repair	4,070.00		
Costs normally incurred by land manager			5,458.00
Access trail development	1,485.00		
Consulting forester fees	3,973.00		
Value received by land manager			8,010.48
Sale of timber from access trails		638.00	
Fertilizer value of sludge nutrients		7,372.48	
Return from increased timber growth		not estimated	
Net value to land manager			$ 2,552.48
Benefit-cost ratio			1.47

Further, the costs related to creating stand access trails and those for repairing equipment subject to travel over stumps could be eliminated by careful planning during the establishment of a plantation scheduled to receive fertilizing applications of sludge at some future time. This could be accomplished by leaving one pair of unplanted seedling rows at 20 m (66 feet) intervals when a forest site is planted. The resultant system of parallel access trails would enable the stand to easily accommodate sludge application vehicles in the future and facilitate entry for intermediate silvicultural operations throughout the rotation.

The above analysis may be somewhat misleading from the standpoint of which parties normally bear which costs and derive which benefits from operational land application programs. Costs attributed to sludge transportation, application and equipment repair are typically assumed by the industry or municipality generating the waste byproduct (Table 5). These expenses are paid by the generator, in the course of selecting the least cost alternative for sludge management, as a portion of facility operation and maintenance. Costs incurred by the land manager are typically for site preparation services required to assist in access trail development. Benefits received by the land owner or manager include revenues from timber sold during trail construction, fertilizer value of sludge nutrients, improved quality of wildlife habitat and increased timber productivity which leads to greater revenue return when the stand is harvested. The average value of the nutrients and trace elements contained in these sludges was $46.07 per Mg ($41.88/ton), which provided a value addition of $406.87 per ha ($164.72/acre). Full scale operational forest land application programs would likely benefit the land manager with an even more favorable benefit-cost ratio than the 1.47 value estimated for this research-demonstration project with its numerous special constraints.

SLUDGE APPLICATION

Liquid sludges from the wastewater treatment facilities in Rogers City and Alpena were applied to the forest floor of the aspen, oak, pine and northern hardwoods sites in northern Montmorency County (Brockway and Nguyen 1986). These cities have very light industrial input into each municipal waste stream. Liquid sludges from Detroit and Alpena were applied to soils in laboratory food chain experiments conducted at Michigan State University. Detroit is widely known for its heavily developed industrial base and has been long thought to generate sludge with high levels of heavy metals and related contaminants.

SLUDGE COMPOSITION

The relative concentrations of macronutrients (N, P, K, Ca, Mg), micronutrients (Na, B, Al, Fe, Mn, Zn, Cu) and heavy metals (Zn, Cu, Ni, Cr, Cd) in the sludges applied to the four forest sites are shown in Table 6. Sludges from Alpena and Rogers City were both rich sources of nitrogen, phosphorus and calcium. Other macronutrients and micronutrients were present at modest levels. Concentrations of heavy metals were relatively low and typical for sludge produced in cities with low levels of industry.

Because of the relatively low levels of potentially toxic metals found in the sludges from Rogers City and Alpena, sludge from the City of Detroit wastewater treatment facility was used

Table 6. Average chemical concentrations in sludges applied on forest sites (Hart and Nguyen 1986).

Element	Aspen[1]	Oak[2]	Oak[3]	Pine[4]	Northern Hardwoods[5]
	mg/kg				
Nitrogen	53,040	32,490	71,840	45,840	85,140
Phosphorus	28,080	32,490	35,920	30,560	41,580
Potassium	2,733	2,389	3,040	2,685	1,295
Calcium	41,902	86,321	64,521	45,534	55,064
Magnesium	4,452	5,763	7,150	4,053	5,445
Sodium	3,151	2,334	4,263	3,648	2,028
Boron	44	4	122	86	30
Aluminum	30,514	19,733	16,164	16,808	8,732
Iron	55,942	56,379	68,113	61,044	50,846
Manganese	706	1,073	431	417	182
Zinc	1,234	1,119	1,201	932	942
Copper	571	434	1,221	516	597
Nickel	43	42	36	43	23
Chromium	182	109	102	106	64
Cadmium	28	8	115	60	8

[1]Alpena sludge, October 1981
[2]Alpena sludge, November 1981 (plot 1)
[3]Rogers City sludge, November 1981 (plots 5 and 7)
[4]Alpena sludge, June 1982
[5]Rogers City sludge, July 1982

in the laboratory food chain studies in hopes of testing the biomagnification potential of heavy metals in sludge from a heavily industrialized source. A comparative chemical analysis of the metal concentrations of Detroit sludge, Alpena Sludge and a commercially available fertilizer (12%N-12%P-12%K) was surprisingly revealing. The comparison showed that, while both sludges contained higher levels of heavy metals than the commercial fertilizer, the heavy metal concentrations in the Detroit wastewater sludge were not substantially different from those in the Alpena sludge (Table 7).

Table 7. Heavy metal concentrations in commercial fertilizer and wastewater sludges from Alpena and Detroit (Haufler and Woodyard 1986).

Metal	Fertilizer	Alpena	Detroit
	mg/kg		
Cadmium	3.2	7.5	13.0
Chromium	24.0	48.8	139
Copper	115	1230	527
Nickel	5.6	36.3	9.8
Zinc	401	1125	1718

SLUDGE LOADING AND DISTRIBUTION

Because of the variation in site characteristics, such as microtopography and vegetation structure, and that encountered in operation of application equipment, such as vehicle speed, discharge rate and tank pressure, a substantial amount of variation in solids, nutrient and trace element loading can be anticipated on any sludge treated forest site. An overall assessment indicated that this variation in loading and distribution of sludge constituents was less than expected (Table 8).

The aspen site was treated with 1,112,878 liters (294,023 gallons) of Alpena wastewater sludge. The average dry solids content of the material was 3.2%, resulting in a mean sludge loading rate of approximately 10 Mg/ha (4.5 tons/acre). The loading rates of nutrients and trace elements were computed from data on area of application, volume of sludge applied and chemical analysis of sludge samples collected during the application period. Loading rates for nitrogen and phosphorus averaged 561 and 291 kg/ha (500 and 260 lbs/acre), respectively. Differences in loading rates for most major elements were generally not statistically significant among plots.

Table 8. Solids, nutrient and trace element loading on forest sites (Brockway and Nguyen 1986).

Constituent	Aspen	Oak	Pine	Northern Hardwoods
	kg/ha			
Solids	9,980	8,019	8,119	9,210
Nitrogen	560.0	400.6	379.4	783.1
Phosphorus	290.5	272.1	252.9	383.7
Potassium	26.21	21.35	22.12	11.89
Magnesium	44.36	50.89	32.25	49.84
Calcium	418.0	619.0	373.5	503.0
Sodium	31.45	25.21	30.18	18.57
Aluminum	304.0	146.3	137.8	79.8
Iron	557.2	491.7	500.9	456.9
Manganese	7.04	6.44	3.80	1.66
Copper	5.68	6.13	4.22	10.82
Zinc	12.29	9.25	7.61	8.60
Cadmium	0.28	0.42	0.36	0.08
Boron	0.44	0.43	0.71	0.27
Nickel	0.42	0.31	0.35	0.21
Chromium	1.81	0.85	0.86	0.58

The oak site was treated with 264,971 liters (70,006 gallons) of wastewater sludge from Alpena (plot 1) and 514,801 liters (136,011 gallons) of wastewater sludge from Rogers City (plots 5 and 7). The average dry solids content of these materials was 3.4%, resulting in a mean sludge loading rate of approximately 8 Mg/ha (3.6 tons/acre). Plot 1 received the highest application rate of 14 Mg/ha (6.2 tons/acre). Over the entire site, the nitrogen loading rate averaged 401 kg/ha (358 lbs/acre), while that for phosphorus was 272 kg/ha (243 lbs/acre). Nutrient loadings for plot 1 were much higher than those for other plots. Because of the different chemical characteristics of the two sludges, significant differences were found between plot 1 and plots 5 and 7 for most major elements, except nitrogen, copper and boron.

The pine site was treated with 1,112,878 liters (294,023 gallons) of Alpena wastewater sludge. The average dry solids content was 2.6%, resulting in a mean sludge loading rate of approximately 8 Mg/ha (3.6 tons/acre). The nitrogen loading rate averaged 379 kg/ha (338 lbs/acre) and that of phosphorus 253 kg/ha (226 lbs/acre). Differences in the loading rates of most elements were generally not statistically significant among plots.

The northern hardwoods site was treated with 673,783 liters (178,014 gallons) of Rogers City wastewater sludge. The average dry solids content was 5.1%, resulting in a mean sludge loading rate of approximately 9 Mg/ha (4 tons/acre). Because of the higher solids content of this sludge, nutrient additions to these plots were higher than those on other sites. The nitrogen loading rate averaged 783 kg/ha (699 lbs/acre) and that of phosphorus 384 kg/ha (343 lbs/acre). Trace element additions were lower on this site than on the other sites. Differences in the loading rates of nutrients and trace elements were not statistically significant among plots.

LABORATORY FOOD CHAIN STUDIES

In a study of a soil-plant-small mammal-raptor food chain, sludges were manually applied to potted soils in a greenhouse environment (Haufler and Woodyard 1986). Nitrogen application rates for the Alpena and Detroit sludges were 584 kg/ha (522 lbs/acre) and 739 kg/ha (660 lbs/acre), respectively. Commercial fertilizer (12%N,12%P,12%K) was also applied as a reference treatment using 600 kg N/ha (536 lbs N/acre).

In the soil-macroinvertebrate detritivore-vertebrate insectivore food chain study, Alpena and Detroit sludges were mixed with soil in a 7:10 ratio to a depth of 7 cm (2.8 inches). Commercial fertilizer was also mixed with soil as a test comparison. The relative metal concentrations of these mixtures indicated that significantly more metal was present in the soil as a result of sludge addition (Table 9).

Table 9. Heavy metal concentrations in greenhouse soils amended with sludge or commercial fertilizer (Haufler and Woodyard 1986).

Element	Fertilizer	Alpena Sludge	Detroit Sludge
	mg/kg		
Zinc	78a	287b	327b
Copper	15.2a	41.6b	34.4b
Chromium	48.8a	56.5b	58.0b
Nickel	20.6a	24.8b	19.5ab
Cadmium	1.63a	3.73b	4.50b

Means in the same row followed by the same letter are not significantly different at the 0.1 level.

ENVIRONMENTAL STUDY RESULTS

Earlier studies in Michigan (Brockway 1983, Urie et al. 1984) and related studies in northeastern (Koterba et al. 1979), southern (Richter et al. 1982, Wells et al. 1984) and western (Bledsoe 1981, Henry and Cole 1983, Zasoski et al. 1983) forests have shown a variety of changes in the ecosystem as a result of sludge nutrient additions. Increased tree growth and improved nutritional quality of wildlife forage plants were among the benefits. Enrichment of groundwater with nitrate-nitrogen and heavy metal biomagnification in the food chain may be potential risks (Sidle and Kardos 1979, Brockway and Urie 1983, Zasoski et al. 1984, Cole et al. 1986). Investigators working on this research-demonstration project examined these processes and related ècosystem dynamics.

FOREST VEGETATION

Plants present in the forest environment are often limited in their growth by low levels of native nutrients. As such, forest vegetation is a primary beneficiary of sludge applied nutrients and organic matter. Woody vegetation is also likely to assimilate and immobilize substantial quantities of trace elements, effectively removing them from cycling in the ecosystem for extended periods.

Tree Foliar Nutrition

Sludge applied nitrogen and phosphorus were rapidly taken up by aspen. Statistically significant increases in foliar N and P were measured on the aspen site by the 1982 season and persisted through the 1984 growing season (Table 10). On the oak site, applied sludge nutrients did not cause increased levels of foliar N and P in red oak and white oak (Table 11). The diminished effect of sludge on this site was thought to be a result of higher native nutrient levels. Sludge applied N and P were rapidly taken up by jack pine and red pine trees. Significant increases of foliar N and P measured in the pine were likely a result of nutrient deficiency prior to treatment (Table 12). Generally sludge applied nutrients were rapidly assimilated on the forest sites and should accumulate in the standing vegetation biomass. Responses from application continued through 1984 and were anticipated to persist for several years until the nutrients became immobilized in woody plant tissue with its slower nutrient cycling rate (Hart and Nguyen 1986).

Table 10. Aspen foliar nutrient concentrations resulting from sludge application (Hart and Nguyen 1986).

Year	Nitrogen		Phosphorus	
	Control	Treated	Control	Treated
	%			
1981	1.80a	1.94b	0.20a	0.21a
1982	1.97a	2.40b	0.21a	0.22b
1983	1.91a	2.61b	0.20a	0.26b
1984	2.04a	2.43b	0.20a	0.23b

Means of the same element in the same row followed by the same letter are not significantly different at the 0.05 level.

Table 11. Red oak and white oak foliar nutrient concentrations following sludge application (Hart and Nguyen 1986).

	Pretreatment 1981	Control 1984	Treated 1984
	%		
Red oak:			
Nitrogen	2.02	2.36a	2.35a
Phosphorus	0.24	0.22a	0.24a
White oak:			
Nitrogen	2.12	2.27a	2.38a
Phosphorus	0.28	0.25a	0.25a

Means in the same row followed by the same letter are not significantly different at the 0.05 level.

Table 12. Jack pine and red pine foliar concentrations following sludge application (Hart and Nguyen 1986).

	Pretreatment 1981	Control 1984	Treated 1984
	%		
Jack pine:			
Nitrogen	1.09	0.90a	1.47b
Phosphorus	0.17	0.14a	0.16b
Red pine:			
Nitrogen	0.96	0.94a	1.13b
Phosphorus	0.17	0.13a	0.14b

Means in the same row followed by the same letter are not significantly different at the 0.05 level.

Short Term Tree Growth

Over the four year post-treatment period on the aspen site, ground level diameter (GLD) of trees increased 23%, from 9.31 mm for controls to 11.41 mm for sludge treated aspen (Figure 6). Over the same period a 48% increase in aspen basal area from 5.71 m^2/ha (24.8 ft^2/acre) to 7.75 m^2/ha (33.7 ft^2/acre) was measured for control and treated groups, respectively (Figure 7). Aspen biomass production increased 57% from 8.46 kg/m^2 (37.7 tons/acre) for controls to 13.27 kg/m^2 (59.1 tons/acre) for sludge treated trees (Figure 8). As of 1985, no decline in this response was observed (Hart and Nguyen 1986).

Significant increases in tree diameter (DBH) growth occurred on the oak, pine and northern hardwoods sites between 1981 and 1985 as a result of access trail construction (thinning effect) and sludge application (Table 13). On each site, the diameter growth differentials between the control and sludge treated groups were significant for the 1981-84 period. A similar pattern of response was observed for basal area increases resulting from treatment. The overall relative proportion of these increases attributed to access trail construction was 24.5% and sludge application was 20.4%, resulting in an average total gain of 49.6% from the complete forest land application treatment (Table 14). Diameter (48 to 78%) and basal area (36 to 56%) growth responses reported here were similar to those of 40 to 60% measured in high yielding Douglas-fir stands of the Pacific Northwest (Zasoski et al. 1983).

Long Term Tree Growth

Levels of site nitrogen and phosphorus were related to indices of stand growth on the oak site using multiple regression analysis (Merkel et al. 1986). The resultant equation accounted for 69% of the variability between stand growth and site nutrient levels. Measurements from 29 oak stands in Manistee, Wexford, Mason and Lake Counties were included in the analysis to serve as a representative data base for untreated sites. Based upon the site nutrient levels present as a result of sludge application, a growth increase of 29% from 3.57 m^3/ha/yr (51.1 ft^3/ac/yr) for control stands to 4.62 m^3/ha/yr (66.1 ft^3/ac/yr) for sludge treated stands was predicted. This estimate closely corresponds to the 21% basal area increase measured during the initial four years following stand fertilization with sludge. Current increases in stand growth from a single application are anticipated to become statistically nonsignificant by 1990.

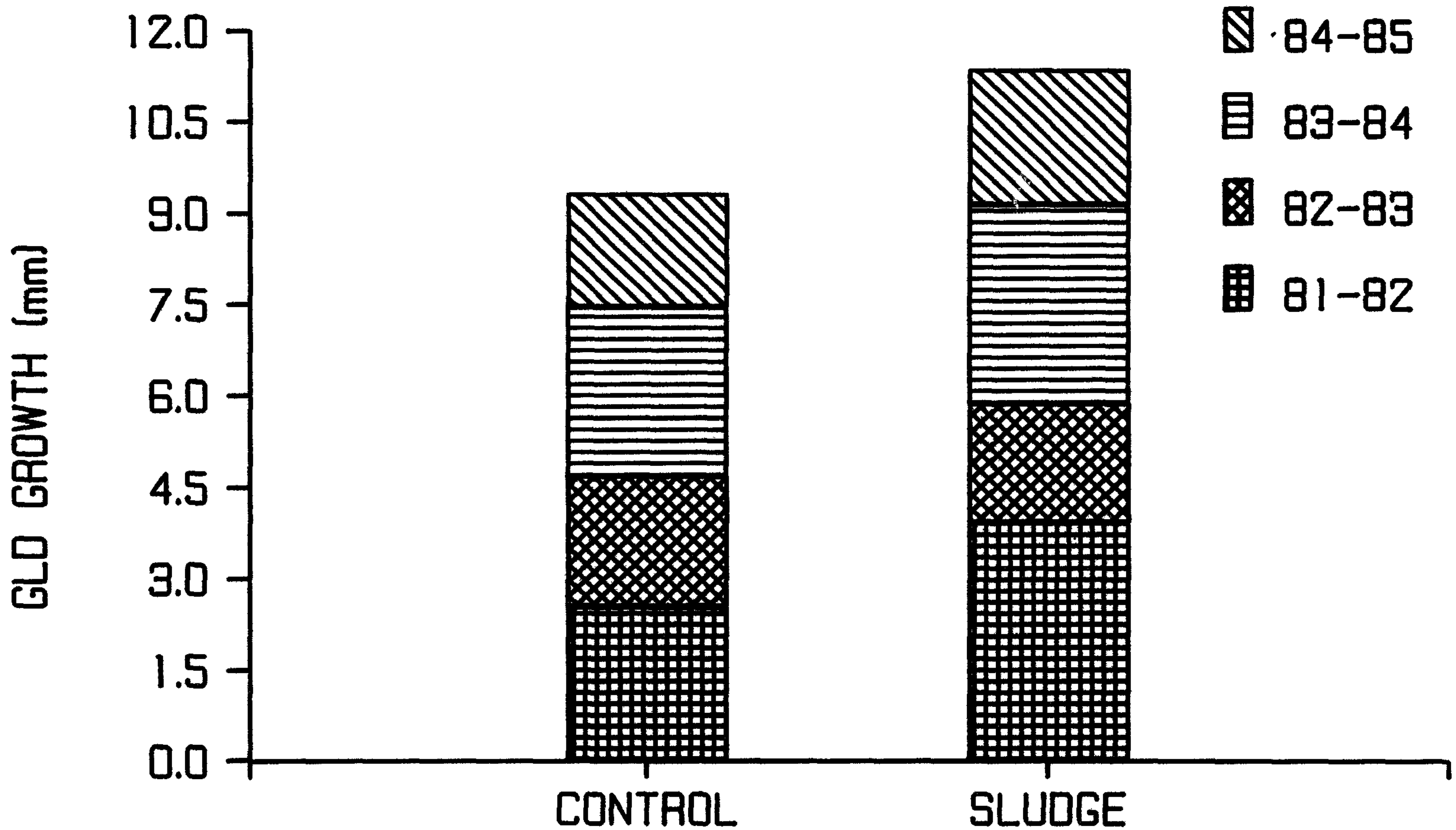

Figure 6. Diameter growth responses of trees at the aspen site (Hart and Nguyen 1986).

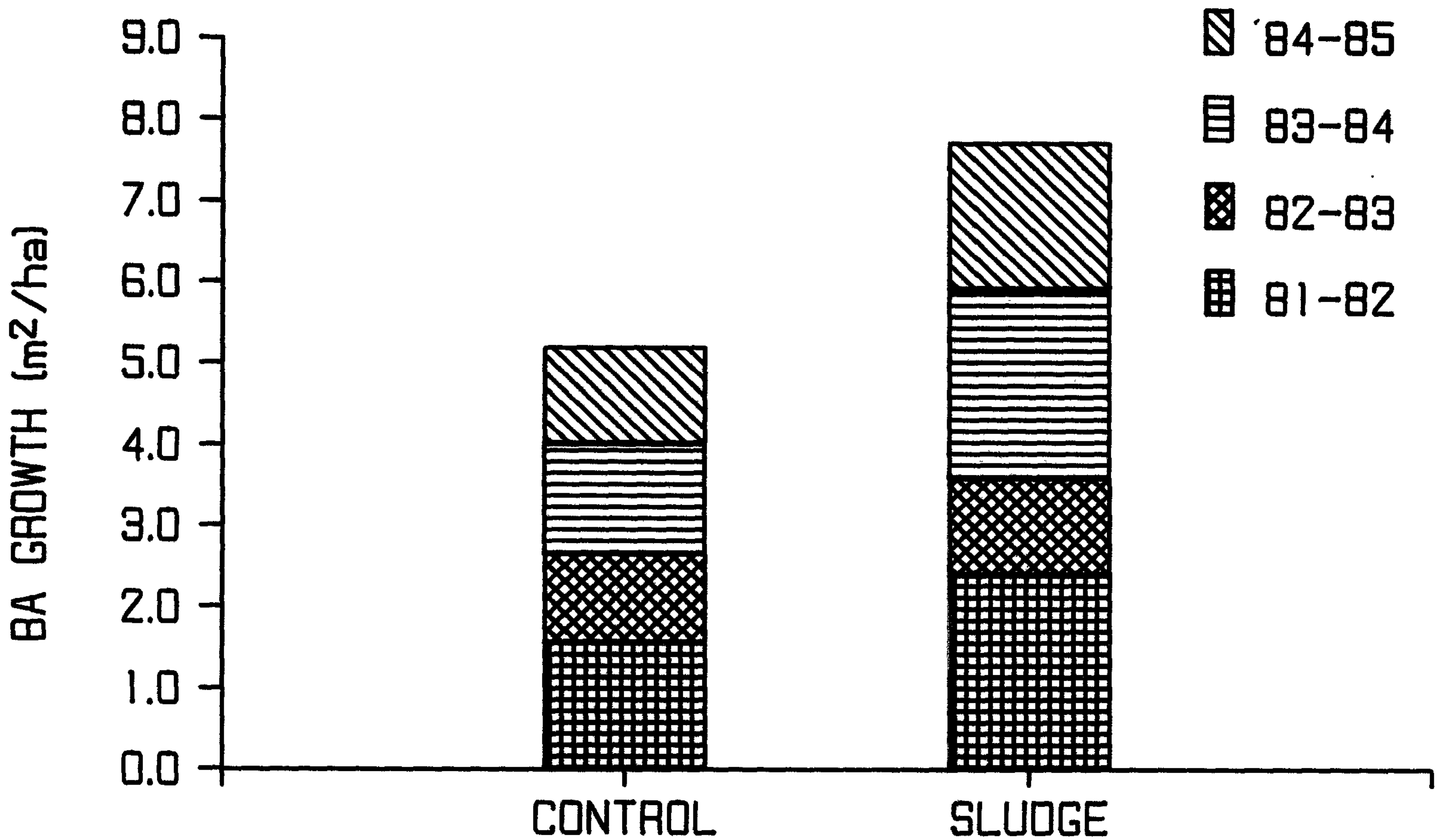

Figure 7. Basal area growth responses of trees at the aspen site (Hart and Nguyen 1986).

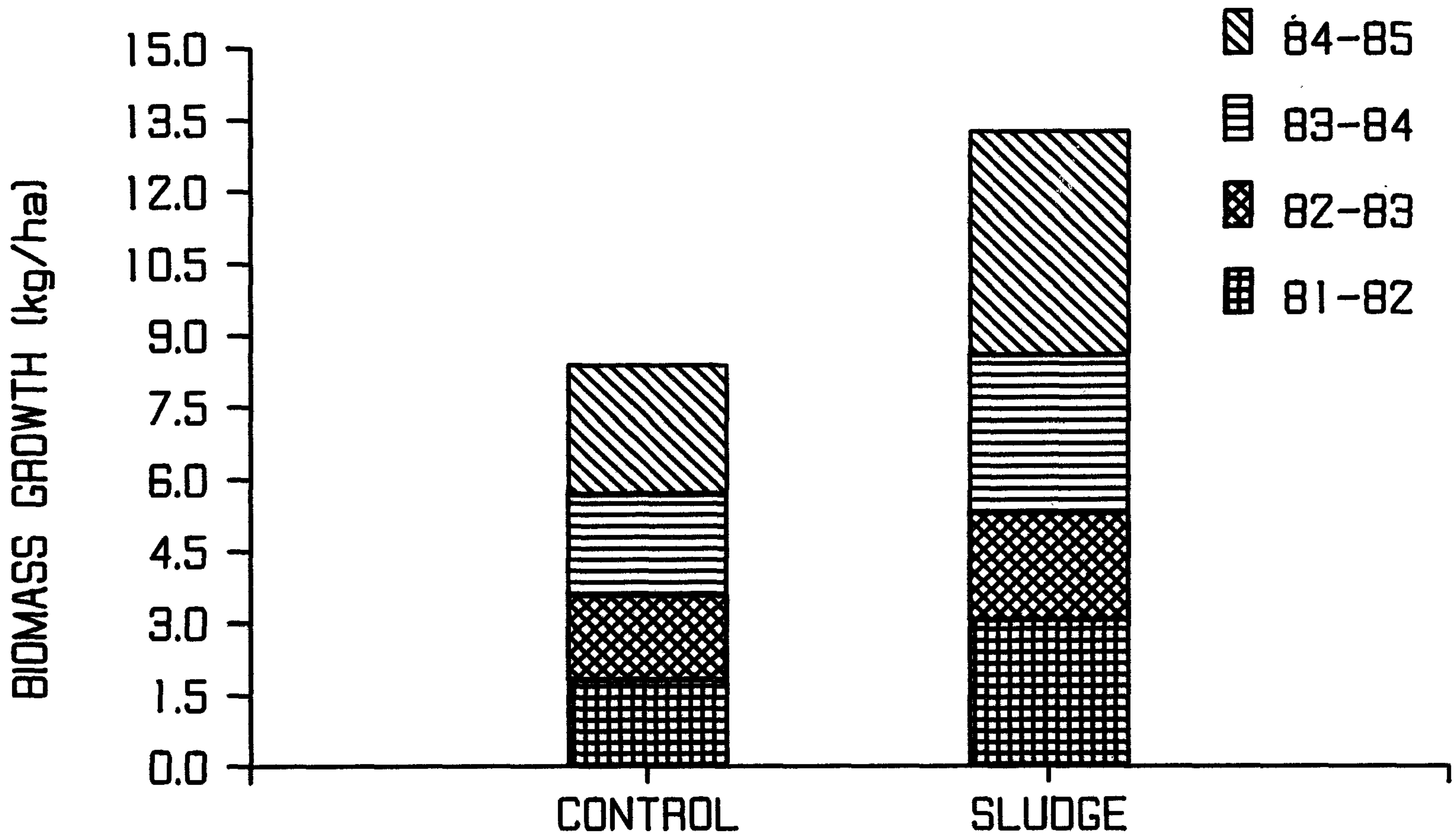

Figure 8. Biomass growth responses of trees at the aspen site (Hart and Nguyen 1986).

Table 13. Tree diameter growth at the oak, pine and northern hardwoods sites (Hart and Nguyen 1986).

Year	DBH	Control	Diameter Growth Trails	Sludge
	cm			
Oak site:				
1981	17.11	-	-	-
1982	17.36	0.22a	0.22a	0.32b
1983	17.78	0.30a	0.41b	0.56c
1984	17.96	0.11a	0.18b	0.24c
1981-84	-	0.63a	0.81b	1.12c
Pine site:				
1981	20.62	-	-	-
1982	20.82	0.24a	0.17b	0.18ab
1984	21.48	0.52a	0.71b	0.76b
1981-84	-	0.76a	0.87ab	0.95b
Northern hardwoods site:				
1981	19.06	-	-	-
1982	19.35	0.29a	0.20a	0.32a
1984	20.12	0.60a	0.75a	0.98b
1981-84	-	0.88a	1.01a	1.30b

Means in the same row followed by the same letter are not significantly different at the 0.05 level.

Table 14. Basal area response factor summary for oak, pine and northern hardwoods (Hart and Nguyen 1986).

	Basal Area Increase Trail Construction	Sludge Application	Combined
	%		
Oak	29.3	21.0	56.4
Pine	26.6	7.7	36.3
Northern hardwoods	17.7	32.6	56.0
Mean	24.5	20.4	49.6

However, successive sludge applications could maintain site fertility at a higher level and ultimately lead to greater stand productivity (Figure 9).

Tree Mortality

Aspen mortality following sludge application was reported at 14.5% for the control group and 41.4% for the treated group (Table 15). The increased mortality was not a direct result of sludge application, but rather the interaction of several factors which predisposed quaking aspen and especially bigtooth aspen to infection by *Armellaria*, *Fusarium* and *Cytospora* fungi that naturally occur in this area. The construction of site access trails in an east-west direction left the stem bark of young aspen trees exposed to direct sunlight for long periods during the day. This exposure often resulted in sunscald injury and points of entry for infecting fungi. The increased nutrient levels in aspen plant tissues resulting from sludge treatment enhanced the palatability of leaves. Elk (*Cervus canadensis* Erxleben) often damaged stems as they attempted to browse on this highly desirable forage. Such injury created a major pathway for fungal infection. Finally, the nitrogen in the sludge may have prolonged the growing season for young trees, thereby predisposing them to winter injury (Hart et al. 1986).

Substantial mortality occurred on the pine site across all plots. This was a result of the normal suppression of saplings which is typical of dry sites. No significant mortality increases were observed on the oak or northern hardwoods sites. Tree mortality, as reported above for aspen, might serve as an economic disincentive for the land manager were it a likely outcome of sludge application. However, such would be a very rare occurance when good forest management practices are otherwise followed.

Understory Vegetation

On the aspen site seedling regeneration and groundcover vegetation were unaffected by sludge application (Hart and Nguyen 1986). However, some undergrowth suppression may have begun as tree growth increased following sludge fertilization. Saplings on the oak site increased significantly in number and basal area following treatment; however, those on the pine and northern hardwoods sites were unaffected. Seedling regeneration increased

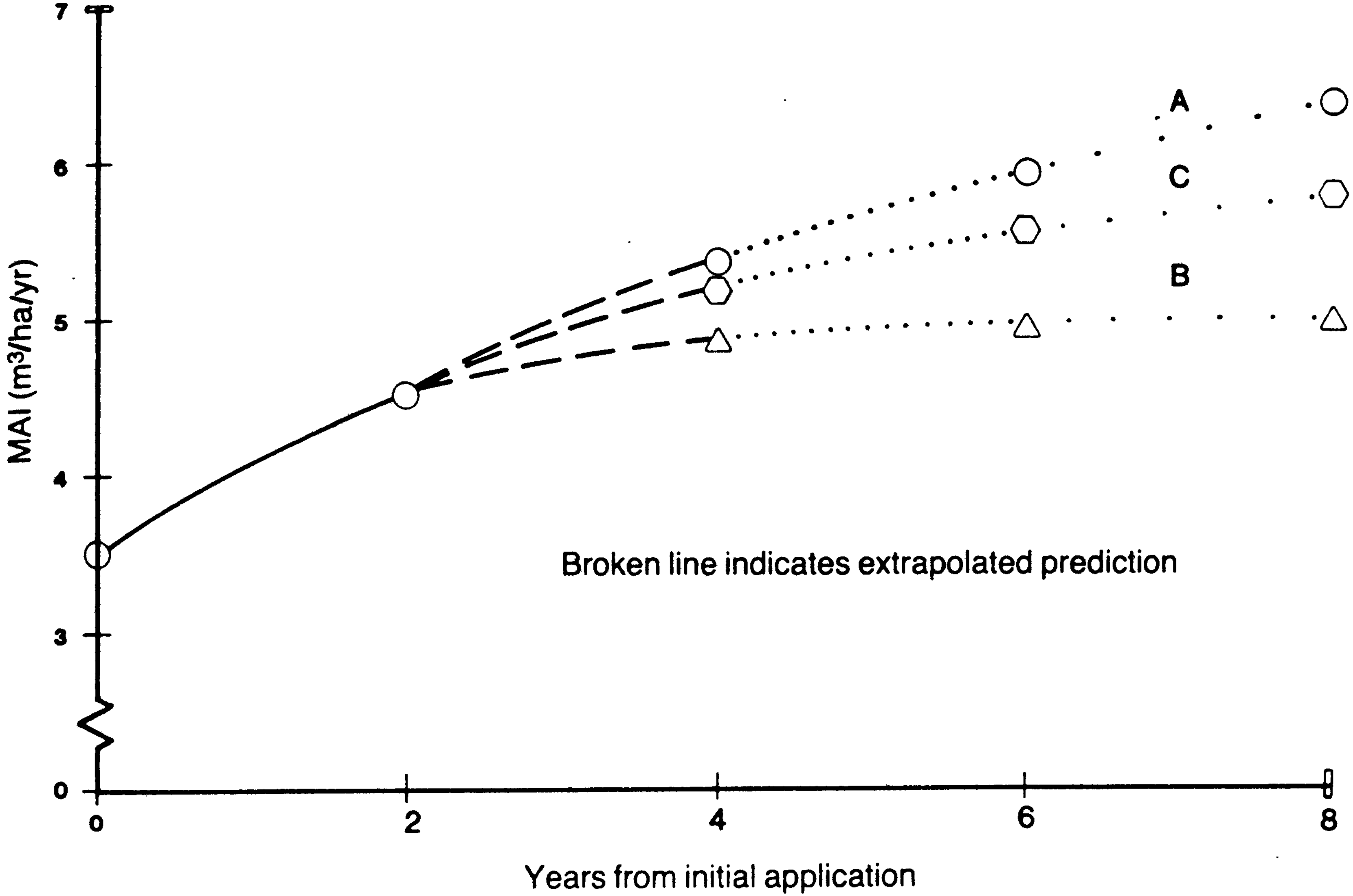

Figure 9. Hypothetical mean annual increment (MAI) curve for oak showing growth resulting at (A) high, (B) low and (C) moderate rates of nutrient retention (Merkel et al. 1986).

Table 15. Aspen stocking and mortality (Hart and Nguyen 1986).

Year	Stocking		Mortality	
	Control	Treated	Control	Treated
	trees/ha			
1981	9106	9733	-	-
1982	8923	7633	183a	2100b
1983	8373	6550	550a	1083b
1984	8206	6161	167a	389b
1985	7789	5700	417a	461a
1981-85	-	-	1317a	4033b

Means in the same row followed by the same letter are not significantly different at the 0.1 level.

on the oak and northern hardwoods sites, but these changes were statistically nonsignificant. Increases in cover of grasses, sedge, forbs and shrubs on the oak and northern hardwoods sites were unrelated to sludge application. Grass and sedge cover on the pine site increased while forb cover decreased, possibly accounting for no increase in seedling regeneration there. Overall understory changes related to sludge application were minimal.

FOREST FLOOR AND SOIL

The forest floor (01 and 02 horizons) is the first ecosystem component where the impact of sludge application is manifest (Brockway 1983). It is believed to be the major repository for applied nutrients and trace elements. These elements, if not directly taken up by plants, may then enter the soil beneath the forest floor through leaching and humus incorporation.

Forest Floor Weight

The initial effect of sludge application in the forest was to increase the weight of the forest floor on each site, a result of solids loading (Hart and Nguyen 1986). The 01 horizon on the aspen site increased from 1453 kg/ha (1295 lbs/acre) to 4348 kg/ha

(3874 lbs/acre). However, the 02 horizon decreased in weight 3000 kg/ha (2673 lbs/acre) as a result of increased microbial decomposition following fertilization. Over the subsequent three years, forest floor weight on this site progressively increased from increasing rates of dry matter production and recycling. The 02 horizon comprised approximately 95% of the total forest floor mass.

Forest floor weight on the oak site was initially increased from 43 Mg/ha (19 tons/acre) to 56.6 Mg/ha (25.2 tons/acre) by sludge application. Pine site forest floor horizons were increased in weight from 31.2 Mg/ha (13.9 ton acre) to 41 Mg/ha (18.3 tons/acre). Forest floor on the northern hardwoods site was decreased by decomposition following application, but this weight loss was not statistically significant.

Chemical Composition

On all sites fertilized with wastewater sludge, forest floor nutrient and trace element levels increased in proportion to the application rate (Hart and Nguyen 1986). Significant increases in the 01 and 02 horizons were noted for several elements and many of these differences persisted throughout the study period (Table 16). The total amount of heavy metals present in the forest floor was quite small, despite the relative differences between control and treated plots. The 02 horizon was the major repository for nutrients and trace elements.

Very little change was observed in the chemical composition of surface and subsurface soils. Within the first year following treatment on the aspen site, small increases in phosphorus and sodium concentrations were measured in surface soils. By 1984 these levels declined to near background. Calcium and iron concentrations did increase in the surface soil of the oak site and calcium, magnesium and iron increased on the pine site following sludge application. Chemical changes in the subsurface soils on all sites were minor or absent.

Element Retention

Three years after sludge treatment, the forest floor on the aspen site generally retained more than 50% of the applied macronutrients, micronutrients and heavy metals, except calcium and cadmium (Table 17). The oak forest floor retained less than

Table 16. Nutrient and trace element content of the forest floor, 1984 (Hart and Nguyen 1986).

Element	Oak Site Control	Oak Site Treated	Pine Site Control	Pine Site Treated	Northern Hardwoods Site Control	Northern Hardwoods Site Treated
	kg/ha					
01 horizon:						
K	6.4a	9.3a	2.62a	4.31b	6.29a	6.80a
Ca	92.7a	136.2a	28.85a	43.95a	116.95a	121.40a
Mg	6.1a	9.9a	3.64a	5.85b	9.16a	10.14a
Na	0.7a	1.3a	0.24a	0.28a	0.50a	0.52a
Al	3.7a	14.7a	4.93a	9.66b	3.72a	5.35a
Fe	3.7a	67.2c	3.04a	33.25b	13.95a	38.50b
Mn	15.2a	21.2a	4.97a	6.45a	6.84a	3.72b
Cu	0.06a	0.59b	0.04a	0.22b	0.25a	0.74b
Zn	0.36a	1.43b	0.30a	0.78b	0.46a	0.75a
Cd	0.006a	0.022b	0.01a	0.01a	0.010a	0.011a
Ni	0.014a	0.048a	0.02a	0.03a	0.017a	0.021a
Cr	0.012a	0.100a	0.01a	0.05b	0.020a	0.037b
02 horizon:						
K	36.9a	43.6a	7.48a	14.72b	54.00a	60.00a
Ca	261.1a	590.5a	47.80a	161.10b	628.00a	1169.00a
Mg	48.8a	73.5b	24.60a	48.10b	122.00a	188.00a
Na	5.2a	7.0a	1.22a	2.00a	6.02a	7.64a
Al	117.0a	202.5b	42.50a	101.20b	214.00a	260.00a
Fe	175.6a	661.9b	37.50a	342.00b	236.80a	972.00b
Mn	136.0a	207.7a	12.90a	20.40a	181.00a	232.00a
Cu	0.6a	4.6b	0.13a	1.99b	0.68a	14.66b
Zn	3.8a	10.9b	0.97a	5.25b	6.18a	18.36b
Cd	0.15a	0.26b	0.04a	0.08b	0.24a	0.55b
Ni	0.31a	0.55b	0.10a	0.29b	0.42a	0.72a
Cr	0.28a	0.92b	0.07a	0.48b	0.39a	0.99b

Means in the same row and on the same site followed by the same letter are not significantly different at the 0.05 level.

Table 17. Forest floor retention of applied elements, 1984 (Hart and Nguyen 1986).

Element	Aspen	Oak	Pine	Northern Hardwoods
	%			
Nitrogen	-	44	-	-
Phosphorus	-	18	-	-
Potassium	82	38	32	28
Calcium	25	47	34	62
Magnesium	84	52	74	135
Sodium	-	9	-	18
Aluminum	50	61	39	108
Iron	73	110	65	178
Manganese	356	-	229	-
Zinc	68	87	70	142
Copper	53	74	48	129
Cadmium	41	29	11	400
Nickel	87	84	46	167
Chromium	68	85	50	114

50% of the applied macronutrients but more than 50% of the micronutrients and heavy metals, except cadmium. The forest floor of the pine site retained less than 50% of the applied macronutrients and approximately 50% of the micronutrients and heavy metals, except cadmium. The northern hardwoods forest floor retained more than 50% of all elements, except potassium and sodium, which are very mobile (Hart and Nguyen 1986).

Because the forest floor, specifically the 02 horizon, acts as the main reservoir for nutrients and trace elements, the degree to which elements are retained has major management implications concerning their availability for plant uptake and leaching to groundwater. Elements with higher retention in the forest floor are likely less mobile and therefore less problematic in managing sites in an environmentally safe manner. Of those elements showing generally lower retention, cadmium was thought to have greatest potential as an environmental hazard through food chain biomagnification. As few nutrients and none of the trace elements were detected as moving into the soil or leaching to the groundwater, it may be concluded that plant assimilation, and denitrification or volatilization in the case of nitrogen, were likely responsible for low rates of retention in the forest floor.

WATER QUALITY

Prior studies have shown that when nutrients are added to the forest ecosystem at rates which exceed its assimilation capacity, the excess in solution are leached (Brockway and Urie 1983). Forest land application programs seeking to minimize the loss of site nutrient capital and the risks of groundwater enrichment or contamination should therefore seek to balance sludge nutrient and trace element additions with the ecosystem assimilation capacity for these constituents. The sludge application rates, based primarily on total nitrogen, used in this research-demonstration project were consistent with those determined as acceptable by earlier USDA Forest Service studies (Figure 10).

Monitoring

Although major episodes of leaching were not anticipated, each study site was carefully monitored with a series of suction lysimeters placed in the unsaturated zone to collect soil leachate and wells installed in the upper saturated zone to directly sample groundwater (Urie et al. 1986). Soil parent materials were of sufficient permeability to prevent surface runoff of water, ensuring that all measurements made in the unsaturated and saturated flow systems of the regional groundwater aquifer reflected the actual impact of sludge addition. Lysimeters were sensitive to chemical changes in water moving through the soil profile, as downgradient wells were affected by dilution from mass movement.

Numerous sludge constituents have been of concern in land application, including organic chemicals, pathogens, certain nutrients and heavy metals. Organic compounds may become volatilized or bound to soil particles. Bacteria and viruses may pass through soil, but do so very poorly in well aerated soils. Phosphate and trace elements are normally adsorped and precipitated strongly in mineral soil. Nitrate, sulfate, chloride and bicarbonate anions are poorly adsorped onto soil particles and readily mobile. Calcium, magnesium, sodium and potassium cations are leached from the soil in proportion with anions, primarily nitrate, during the spring and fall periods of groundwater recharge. The nitrate form of nitrogen is of principal importance to public health, as concentrations exceeding the 10 mg/l USEPA potable water standard are known to cause methemoglobin disease in humans.

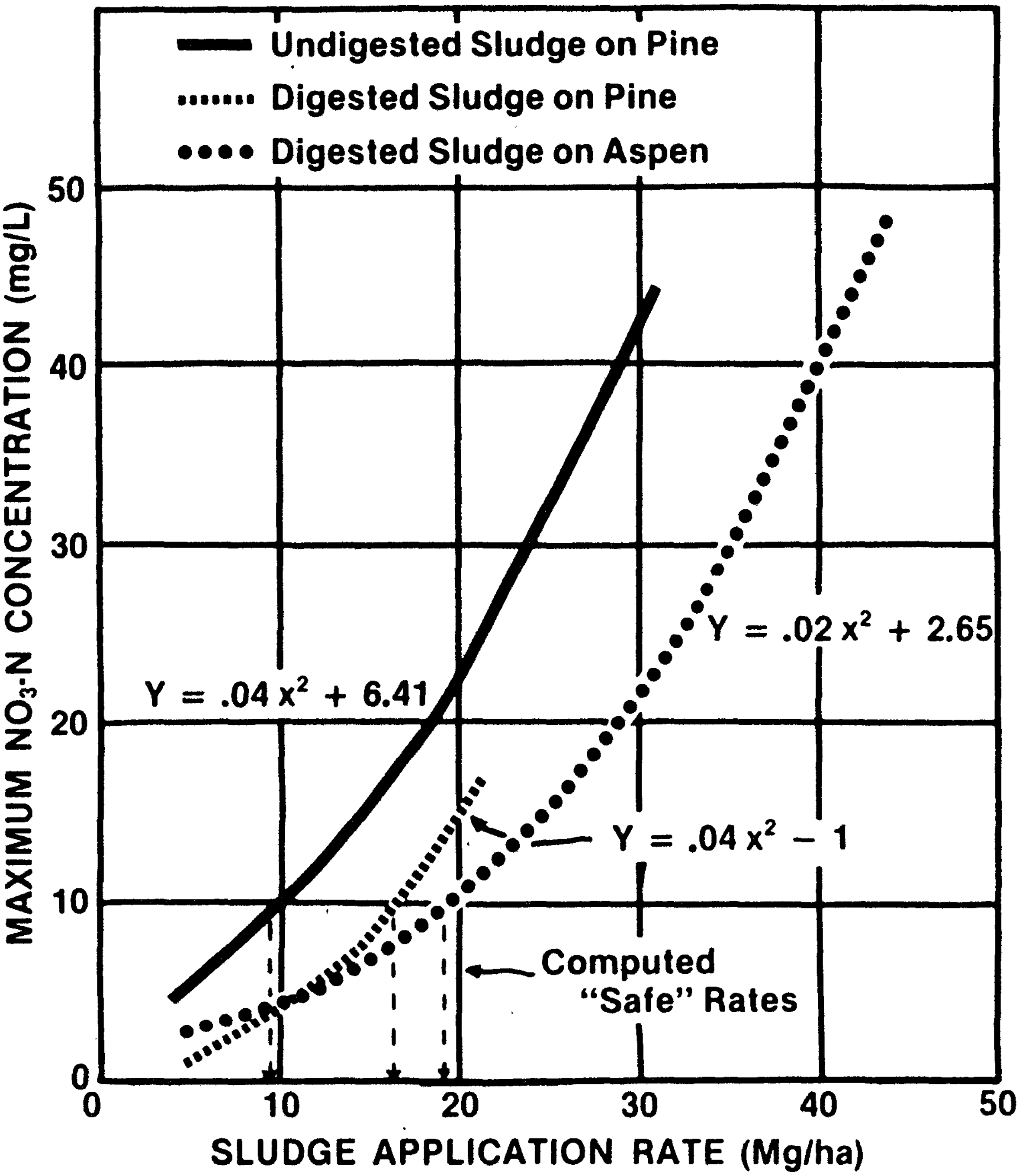

Figure 10. Relation of sludge application rate to nitrate leaching (Brockway and Urie 1983).

Nitrate Leaching

Nitrate-nitrogen is generated as the end result of organic nitrogen mineralization to ammonia and further nitrification to nitrite and nitrate (Figure 11). Nitrate which is not immobilized, denitrified or taken up by vegetation is then subject to leaching loss to groundwater. In sludge amended ecosystems, nitrate is the dominant anion and, because it adheres weakly to soil particles, is highly mobile.

During the first year following sludge application, soil water samples collected from lysimeters on all treated sites showed nitrate levels elevated above those on control plots (Urie et al. 1986). On the aspen site, nitrate levels less than 1 mg/l increased to 4 mg/l. On the oak site, nitrate concentrations between 1 and 2 mg/l increased to 6 mg/l. On the pine site, nitrate levels increased from less than 1 mg/l to 13 mg/l. On the northern hardwoods site, nitrate levels increased from less than 1 mg/l to 4 mg/l. These increases were the result of rapid nitrification of the ammonia present in the sludge which led to a modest surplus in site nitrate levels. Soil water nitrate levels rapidly decreased to near background levels following this initial pulse (Figure 12).

In subsequent years, organic nitrogen was more slowly mineralized to ammonia and nitrified to nitrate (Urie et al. 1986). The impact of nitrate on groundwater wells was thus delayed and muted by dilution. On the aspen site, peak nitrate concentrations of 5 mg/l were measured in groundwater during the fall of 1983. On the pine site, nitrate levels peaked at 4.9 mg/l in November 1983. On the northern hardwoods site, peak nitrate concentrations of 3.9 mg/l were recorded in September 1985. The one to two year delay in peak arrival between soil water from lysimeters at 120 cm (4 feet) in the unsaturated zone and groundwater from wells several meters in the saturated zone is typical for nitrate movement in these ecosystems. Such delays result from differential rates of nitrification, rainfall and snowmelt events closely associated with the local climate.

Nitrate leaching among the forest sites was highest on the aspen and pine sites, followed by the oak site and least on the northern hardwoods site. These differences appear to be a complex interaction of sludge type, time of application, depth to water table, soil textural properties and the manner in which different plant communities were able to utilize sludge nutrients. The Alpena sludge applied to the aspen, pine and oak sites did

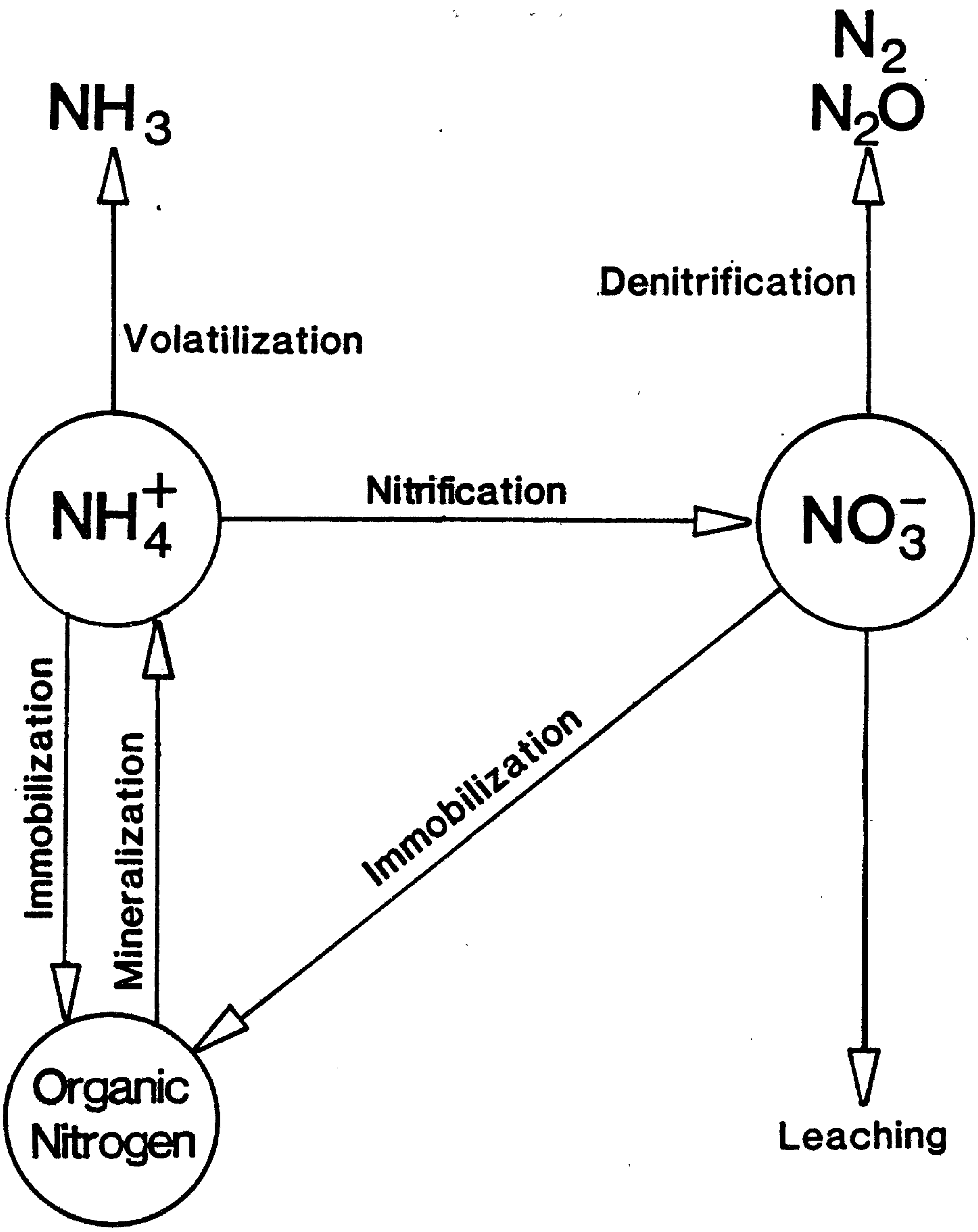

Figure 11. The sludge nitrogen cycle (Burton 1986).

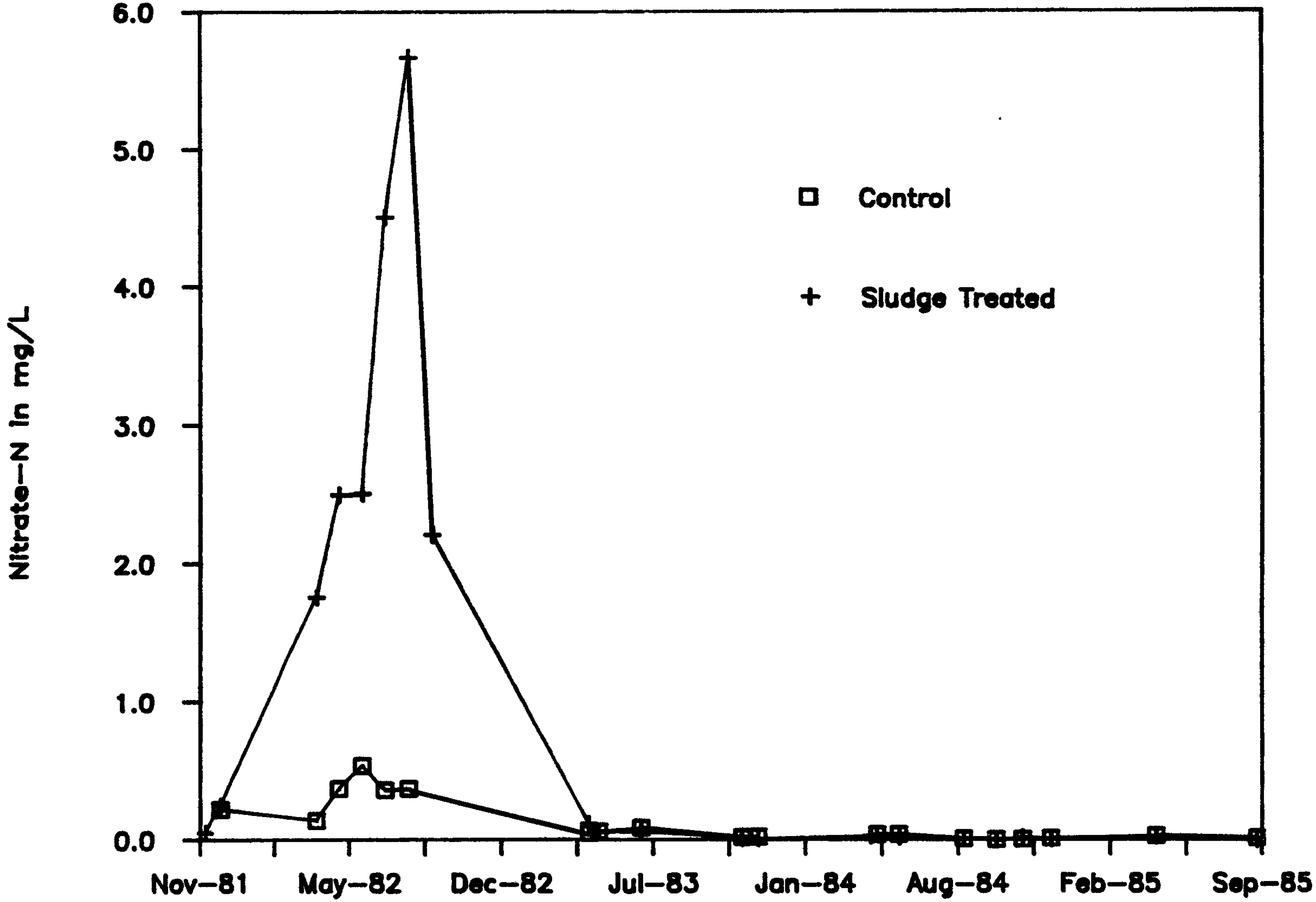

Figure 12. Soil water pattern for nitrate (Urie et al. 1986).

have higher levels of available nitrogen than did the Rogers City sludge. The aspen site contained a juvenile stand with an irregular distribution across the area. Young stands are noted for high rates of nutrient uptake, but also for less efficiency in retaining nutrients in an internalized nutrient cycle than more mature forests. Soils on the northern hardwoods site contained textural bands which could have served as temporary sites of denitrification in the soil profile, leading to less nitrate leaching. The timing of sludge application, during the summer growing season on pine and northern hardwoods and the fall dormant season on aspen and oak, may have also provided a differential impact.

Groundwater nitrate concentrations measured throughout this study remained well below the USEPA 10 mg/l potable water standard, indicating that temporarily elevated soil water nitrate levels in the unsaturated zone do not directly translate to equivalent levels of groundwater enrichment in the saturated zone. The overall movement of nitrate-nitrogen to groundwater was minor on all sites. The sludge application rates, based on total nitrogen, used in this study were therefore demonstrated to be environmentally suitable for these and similar forest ecosystems.

Leaching of Other Elements

Unlike nitrate, ammonia-nitrogen exhibited no significant increases in leaching following sludge application (Urie et al. 1986). Ammonia ions are typically bound tightly to soil particles by cation exchange and were mostly taken up by plant roots as they became available. The leaching of nitrate did cause an accompanying leaching loss of cations from the soil. This process maintains the electrovalent equilibrium in soils subject to leaching. Cation losses were highest during peak nitrate leaching episodes and declined as nitrate leaching decreased (Figure 13). The respective declines in soil water concentrations for calcium, magnesium, potassium and sodium were from 15 to 5 mg/l, 5 to 1 mg/l, 2 to 0.4 mg/l and 6 to 1.5 mg/l. Soil water data indicated that no significant leaching losses of zinc, manganese, cadmium, boron, copper, nickel or chromium to groundwater occurred. These elements remained largely in the forest floor or were taken up by vegetation.

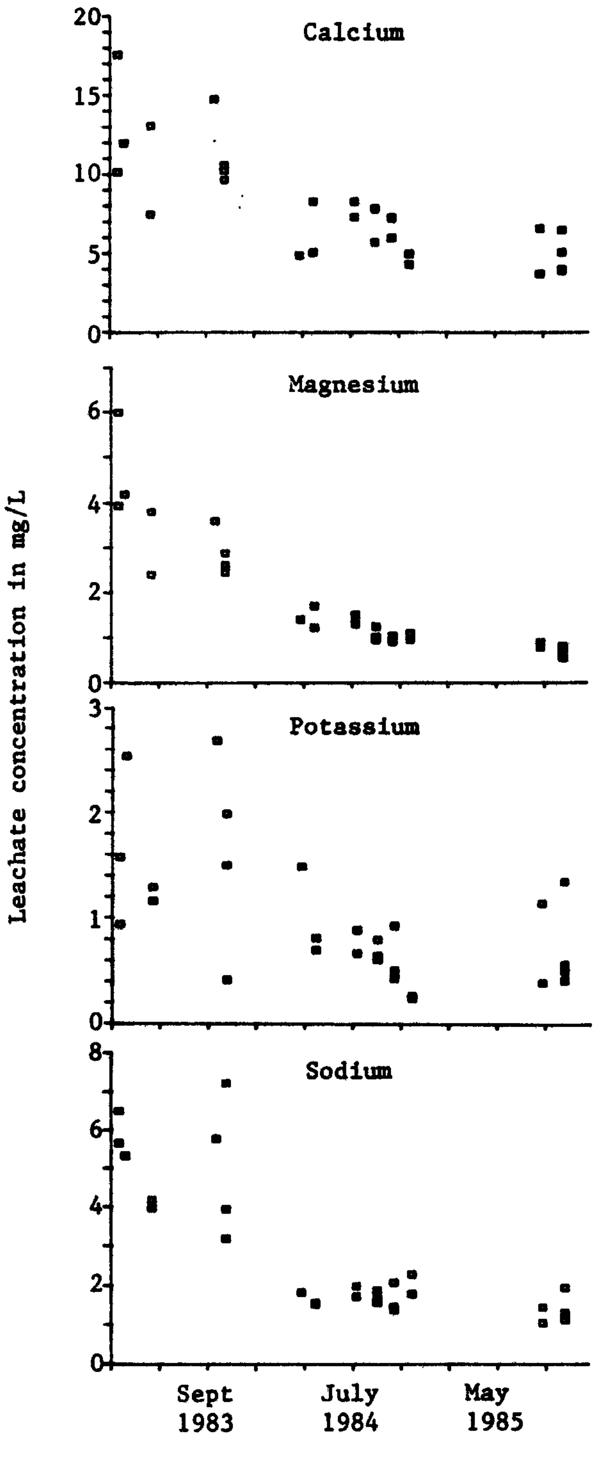

Figure 13. Concentrations of calcium, magnesium, potassium and sodium in soil water (Urie et al. 1986).

WILDLIFE

Sludge nutrient additions which result in greater levels of vegetation production and higher levels of soil fertility were found to enhance the quality of wildlife habitat and generally benefit wildlife populations. Studies showed an increase in the nutritional quality of wildlife food plants. The potential for transmission of potentially toxic heavy metals in the food chain was minimal when proper sludge quality controls, application rates and site selection procedures were used in program planning.

Habitat

Although species composition of the plant community was unaffected, sludge application resulted in significant changes in the vegetation structure on all four study sites (Haufler and Woodyard 1986). Both the quantity of total cover and vertical distribution of cover increased following sludge addition. Increases of vertical cover were measured in 88% of the plant species present in the lower 2 m (6 feet) strata (Haufler and Campa 1986). Horizontal cover (stem density) also increased for 56% of the species present. Increases in annual primary production were mostly observed in herbaceous species (Haufler and Woodyard 1986). Herb production increased 200% on the aspen site in 1982, then declined to levels 50% greater than controls by 1984. A similar but less pronounced pattern was observed on the other study sites.

Structural improvement in habitat was greatest in the pine, aspen and oak sites and least on the northern hardwoods site. Responses were greater when sludge was applied during the dormant season. In the northern hardwoods stand, sludge was applied after the flush of spring leaves, resulting in increased seedling mortality from smothering by solids. The generally richer soils on the northern hardwoods site may have further contributed to the muted understory response to sludge application (Haufler and Woodyard 1986).

Ungulates, such as deer and elk, were observed to browse more heavily on sludge treated areas. Browse utilization was highest on sludge treated plots on the aspen site and progressively less on the northern hardwoods, pine and oak sites. This activity was closely associated with the presence of access trails which provided greater ease of movement and higher levels of nutrients contained in key forage plant species (Haufler and Campa 1986).

Within one year following sludge application, significantly increased levels of protein (20 to 50%) and phosphorus were measured in forage. This improvement in the nutritive quality of wildlife food persisted until the third growing season when nutrient levels decreased to near background (Haufler and Woodyard 1986). Protein is a critical factor in deer forage, with low background levels normally limiting population growth. Higher protein levels in forage may have accounted for increased deer use, resulting in a higher rate of fawn production in sludge fertilized areas.

Populations

Habitat changes in vertical and horizontal cover and nutritional improvement in food plants have been favorably associated with wildlife population dynamics. Bird diversity in temperate climates is known to increase in response to such habitat enhancement. Small mammal populations responded in positive fashion to habitat improvements resulting from sludge application. Within one year of sludge fertilization, small mammal populations on the aspen site increased 100%, then declined to near background by 1984 as nutrients became assimilated into unavailable woody vegetation (Haufler and Woodyard 1986).

Food Chain Assessments

At the sludge application rates used in this research-demonstration, a heavy metal toxicity hazard to wildlife consuming vegetation grown on sludge amended sites or to higher trophic groups (carnivores and man) consuming prey species did not exist (Haufler and Woodyard 1986). Concentrations of heavy metals found in forage plants on sludge treated plots were well below maximum safe levels (Underwood 1977). As with all other field studies of free ranging small mammals, native species here did not accumulate toxic metals in their body tissues.

In the laboratory small mammal-raptor food chain study, significantly increased concentrations of cadmium, chromium and zinc were found in ryegrass grown on soil amended with Alpena sludge and Detroit sludge (Table 18). Tissue bioassays of small mammals consuming the ryegrass revealed that relatively small, statistically nonsignificant accumulations of cadmium and zinc occurred and were restricted to liver and kidney tissues. While

Table 18. Heavy metal concentrations in ryegrass grown on soil receiving sludge or commercial fertilizer (Haufler and Woodyard 1986).

Treatment	Cadmium	Chromium	Copper	Nickel	Zinc
	mg/kg				
Fertilizer (12-12-12)	0.32a	0.47a	3.6a	1.1a	44a
Alpena sludge	0.78b	0.91b	3.7a	1.0a	73b
Detroit sludge	0.93b	0.95b	3.0a	1.1a	60b

Means in the same column followed by the same letter are not significantly different at the 0.1 level.

cadmium and zinc concentrations in the laboratory were twice those found in the field studies, they were not considered hazardous to the health of small mammals or raptors at higher trophic levels (Haufler and Woodyard 1986).

Liver and kidney tissue taken from whitetail deer harvested on the sludge treated aspen site contained slightly elevated levels of cadmium and zinc (Table 19). Concentrations of 3 mg/kg and 31 mg/kg were well below the 200 mg/kg level of cadmium considered hazardous to vertebrates. Zinc levels as high as 858 mg/kg were also in the nonhazardous range of less than 1000 mg/kg. Heavy metal toxicity was an unlikely event in this study, because the metal application rates with sludge were well below those found to produce chronic toxicities in laboratory tests (Haufler and Campa 1986).

In the laboratory detritivore-insectivore food chain study, earthworms raised in soil amended with Alpena and Detroit sludge accumulated approximately five times more cadmium, chromium, copper and zinc in their tissues than did the control group (Haufler and Woodyard 1986). These significant increases were the result of direct ingestion of sludge and assimilation of the heavy metals present (Table 20). Woodcock fed an exclusive diet of these earthworms for 30 days accumulated twice the cadmium in their liver and kidney tissues than did the control group (Table 21). However, the cadmium concentrations of 6 to 36 mg/kg were well below the 200 mg/kg threshold considered hazardous to vertebrate health. On an exclusive diet of sludge-raised

Table 19. Heavy metal concentrations in tissues of whitetail deer harvested on aspen site in November 1982 (Haufler and Campa 1986).

Tissue	Cadmium	Chromium	Copper	Nickel	Zinc
	mg/kg				
Muscle	1.08	1.26	9.39	1.70	399
Heart	0.81	0.43	19.57	0.60	397
Kidney	31.36	0.85	21.16	1.00	858
Liver	3.13	1.59	474	1.53	688

Table 20. Heavy metal concentrations in earthworms raised in soil receiving sludge or commercial fertilizer (Haufler and Woodyard 1986).

Treatment	Cadmium	Chromium	Copper	Nickel	Zinc
	mg/kg				
Fertilizer (12-12-12)	5.0a	16.5a	9.6a	21.1a	21.0a
Alpena sludge	19.2b	67.4b	37.9b	35.4a	85.4b
Detroit sludge	27.4b	47.7b	24.9b	19.8a	117b

Means in the same column followed by the same letter are not significantly different at the 0.1 level.

Table 21. Cadmium concentrations in tissues of woodcock fed earthworms raised in soil receiving sludge or commercial fertilizer (Haufler and Woodyard 1986).

Treatment	Liver	Kidney	Heart	Muscle	Bone
	mg/kg				
Control	3.12a	17.9a	0.78a	1.25a	0.05a
Fertilizer (12-12-12)	1.81b	12.6b	0.57a	0.69a	0.02a
Alpena sludge	7.38c	30.4c	0.61a	0.97a	0.04a
Detroit sludge	6.21c	36.1c	0.56a	1.12a	0.02a

Means in the same column followed by the same letter are not significantly different at the 0.1 level.

earthworms, two years would be required to reach kidney cadmium levels which may be lethal to woodcock. In free ranging and migratory species such as woodcock, confinement to such a narrow diet is extremely unlikely. Heart, muscle and bone tissue showed no accumulation of heavy metals during this very intensive feeding trial. Minimal risk to human consumers from woodcock is anticipated because lowland forests which serve as the primary habitat for woodcock are systematically excluded from sludge application because of higher water tables and liver and kidney, the only tissues shown here to accumulate cadmium, are discarded by hunters prior to consuming their game.

Nutrition and Sludge Quality--

Sludge application in the forest provides the plant and animal community with numerous nutrients and trace elements needed for growth and related physiological processes. Nitrogen, phosphorus, potassium, calcium, magnesium, sodium, chloride, sulfur, boron, silicon, iron, manganese, cobalt, molybdenum, zinc and copper are essential for proper plant nutrition. Animals also require many of these elements plus iodine, selenium and chromium in trace amounts.

Certain heavy metals present in sludge at modest levels may be beneficial in plant and animal nutrition. However, several (lead, nickel, cadmium and mercury) are toxic and of no known value and others (zinc, copper, chromium and molybdenum), while needed at lower levels, may be toxic at higher concentrations. Among these, cadmium represents the greatest hazard to animals in that it has previously been found to accumulate at levels which do not injure plants but may be deleterious to animals (Baker et al. 1977).

Because of the toxicity hazard to animal (and human) health from high levels of heavy metals, poor quality sludges containing these are best excluded from consideration for land application in forests. When adequate sludge quality control is combined with appropriate sludge application rates, the heavy metals present in sludge are a minimal risk for plant, wildlife and human populations. Given prudent planning and monitoring, upland forests can be recommended as sites for sludge recycling while posing little risk to wildlife or humans consuming wildlife (Haufler and Woodyard 1986).

SOCIOLOGICAL STUDY RESULTS

This study and previous research have demonstrated that the biological, physical and economic challenges of forest land application can be adequately addressed through prudent sludge quality control, site selection and project management. However, natural resource and environmental programs of today must often be conducted in highly visible fashion under the watchful eyes of a frequently skeptical public. Citizen interest in the conduct of these programs is a natural extension of the normal curiosity and concern residents have about activities which may affect their quality of life.

Public agencies and, to a lesser degree, private industry must be sensitive to these sociological dynamics in order to reassure residents about the potential risks, enlist citizen support in beneficial endeavors and achieve program goals which represent a social good for local and regional publics. Citizen participation in the planning process of forest land application programs will not guarantee success, but neglecting public input will most certainly doom any project proposal to failure. The survey of public beliefs and opinions conducted in this study greatly aided agency staff in understanding the nature of information needed for public education materials developed to foster effective citizen participation in planning local forest land application programs.

PUBLIC OPINIONS AND CONCERNS

A public opinion survey conducted in the forested counties of northern Michigan indicated that, while two-thirds of residents believe sludge generation to be a significant problem for cities and industry, a major portion were undecided (Figure 14) about the practice of sludge application on forest land (Peyton and Gigliotti 1986). Very little technical information concerning the risks and benefits of various sludge management alternatives was previously available to the general public and largely accounted for the absence of strongly held opinions. The major task in developing effective public involvement is one of remediating deficient rather than inaccurate knowledge. Further, a large segment of the public (87%) indicated an interest in learning more about sludge management practices.

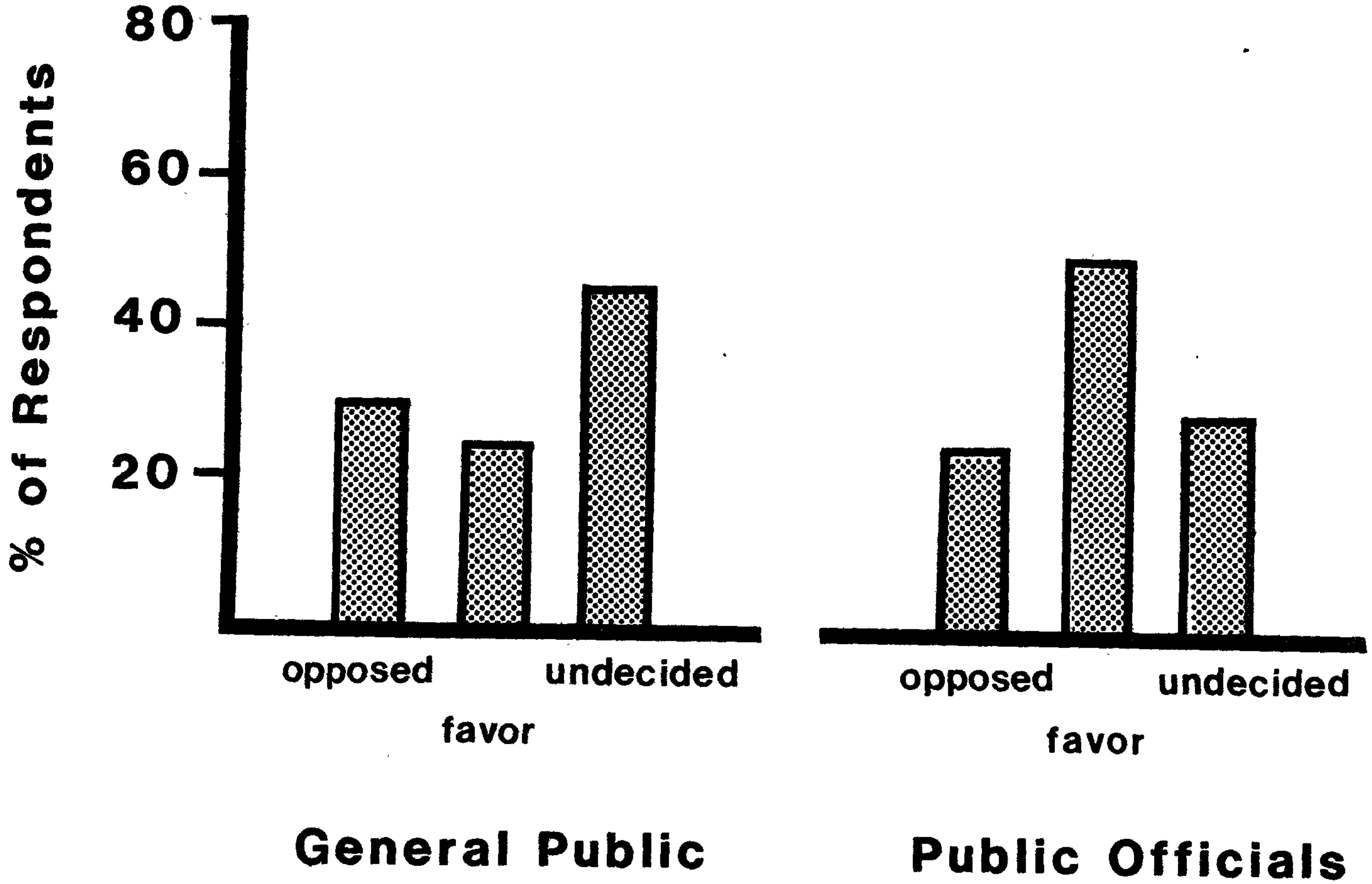

Figure 14. Public attitudes toward forest land application of sludge (Gigliotti and Peyton 1986).

In the context of current public knowledge, human health and environmental quality are of greatest concern and economics and esthetics of least concern to residents considering sludge management options (Figure 15). Public preference among numerous options is a direct result of the perceived impact each will have on human health and second on environmental quality (Peyton and Gigliotti 1986). Although forest land application is the second most preferred sludge management alternative (Figure 16), incineration is most preferred only because of the perceived human health protection it offers. When the public becomes aware of the major health, environmental and economic limitations inherent with incineration which restrict its availability to very few large generator facilities, forest land application may become an increasingly attractive sludge management option.

Forest land application of sludge is an emerging natural resource management issue which has not reached disruptive status with development of strongly polarized interest groups (Peyton and Gigliotti 1986). To minimize opportunity for its development to a disruptive level, forest land application proposals must not be introduced into the planning process as preformed alternatives to be accepted or rejected. Rather, the public must recognize that no decision will be made until they have had opportunity to learn about, participate in evaluation of and influence the final selection among the full range of options. Schematic representations for developing and implementing a planning process are depicted in Figures 17 and 18, respectively. These illustrations, from a public involvement manual (Gigliotti and Peyton 1986) developed during this study, outline steps appropriate to conducting a program for effective citizen participation in the sludge management planning process.

PUBLIC EDUCATION MATERIALS

Public officials (Figure 14) and members of environmental-outdoor organizations are substantially more favorable toward forest land application than the general public. Recreationists who anticipated a loss in the quality of their outdoor experience were much less favorable. Educational programs must therefore make a factual distinction between perceived and actual loss in quality. It should be emphasized that land application programs typically affect relatively small acreages and few individual forest users. Education programs should also convey information to nonresident users of candidate forest sites.

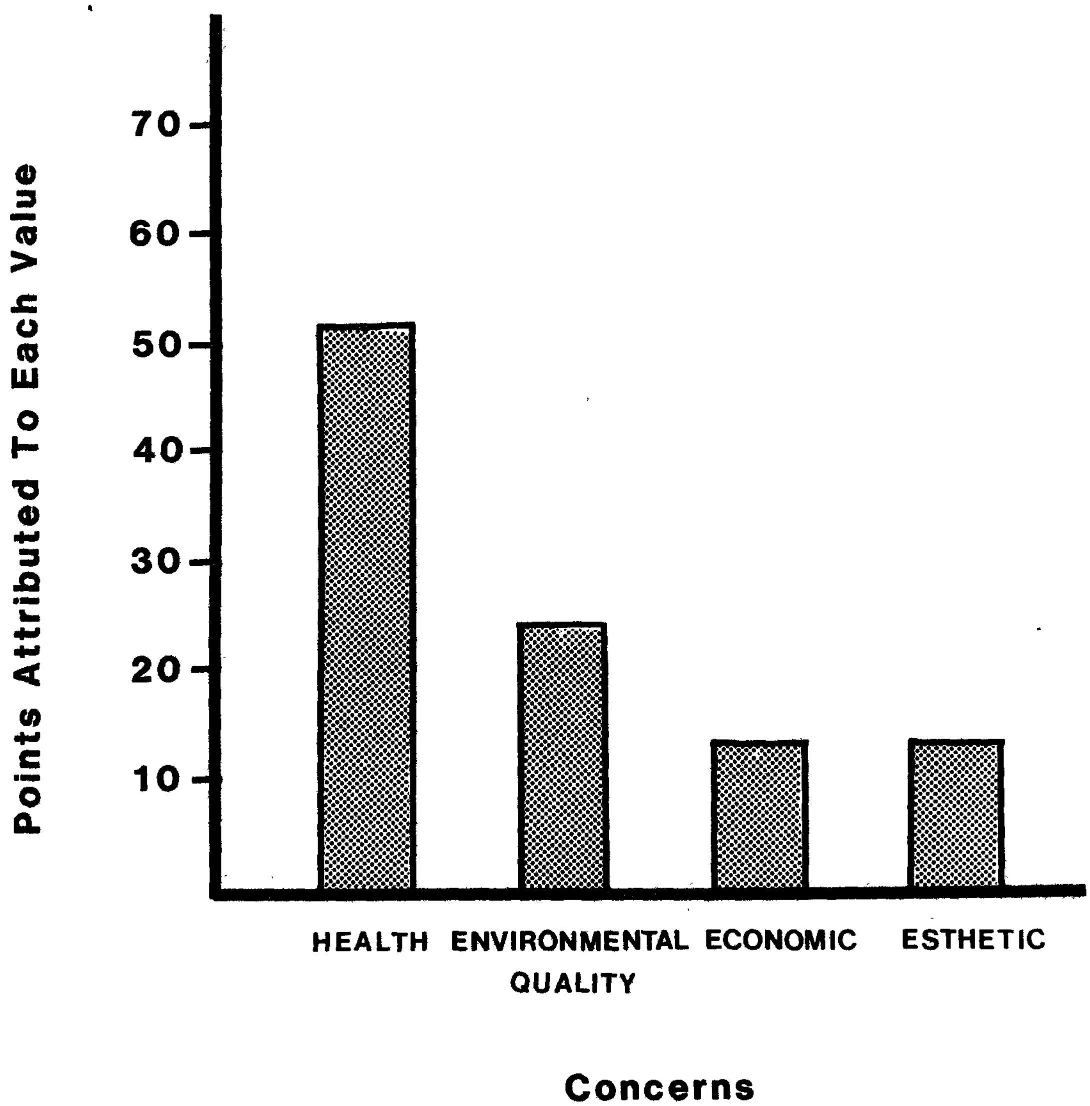

Figure 15. Public priority of concerns about sludge management practices (Gigliotti and Peyton 1986).

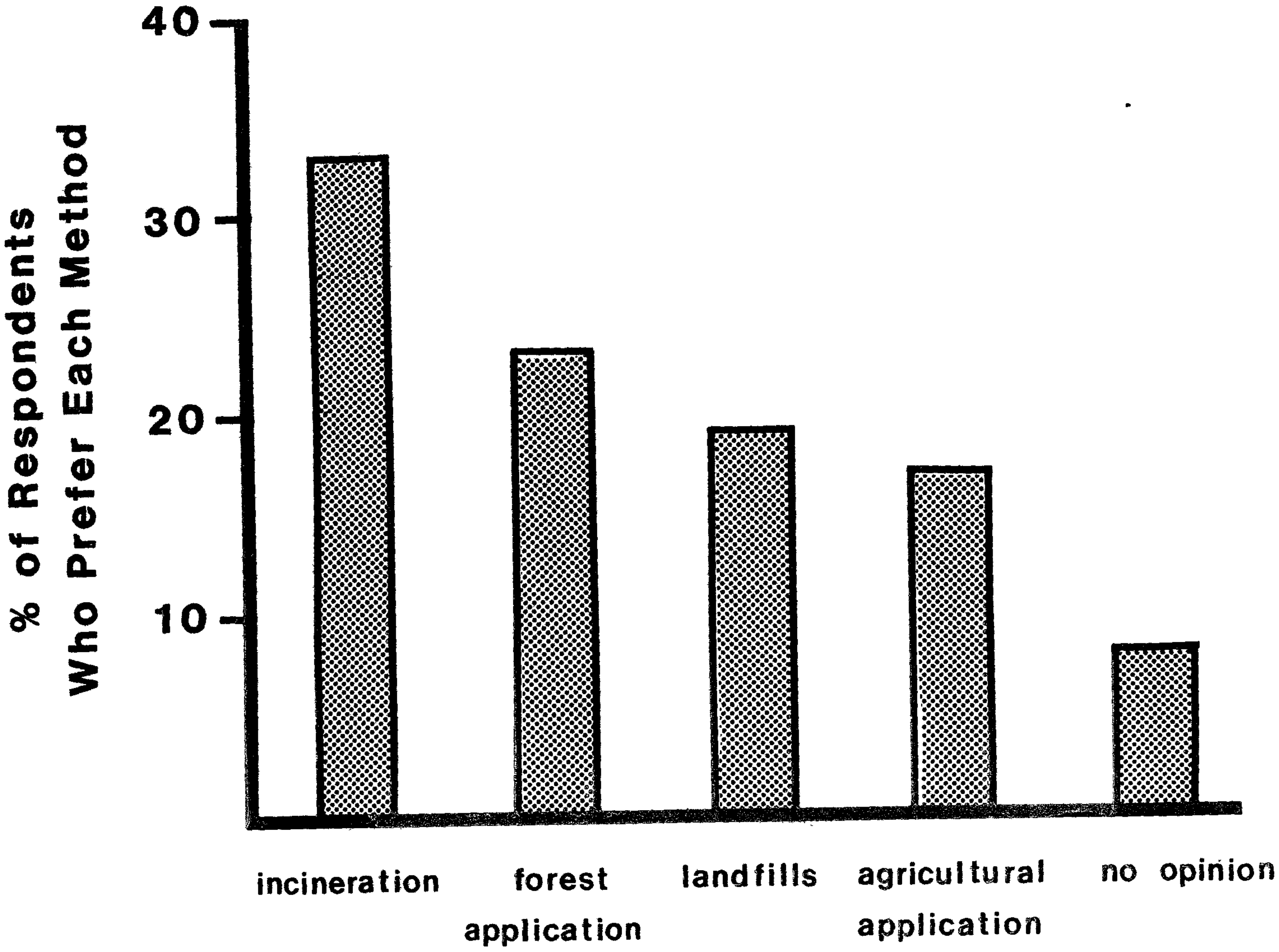

Figure 16. Public preference for sludge management alternatives (Gigliotti and Peyton 1986).

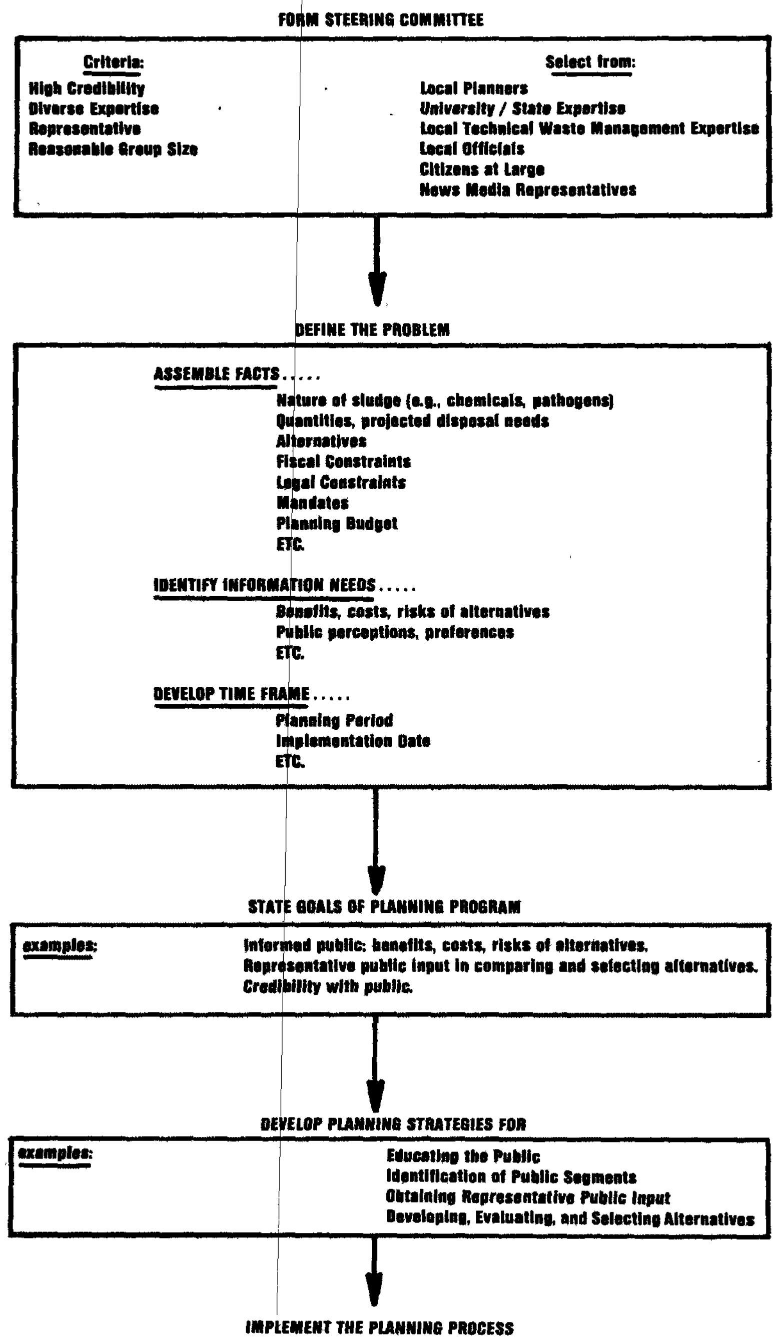

Figure 17. Developing a planning process (Gigliotti and Peyton 1986).

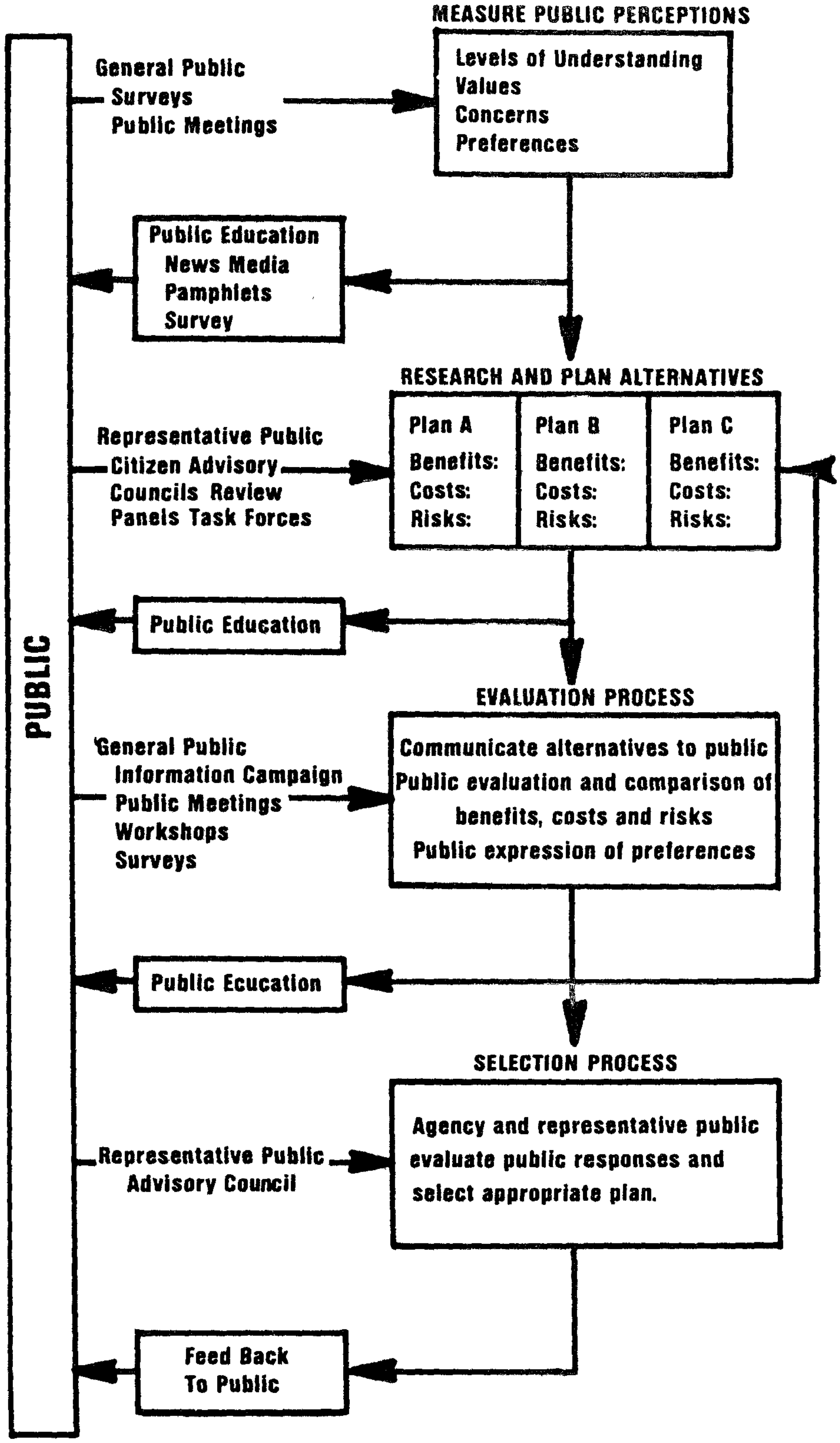

Figure 18. Implementing a planning process (Gigliotti and Peyton 1986).

Educational materials developed to improve public understanding of sludge management practices will be most useful if information on risks and benefits of all options is provided (Peyton and Gigliotti 1986). Because citizens who feel most influential in the outcome of a planning process are more likely to become involved, these materials should also teach members of the public how to become effectively involved. The planning process is best approached without preselected options and should involve the public in simultaneous evaluation of each possible sludge management alternative. To increase citizen perception of influence as well as familiarize individuals with new technology, the public should be provided with constant feedback before, during and after forest land application programs are developed and implemented.

Recognizing that forest land application of wastewater sludge is a relatively unfamiliar practice to a large segment of the population, public involvement early in the planning process is essential to program success, especially when proposals include fertilization of publicly owned forests. Citizens are willing to take responsibility for management of sludge generated in their own communities, but most (73%) do not wish to have their locale become a dumping site for distant communities (Peyton and Gigliotti 1986). Because of this prevailing view, forest land application programs should restrict sludge use to that from local sources. However, this attitude may change as education programs persuade the public to perceive sludge as a resource rather than waste.

In consideration of the above, public education materials developed during this project focused upon two major areas. First, emphasis was placed upon development of a booklet which provides basic background information on wastewater treatment technology and compares the relative benefits and risks of numerous sludge management alternatives (Assaff et al. 1986). The document uses nontechnical language to discuss the advantages and disadvantages of traditional and innovative sludge management options. Second, emphasis was directed toward developing a guidance manual which would aid local units of government, industries and others in conducting a program planning process which would effectively incorporate public input (Gigliotti and Peyton 1986). Through these publications, the public can have access to accurate information about sludge management alternatives and to a planning process which produces outcomes agreeable to its interest.

SIGNIFICANCE TO AGENCY PROGRAMS

Development of technology which affords new waste management alternatives has had effects both upon agency regulatory programs and the regulated community. Numerous consultants and contractors who service the regulated community have taken note of recent developments and responded with requests for additional information about the new technology. Individual citizens, public interest groups and media representatives have also sought technical information concerning the benefits and risks of land application. Further, because forest land application may involve the use of public as well as private forests, agency natural resource and land management programs must be prepared to deal effectively with an increasing number of requests to utilize State Forest land as recycling sites in the future.

EXISTING LAND APPLICATION PROGRAM

Currently in the MDNR Bureau of Environmental Protection, divisions exist which focus primary attention upon air quality, water quality, pollution clean up and waste management. Local programs for recycling waste upon farm, forest and disturbed lands are coordinated through and authorized by the staff of the Land Application Unit. Unit staff is comprised of scientists and engineers whose expertise includes the fields of waste treatment technology, toxicology, biochemistry, soil chemistry, soil management, crop science, geology, hydrology, forest ecology, silviculture and forest management. The principal wastes regulated by the unit are wastewater sludges generated by municipalities and industries and waste residuals produced as byproducts of commercial enterprises. Recycling of the nutrients, trace elements and organic matter present in these materials is permitted on land under authority of NPDES permits or Public Act 245 groundwater discharge permits.

The basic principle which guides land application programs statewide is that of balancing nutrient additions with crop nutrient demands, while not exceeding the trace element assimilation capacity of the soil. Following this guide has typically resulted in increased crop yields, improved soil fertility and, with periodic crop removal, avoidance of undesirable accumulations of nutrients and trace elements in the soil. With proper management, land application represents a unique opportunity to recycle with 100% efficiency wastes which would be potentially troublesome in landfills, groundwater or surface water but are valuable fertilizers on the land.

Considering the widespread generation of recyclable waste treatment byproducts and the variety of sites on which they are applied, the Land Application Program ranks as one of the most important in protecting public health and environmental quality in Michigan. While entire divisions have been formed to protect air and water resources, the Land Application Unit is the sole entity in MDNR responsible for protecting our most basic resource, the soil and its productive potential. The degree to which program management is conducted on a sound scientific basis has direct and profound implication for the safety of the human food chain.

DEVELOPMENT OF TECHNICAL GUIDANCE

The Land Application Program was established in 1978 in the Water Quality Division of MDNR to provide technical assistance in managing the increasing volumes of sludge generated by municipal wastewater treatment facilities. At that time, landfill space was dwindling and fuel costs for sludge incineration continued to rise to prohibitive levels. Independent attempts at land application of sludge met with only intermittent success as a great deal of uncertainty surrounded proper site selection, application rates and management procedures.

Initial staff efforts in program development focused upon farm land application because the greatest portion of sludge was generated in the predominantly agricultural region of southern Michigan and a great wealth of scientific data existed from studies of sludge application on agricultural soils. In consultation with research scientists in the Department of Crop and Soil Sciences at Michigan State University and the USDA Cooperative Extension Service, preliminary guidance for sludge application on farm land was adopted. The guiding principles were firmly based upon scientific findings and reflected a conservative approach in protecting public health and environment. Emphasis was placed upon nutrient addition, trace element accumulation, pathogen control, site selection and proper sludge handling procedures.

In 1980, Land Application Unit staff conducted a sampling survey of sludges produced at all municipal wastewater treatment plants in Michigan. Samples were analyzed by researchers at

Michigan State University for content of nutrients, trace elements and potentially toxic organic chemicals (Jacobs et al. 1981). These results further strengthened the data base upon which the Land Application Program was developing.

By 1982, the preliminary guidance for sludge application on agricultural land was consolidated under single cover in "The Michigan Municipal Wastewater Sludge Management Program" (MDNR 1982). In 1984, this booklet was revised to reflect administrative changes within MDNR, including specifics related to permitting procedures, preparation of approvable sludge management plans and inclusion of all recyclable wastes suitable for application to the soil (MDNR 1984). In 1986, sludge application methods for forest and minespoiled land were incorporated into the basic program document, "Guidance for Land Application of Wastewater Sludge in Michigan" (MDNR 1986).

Criteria for proper management of sludge application on forest land have been developed from the results of this and related studies in Michigan and numerous research efforts in other regions. Research studies in the Pacific Northwest (Bledsoe 1981, Henry and Cole 1983, Zososki et al. 1983, 1984, Cole et al. 1986), Southeastern (Richter et al. 1982, Wells et al. 1984) and Northeastern United States (Sopper and Kerr 1979, Koterba et al. 1979, Sidle and Kardos 1979) have shown that sludge application can be successfully practiced in a variety of forest environments. However, differences in climate, topography, soil and vegetation characteristic of each region demand that application techniques and regulations be tailored to meet the needs of practitioners in a specific environment. Guidelines developed from our research in Michigan should therefore be used with caution beyond the Great Lakes Region and with special attention to environmental conditions prevailing in each specific locale.

The presence of tree roots in the forest environment under most circumstances rules out the direct subsurface injection of sludge into the soil. Rather, sludge must be typically applied upon the forest floor. Liquid sludges have proven in previous research to make better contact with the biologically active portion of the forest floor and soil, as they rapidly infiltrate these components and are readily covered by litterfall during subsequent periods of senescence. Dewatered sludge cake, by contrast, remains perched upon the forest floor for longer periods in a manner which does not allow as rapid decomposition and incorporation of nutrients into the ecosystem (Richter et al.

1982). Persistence of dewatered sludge cake upon the forest floor may also represent a real or perceived threat to human health. For these reasons, best management practices dictate that only liquid and rewatered sludge should be land applied in Michigan forests.

The use of wastewater sludge as fertilizer in the forest is largely to increase production of nonfood chain commodities (ie., wood products). However, numerous food plants consumed directly by wildlife and directly or indirectly by humans also come from forest land. Two concerns associated with sludge applications have been persistence of pathogenic microorganisms and bioaccumulation of heavy metals in the food chain.

Pathogens are always present in wastewater sludge and represent a potential hazard for disease transmission to those who come into direct contact with this material. To minimize this risk, unstabilized raw sludges may not be applied to land in Michigan. Rather, federal and state guidance requires that all land applied sludges undergo a "process to significantly reduce pathogens" such as anaerobic digestion, aerobic digestion, air drying, composting and lime stabilization to effectively reduce pathogen numbers. For an added level of protection, a "process to further reduce pathogens" may be used to decrease the likelihood of disease transmission. When the resulting sludges are land applied, die off of the remaining pathogens is quite rapid from the effects of solar radiation, desiccation and interaction with native soil microorganisms.

The presence of potentially toxic materials in sludge, such as heavy metals and organic chemicals, represents another area of concern in forest land application. While zinc, copper, lead, nickel, chromium and cadmium have been shown to be toxic at high concentrations to agricultural crops, their toxic effects have not been observed in forest plants, perhaps because these wildtypes have retained greater genetic plasticity in adapting to the widely variable chemical environments of forest soils. Because these elements reach animal consumers indirectly through vegetation and are largely in organically bound forms, documented food chain transmission has not been reported in Michigan. Sludges, based upon the presence of heavy metals, have been partially categorized into low level (Class 1), moderate level (Class 2) and elevated level (Class 3) groups (Table 22). While sludges in all categories may be applied to land, increased levels of sludge and site monitoring are required for Class 2 and Class 3 land application. Sludge application rates are ultimately

Table 22. Catagories of sludge chemical quality (MDNR 1986).

Constituent	Class 1	Class 2	Class 3
	mg/kg		
Cadmium	< 5	5-125	> 125
Chromium	< 50	50-5000	>5000
Copper	<250	250-2000	>2000
Lead	<250	250-2000	>2000
Mercury	< 2	2-10	> 10
Nickel	< 25	25-1000	>1000
Zinc	<750	750-5000	>5000
Selenium	< 10	10-80	> 80
Molybdenum	< 10	10-50	> 50
Arsenic	<100	100-2000	>2000
PCB	< 1	1-10	> 10

Table 23. Metal accumulation factors (MDNR 1986).

Element	Metal Accumulation Factor (MAF)
Lead	100
Zinc	50
Copper	25
Nickel	10

limited by allowable maximum annual and lifetime site metal accumulations. The maximum lifetime site metal accumulation (lbs/acre) is the product of soil cation exchange capacity (CEC) at a specific site and the metal accumulation factor (MAF) seen in Table 23. Each MAF represents the relative mobility of a specific heavy metal in soil as determined from research findings. The maximum annual site metal accumulation is one-twentieth of the lifetime maximum, assuming a useable site life of at least 20 years. Standards have not yet been established for land application of most organic chemicals and research in this area is continuing.

Sludge application rates for forests have been primarily based upon nitrogen (not including losses from volatilization or denitrification), as it is most frequently limiting to growth (Table 24). These have been determined by balancing nutrient additions with site nutrient assimilation capacity, a principle similar to that used for agricultural land application. Because forests are complex ecosystems and nutrients may be stored in the forest floor for substantial periods, forest sites may receive sludge applications which supply sufficient nutrients to last an interval of up to five years. Application rates of total nitrogen up to 445 kg/ha (500 lbs/acre) have been demonstrated to benefit forest growth while ensuring adequate protection for groundwater quality.

In Michigan, stands of all ages appear to respond well to sludge application. Forests of varying age will, however present a different set of structural and biological challenges. In each case, it is essential that adequate care be taken to minimize injury to the forest site. Precautions such as use of high flotation tires on sludge application vehicles are considered mandatory on all sites to avoid soil damage from compaction.

In established forest stands, sludge delivery systems that have proven most effective are all-terrain tank vehicles which travel a set of prepared parallel trails and distribute liquid sludge from fixed or rotating spray guns. These provide uniform coverage, confine traffic to established trails and are demonstrated cost-effective. The stand density and effective spray distance of the guns determines the distance interval between trails. On most sites, adequate access can be achieved by removal of some existing trees or use of existing fire control lanes.

In recently established stands (ie., plantations), sludge may be applied as in older stands. However, because of the shorter stature of newly planted trees, sludge will be sprayed upon tree foliage. Because of the danger of solarization of sludge coated leaves, application is best conducted prior to or during rainfall events or during the dormant season. As physical structure of such a forest site is quite open, greater advantage is afforded in ease of sludge distribution over greater distances, hence more cost efficient application vehicle operation.

Table 24. Recommended rates for wastewater sludge application in Michigan forests assuming a five-year retreatment interval (MDNR 1986).

Forest Type	Age (years)	Sludge Application Rate --------Nitrogen------- Available (lb/A/yr)	Total (lb/A/5 yrs)
Aspen	0 to 5	50	250
Aspen	5 to 20	100	500
Aspen	over 20	50	250
Northern Hardwoods	0 to 10	40	200
Northern Hardwoods	10 to 30	80	400
Northern Hardwoods	over 30	40	200
Oak-Hickory	0 to 10	50	250
Oak-Hickory	10 to 30	100	500
Oak-Hickory	over 30	50	250
Elm-Ash-Cottonwood	0 to 5	50	250
Elm-Ash-Cottonwood	5 to 20	100	500
Elm-Ash-Cottonwood	over 20	50	250
Scrub oak	0 to 20	20	100
Scrub oak	over 20	40	200
Red, White, Jack Pine	0 to 10	50	250
Red, White, Jack Pine	10 to 30	40	200
Red, White, Jack Pine	over 30	20	100
Spruce-Fir	0 to 10	40	200
Spruce-Fir	10 to 30	30	150
Spruce-Fir	over 30	20	100
Northern White-cedar	0 to 20	40	200
Northern White-cedar	over 20	20	100

On recently clearcut harvested sites appears the greatest opportunity for operational ease of sludge application. However, unique problems are also encountered in this environment. Studies in the Pacific Northwest measured significant effects on tree survival, competition from weeds (Archie and Smith 1981) and deer browsing (West et al. 1981) following sludge application. Although standing trees may no longer be present to interfere with sludge distribution, application vehicle access to and movement about newly clearcut sites can be hindered by the presence of logging slash.

Of the factors which contribute to program success, careful selection of land application sites is of major importance. Sites selected for land application of sludge should be located where they are not permanently or periodically influenced by flooding. Bottomlands containing alluvial plains or swamps are best avoided. The water table must be maintained no less than 76 cm (30 inches) below the soil surface at the time of sludge application. Soils classified as poorly drained are generally not suitable for forest land application. In Michigan, the maximum slope limitation for surface applied sludge is 6%; however, steeper sites may be used if no significant surface runoff hazard exists. Although the potential for sludge solids runoff during a rainfall event is recognized, the moderate rainfall, high infiltration capacities of forest soils and regulatory limitations on slope steepness greatly decrease the likelihood of such an incident. Sludge has been successfully applied on slopes up to 30% in the Pacific Northwest, underscoring the differing management practices appropriate for various forest environments. Minimum isolation distances of 152 m (500 feet) to homes and commercial buildings and 46 m (150 feet) to wells, surface waters, public roads and property lines must be observed. No sludge may be applied within 610 m (2000 feet) of a municipal water supply well.

For each proposed forest land application site, the following information must be provided to MDNR: (1) a site management history indicating stand age, previous and planned harvest and stand improvement activities, previous fires and importance as wildlife habitat or recreational area, (2) a plat map showing general site location by township and section and land ownership including name and address of land manager, (3) an air photo showing site proximity to structures, roads, streams and lakes, (4) a soil survey map showing soil type, drainage class, surface slope and topographic position of the site, (5) a vegetation cover type map showing species composition, age class, basal area and stocking of the forest stand and (6) a computation of sludge application rate and the nutrient and trace element loading rates. The proposed rate must be based on recent chemical analyses of the sludge and soil. The interval between sludge reapplications on the same area should be specified.

In regions of milder winter climate, such as the Pacific Northwest, little if any restriction is necessary for winter season application. At lower elevations, nearly all precipitation is received as rainfall and frozen soils are nearly unknown. Under such conditions, sludge application in the forest may continue unimpeded throughtout the year.

In Michigan, sludge application in winter when the soil is frozen or snow covered is always done with increased risk to the environment or public health. Applied sludge remains perched above the forest floor for long periods where unanticipated heavy rainfall or sudden thawing may result in lateral movement of solids off the site. The fact that granular rather than concrete frost forms beneath the canopy over forest soils minimizes this risk to large extent. However, as with agricultural lands, winter season sludge application should only be undertaken when no other reasonable option remains. The following standards are to be met in site selection and program operation when winter season sludge application is proposed.

(1) Surface slope of the site must not exceed 2% and pose no reasonable probability for surface runoff of applied sludge solids.

(2) Soils on the site should be classified as well drained or moderately well drained.

(3) The forest stand present must be fully stocked with canopy cover no less than 60%.

(4) A minimum isolation distance of 152 m (500 feet) to homes, commercial buildings, wells, surface waters, public roads and property lines must be observed.

(5) Liquid sludge applications must be limited to a maximum of 93,490 liters per ha (10,000 gallons per acre).

(6) No established winter recreation uses (eg. resorts) are allowed on the site.

(7) Each site must be submitted to MDNR by September 15th prior to the winter during which it is proposed for sludge application.

(8) Each site must be clearly identified by signs which indicate that the area has been fertilized with wastewater sludge to increase tree growth and improve wildlife habitat.

Ultimately, application sites will be selected as part of the local program planning process. When programs are targeted for use of publicly owned lands, each citizen may feel the need to be consulted or at least represented somewhere in the planning process. Very early in the planning phase of a sludge management program the sludge generator should meet with the forest land manager to screen candidate land application sites. Discussion should also thoroughly address the issues of conflicts with public user groups and compatibility with silvicultural objectives of the land manager. Because of the high nontimber values of Michigan forests, recreational user groups are most likely to be in conflict with sludge application. This may not always be so, as fertilization of forests enhances certain amenities considered desirable by recreationists. However, recreational users are most likely to feel displaced by a recent sludge application and preliminary screening of candidate sites should consider this factor.

IMPACT ON ENVIRONMENTAL PROGRAMS

The major effect of developing forest land application technology has been to afford generators of wastewater sludge an additional alternative for utilization of this byproduct. This option is of particular importance to communities and industries located in the forested northern two-thirds of Michigan and similar regions in neighboring states. Now that guidance is available for properly conducting forest land application programs, these communities and industries may soon gain access to an expanded land base which was previously unavailable for this purpose. Also of major importance to forest land owners and managers will be the availability of an essentially free source of nutrients and organic matter with which to enhance forest sites. The total fertilizer value of Michigan's sludge resource has been estimated to exceed five million dollars.

To ensure that information concerning forest land application technology is disseminated in timely fashion, increased levels of staff time and agency financial resources will be required in local program planning, training sessions, informational meetings and travel. Interest expressed in transporting downstate sludges to northern forest sites is likely to be met with opposition from local residents. This situation will continue until the public begins to perceive sludge as a resource rather than waste. Some individuals are anticipated to maintain a skeptical view of land application, as all possible questions concerning risks have not been answered and research is continuing on several fronts.

IMPACT ON RESOURCE PROGRAMS

A major effect of developing forest land application technology has been to provide private forest land owners and public forest land managers with an economical means of using fertilization as a silvicultural treatment. The nutrient resources available allow opportunity for increasing forest productivity and enhancing the quality of wildlife habitat. The ultimate impacts of these uses will be increased income from sale of increased timber volumes and increased carrying capacity for game and nongame wildlife populations. Benefits will accrue for commercial and recreational users of the land. Forest land application represents the linkage between a compelling waste management need and a profitable land management opportunity. Private landowners and agency forest and wildlife managers have expressed interest in utilizing this technology to the benefit of their respective resource management objectives.

As in any matter which is new or potentially controversial, incorporation of forest land application technology into the existing administrative framework has proceeded with caution. Existing workloads, personnel ceilings and budgetary limitations slow the process of integration. Sludge fertilization is also perceived as one more use competing with a vast array of more traditional forest uses. Recreational users of the forest who perceive a loss in the quality of their experience from forest land application may greatly add to the scheduled workloads of forest managers. Relations between agency staff and local government officials may be strained as the result of forest land application proposals on public forest land within their jurisdiction. Despite these complications, agency resource managers appear generally favorable toward forest land application and seem committed to incorporating this technology into their selection of land management tools.

INFORMATION DISSEMINATION

A major function of Land Application Unit staff has been to provide technical assistance to sludge generators who wish to develop land application programs. These regulatory contacts with municipalities and industries will increasingly involve evaluation of the forest land alternative for treatment of waste byproducts. A growing number of these meetings will also involve direct contact with forest land managers from the private and public sectors who share a common interest with the waste generator. At such meetings the technical guidance criteria will be reviewed and public participation in planning discussed.

As part of statewide program development, information sharing sessions have been conducted for the public at Cooperative Extension Service sponsored workshops and a MDNR sponsored conference. These meetings have reviewed technical study findings, discussed application technology, encouraged public involvement and visited sludge fertilized sites. In the future, agency sponsored training sessions will be conducted for regulatory and resource management staff, consultants, local officials and interested citizens. Seminars organized to discuss forest land application information with numerous public interest groups are also planned.

FUTURE DIRECTION

With the current state of the art in forest land application, a technology which is firmly based in sound scientific research is at hand. The major task at this time is to disseminate accurate information concerning its benefits and risks to all interested groups, public or private, regional or local. Technical assistance provided to waste generators and land managers will also include information on the forest land application alternative.

This agency will continue to monitor the results of local programs which involve forest land application and public opinion that develops and evolves in response to program conduct. Staff will continually refine statewide program criteria as new technical and sociological data become available. The Land Application Unit will continue seeking funds to develop research studies which address (1) the long term and retreatment effects of forest land application and (2) the environmental fate of organic chemicals land applied in the forest.

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15. SUPPLEMENTARY NOTES

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16. ABSTRACT

A five-year research-demonstration project to examine the logistical, economic, environmental and sociological aspects of municipal wastewater sludge application was conducted on State Forest land occupied by forest types of major commercial importance in northern Michigan. Sludge applications of 9 Mg/ha resulted in increased levels of nutrients in forest floor and vegetation and increased tree growth and understory productivity. Improvement in the structural complexity of wildlife habitat and the nutritional quality of important wildlife food plants was observed. Wildlife numbers and browse utilization increased on sludge treated areas. Food chain biomagnification studies found no significant risk of heavy metal transfer to wildlife or humans. Public preference among various sludge management alternatives is a direct result of the perceived level of protection each affords public health and environmental quality. While forest land application was the second most preferred option, as the public comes to recognize the environmental hazards and economic limitations inherent with incineration and the value of sludge as a byproduct resource, forest land application should receive increasing attention as a preferred sludge management alternative. State regulatory and resource management authorities are committed to use of this newly developed technology in addressing waste management and land management issues.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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