SILVICULTURAL USE OF WASTEWATER SLUDGE

Applying wastewater sludge to forestland represents an important land-management opportunity that also addresses an environmental need.

By James B. Hart, Phu V. Nguyen, Dean H. Urie, and Dale G. Brockway

Generation of wastewater sludge in the United States has become a problem of increasing proportion, with annual production at 4 million tons in 1970 (Walsh 1976) and 7 million tons currently (Maness 1987). While population and industrial growth have contributed to this problem, legislation requiring higher standards of treatment for wastewater processed in the 15,378 wastewater treatment plants nationwide has been primarily responsible for the increased production of sludge (U.S. Environmental Protection Agency 1985). The Federal Water Pollution Control Act Amendments (P.L. 92-500) of 1972 cited land application of sludge as a major alternative for eliminating nutrient-rich discharges into surface waters (Morris and Jewell 1977), and early studies identified it as an innovative, cost-effective, and environmentally sound recycling technology (Forster et al. 1977).

While sludge application on agricultural land has received more research attention, forestland studies have also yielded promising results. Research indicates that there are many unique advantages to applying sludge on forestland because of site characteristics, ecological structure, and mode of nutrient cycling (Smith and Evans 1977):

- Forest crops are generally nonedible, thereby diminishing the risk of human exposure to elements that may be hazardous in the food chain.
- Although adapted to the low ambient nutrient levels in forest soils, native plants respond to sludge application with significant nutrient and biomass increases (Brockway 1983, Zasoski et al. 1983, Wells et al. 1984). The long-term accumulation of biomass affords substantial storage capacity for certain elements over the period of a rotation, and harvests offer a means of removing elements from treated sites.
- Forest soils are generally porous (resulting in minimal surface runoff of applied nutrients) and often nutritionally impoverished (providing opportunity to substantially increase soil organic matter and nutrient levels through sludge application).
- Typically, forest sites are far removed from large population centers and are used for dispersed recreational activities, minimizing the opportunity for human contact with recently applied sludge.

Application of sludge to forestland has the principal goal of delivering nutrients to the site at a rate that does not exceed the assimilation capacity of the ecosystem. By not exceeding this rate, growth benefits can be obtained without deleterious side effects such as contaminating groundwater, degrading environmental esthetics, and impairing biological processes. Because forest ecosystems vary in structure and manner of nutrient cycling, numerous studies have been conducted during the last decade in forest types of major commercial importance (Sopper and Kerr 1979, Bledsoe 1981, Brockway and Urie 1983, Henry and Cole 1983, Urie et al. 1984, Wells et al. 1984). By improving our understanding of how wastewater

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sludge application on forestland can become an operationally useful means of augmenting the nutrient cycle, these studies have addressed an important environmental need and developed an attractive forest management opportunity.

In 1975, scientists at the USDA Forest Service North Central Forest Experiment Station initiated a series of small plot studies in the forests of northern Michigan to assess the growth and environmental responses of various sludge types applied at widely ranging rates (Urie et al. 1978). Biomass and nutrient concentration increases appeared first in understory vegetation, indicating wildlife habitat improvement as an important benefit of sludge application (Brockway 1983). Tree growth increases were rapid in aspen coppice, but significant in pine plantations only after several years. Soil leachate and groundwater nitrate-N concentrations were related to paper mill and municipal sludge application rates for aspen and pine forests. When referenced with the U.S. Environmental Protection Agency (EPA) 10 parts per million (ppm) water quality standard, maximum acceptable application rates were determined for various sludges and forests in Michigan (Brockway and Urie 1983). Maximum acceptable application rates varied by sludge type because each sludge, as it decomposes, releases nitrogen at a different rate *(table 1)*. Results of these studies were later used to prescribe sludge application rates for a large-scale research demonstration.

Initiation of Research Demonstration

In 1980, an operational-scale forestland application study was jointly initiated by the EPA, Michigan Department of Natural Resources, and Michigan State University's Department of Forestry and Department of Fisheries and Wildlife on areas of sufficient size to examine the silvicultural, hydrologic, wildlife, social, logistic, and economic aspects of sludge fertilization. Sociological studies were conducted throughout the state using survey questionnaires. Ten-year-old aspen *(Populus* spp.) coppice and 50- to 70-year-old northern hardwoods, mixed oak, and red pine–jack pine stands of 40 acres were selected on state forestland in northern Michigan's Montmorency County. Treatments in each stand, replicated three times and randomly assigned to individual 3.8-acre plots, consisted of control, application trails only, and sludge application from trails. Standard sample collection, measurement, and statistical procedures were used to assess treatment effects (Brockway and Nguyen 1986, Burton et al. 1986, Campa et. al 1986, Hart et al. 1986, Merkel et al. 1986, Nguyen et al. 1986, Woodyard et al. 1986).

Sludge Application

Sludge application was conducted in October and November 1981 on oak and aspen and in June and July 1982 on pine and northern hardwoods. Anaerobically digested sludge from the municipal wastewater treatment facilities in Alpena and Rogers City, MI, was transported 50 miles by tank truck to the demonstration area. Sludge was then transferred to an all-terrain tank vehicle equipped with high flotation tires, a standard pressure-vacuum pump, and a three-nozzle system that evenly sprayed the prescribed amount of liquid on the forest floor (see cover photo). Substantial sludge solids and nutrients were applied on a unit area basis to treated plots *(table 2)*.

Silvicultural Responses

Short-term oak, pine, and northern hardwoods growth. Stand growth was evaluated by measuring tagged trees 4 inches or greater diameter at breast height prior to treatment and periodically over 4 years. Tree mortality in jack pine was high as a result of natural aging but was negligible for red pine, oak, and northern hardwoods. Basal area growth increased significantly each year in all sludge-treated stands, except for oak in 1981–82. Total basal area growth increases from 1981 to 1985 were 56 percent, 36 percent, and 56 percent for oak, pine, and northern hardwoods, respectively *(fig. 1)*. During the same period, diameter growth increased 78 percent, 25 percent, and 48 percent for oak, pine, and northern hardwoods, respectively.

Sapling numbers and basal area were increased by sludge application and trail clearing but were also influenced by climatic fluctuations and wildlife browsing. Tree seedling numbers and total groundcover were not changed except under pine, where grasses and

Table 1. Available nitrogen in sludge during first year following application.

Sludge type	Liquid	Dewatered
	lb/dry ton	
Undigested	50–80	20–40
Aerobically digested	30–60	16–30
Anaerobically digested	30–60	10–20
Composted	—	2–10

Table 2. Sludge volume, solids, and nutrient application rates.

Constituent	Aspen	Oak	Pine	Northern hardwoods
Liquid volume (gal)	294,000	206,000	294,000	178,000
Solids (dry ton/ac)	4.5	3.6	3.6	4.0
Nitrogen (lb/ac)	500	358	338	699
Phosphorus (lb/ac)	260	243	226	343
Potassium (lb/ac)	23	19	20	11
Calcium (lb/ac)	372	551	333	448
Magnesium (lb/ac)	39	45	28	45

sedges increased while shrubs and forbs decreased. Competing vegetation neither negated overstory tree growth nor diminished tree regeneration.

Pine foliar nitrogen and phosphorus concentrations 2 years after application were higher and related to increased nutrient levels in the forest floor, surface soil, and soil water. Significant increases in foliar phosphorus concentrations occurred in red oak 3 years after treatment.

Short-term aspen growth. Aspen growth was assessed by measuring the ground-level diameter of stems, performing destructive sampling for biomass, and monitoring tree mortality. First-year mortality of 21.6 percent on treated areas was significantly higher than the 2 percent recorded on control plots (Hart et al. 1986). Increased mortality on sludge-fertilized areas was attributed to increased sunscald, elk browsing, and elk breakage, which predisposed aspen clones to disease infections by *Cytospora chrysosperma*, *Armillaria mellea*, and other pathogens. While sludge did not directly cause the increase in mortality, the nutritional enhancement of aspen foliage resulted in increased elk browsing. Four-year growth of aspen at ground-level diameter increased 23 percent, basal area increased by 48 percent *(fig. 1)*, and biomass was 57 percent greater than controls.

Tree seedling numbers were unaffected during the 1981 to 1985 period by sludge application. Although grass, sedge, and total groundcover temporarily increased in 1983–84, competition from shrubs, forbs, and grasses did not diminish regeneration or stand growth.

Foliar nitrogen and phosphorus concentrations rapidly increased following application. Available forms of sludge-applied nutrients quickly entered the biological nutrient cycle and promoted increased growth throughout four growing seasons. Tree growth responses appeared to continue through the fifth growing season.

Long-term growth. An independent approach was used to assess the potential for long-term forest productivity responses in oak (Merkel et al. 1986). Oak site fertility differences 2 years following sludge application were equivalent to a mean annual growth increase of 15 cubic feet per acre per year based on fertility-growth regressions from 29 stands sampled in adjacent areas. This represented a 29 percent growth response that should continue as long as sludge fertilization maintains these forest floor and soil fertility differences. This estimate corresponds closely to the 21 percent basal area growth response measured on fertilized oak plots from 1981 to 1984. A program of repetitive sludge applications should substantially increase long-term productivity in oak and similar forest types.

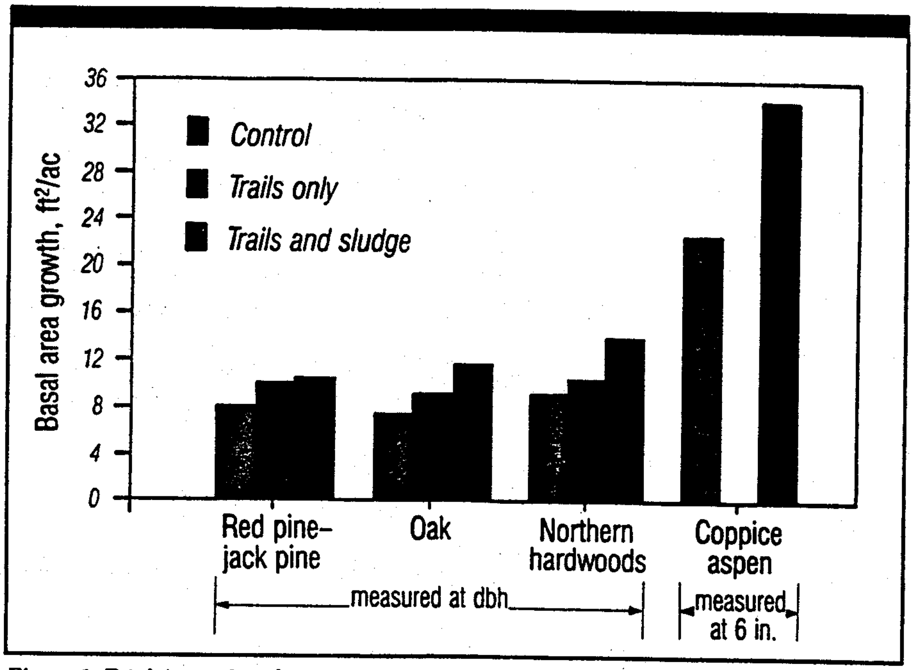

Figure 1. Total 4-year basal area growth response of trees at pine, oak, northern hardwoods, and aspen stands to trails and trails plus sludge compared to control areas.

Forest Floor and Soil Responses

Major portions of sludge-borne nutrients and trace elements were retained as unavailable, undecomposed forms in the humus of the forest floor 4 years following application. Nutrients in available forms moving from forest floor to mineral soil were readily taken up by plants, because no significant fertility changes were observed in surface or subsurface soils. With no major loss of site nutrients detected, sludge application rates on these forest types did not exceed short-term ecosystem assimilation capacity. The long-term fate of accumulated nutrients and trace elements remains uncertain in the event of fire or harvest, which leads to their

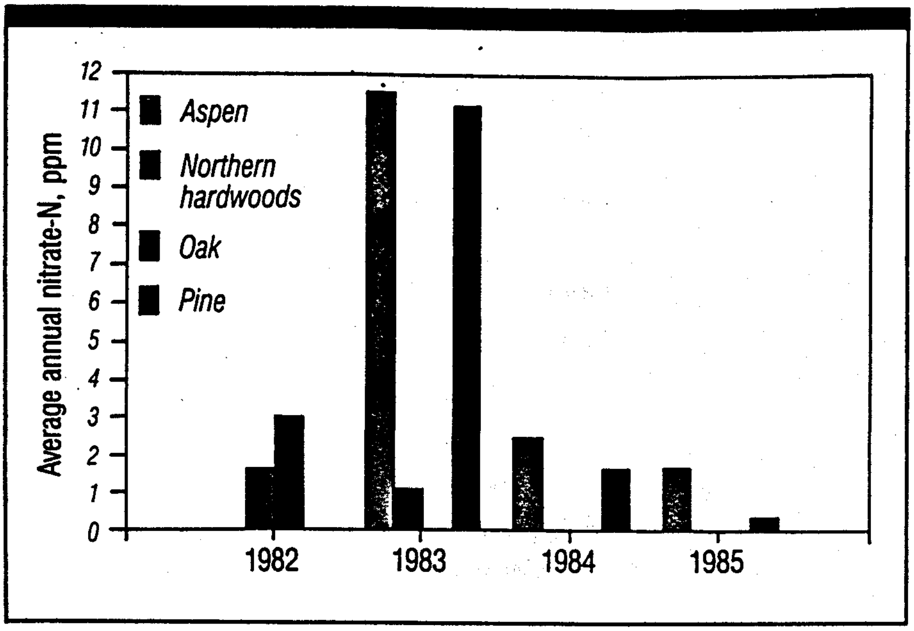

Figure 2. Mean annual nitrate-N concentrations in soil leachate at 4 feet on aspen, northern hardwoods, oak, and pine sites following sludge application (Burton et al. 1986).

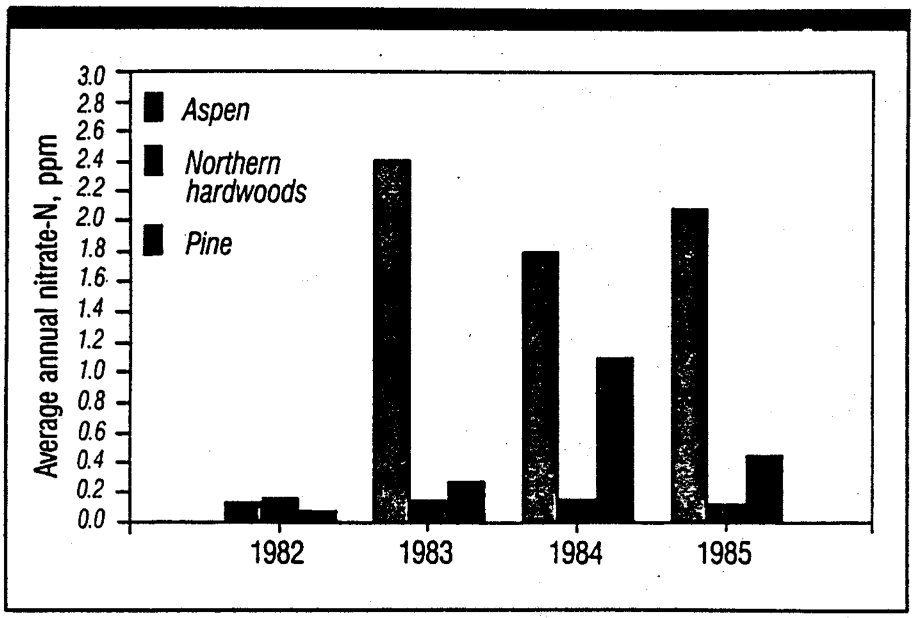

Figure 3. Mean annual nitrate-N concentrations in groundwater at 10 to 26 feet on aspen, northern hardwoods, and pine sites following sludge application (Burton et al. 1986).

rapid release from the forest floor. The relative stability of sludge and the role of the forest floor as a repository for applied nutrients and trace elements are important considerations in properly managing forestland application.

Hydrologic Responses

Soil solution chemistry. Changes in water quality immediately below the major root zone at 4 feet were measured in samples drawn from the soil solution by pressure-vacuum lysimeters. Nitrate-N concentrations *(fig. 2)* were consistent with those predicted from earlier USDA Forest Service studies (Brockway and Urie 1983). While the 10 ppm EPA water quality standard is not directly applicable in the unsaturated zone, the maximum nitrate levels measured in soil solution were proportional to the maximum levels detected in groundwater. In aspen and pine, maximums exceeded 15 ppm for several months, while maximums under oak and northern hardwoods remained below 5 ppm (Burton et al. 1986). Trends of leaching for nitrate anions were related to those for calcium and magnesium cations.

Initial nitrate increases in the soil solution resulted from nitrification of ammonia-N applied in the sludge. This was followed by mineralization of organic nitrogen at rates within the assimilation capacity of the vegetation. The nitrogen mineralization capacity of the forest floor remained high for at least 3 years after sludge was applied, presumably a result of the added organic-N reserve and the introduction of mineralizing and nitrifying bacteria. Laboratory tests showed that mineralization rates in the forest floor and upper mineral soil under pine were much lower than under deciduous trees (Burton et al. 1986).

Groundwater quality. The quality of groundwater at depths from 10 to 26 feet was measured only under pine, aspen, and northern hardwoods *(fig. 3)*, because depth to the phreatic aquifer beneath the oak stand exceeded 90 feet, making sample collection impractical. Increases in nitrate-N, the dominant element leached from sludge-fertilized forest soils, occurred immediately after the first groundwater recharge event following application. Nitrate concentrations reflected sludge nutrient additions, but remained well below the 10 ppm EPA water quality limit (Burton et al. 1986). Elevated nitrate concentrations were the only chemical change measured that was consistently related to sludge application. Measures of sulfate, chloride, and conductivity were weakly related, and those of trace elements were unrelated to sludge application.

Wildlife Responses

Habitat and populations. Sludge applications resulted in significant changes in the plant communities present. While species composition was unaffected, the quality and vertical distribution of cover beneficial to important wildlife species was substantially enhanced (Campa et al. 1986). Groundcover vegetation was universally increased, and the greatest gains in vertical cover were observed in the lower 6 feet strata. Annual production of herbaceous species under aspen increased 200 percent 1 year following sludge fertilization and remained 50 percent higher than untreated areas 3 years later. A similar response of lesser magnitude was observed in oak, pine, and northern hardwoods. The nutritional quality of wildlife forage plants also improved within 1 year of sludge fertilization. Forage protein and phosphorus increases of 20 to 50 percent were observed to persist for three growing seasons following sludge application.

Improved habitat structure and forage nutritive quality increased populations of small mammals within 1 year of sludge application (Woodyard et al. 1986). Browsing by white-tailed deer and elk increased significantly on sludge-fertilized areas in response to improved forage quality, increased cover density, and greater ease of movement along access trails (Campa et al. 1986). Protein is a critical factor in deer forage, with low background levels frequently limiting fawn production. Higher forage protein levels resulting from sludge fertilization may lead to an increased birth rate for fawns.

Food chain. Concern has been expressed about the potential for bioaccumulation and transmission of heavy metals and toxic organic chemicals between trophic levels in the food chain. Bioassays of plant and animal tissues from organisms exposed to sludge-fertilized soil in upland forest and laboratory trials indicated only a minor accumulation of toxicants to levels that would not be harmful to forage plants, herbivores, or carnivores at higher trophic levels, including humans (Woodyard et al. 1986). Serial feeding trials conducted in the laboratory using sludge from a heavily industrialized municipality (Detroit, MI) yielded minor accumulations of cadmium, chromium, and nickel in mice kidney and liver tissue not unlike those found in free-ranging small mammals sampled during field studies where sludge was applied from local sources with little industrial input.

Only when laboratory-confined woodcock, a lowland insectivore, were fed an exclusive diet of earthworms grown in soil treated with sludge contaminated by high levels of heavy metals did kidney tissues show significantly elevated but nonlethal concentrations of cadmium (Woodyard et al. 1986). Since free-ranging woodcock would not forage so intensively on sludge-treated upland forest sites, and because their entrails are discarded by hunters prior to consumption, the actual risk to human health from cadmium transmission by this route is minimal.

Existing sludge management guidelines recommend avoiding sites with high water tables and strongly discourage land application of highly contaminated sludges (Urie and Brockway 1986). Therefore, upland forests can be recommended as sites for productively recycling sludge nutrients with minimal risk to wildlife or humans.

Operational Considerations

Logistics. Stand preparation is an important consideration in planning for sludge application to forests (Brockway and Nguyen 1986). In addition to selecting or adjusting characteristics such as species composition, age class distribution, and stocking density to maximize the biological response to fertilization, provision must also be made for suitable access to distribute sludge uniformly. While many mobile and stationary irrigation systems have been tested, best operational results have been achieved with all-terrain tank vehicles on prepared access trails spraying a uniform cover of liquid sludge on the forest floor. In Michigan, access trails were 16 to 20 feet wide, spaced at intervals of 66 feet, and oriented in a north-south direction to minimize sunscald on the bark of newly exposed residual trees (Hart et al. 1986). Although these dimensions caused removal of 20 percent of the stand area for access trails, using spray equipment capable of reaching greater distances or using existing trails would require removal of little or no area from production (Henry and Cole 1983).

Sludge from generator facilities is normally transported as a liquid (3 to 8 percent solids) in large tank trucks to the forest site, where it is transferred to an application vehicle. An application vehicle should have high-flotation tires to minimize soil compaction and a pressure-vacuum pump to fill and empty its tank. In Michigan, liquid sludge was laterally discharged up to 33 feet from the vehicle through three spray nozzles arranged to cover near, intermediate, and distant bands of the forest floor (Brockway and Nguyen 1986). Vehicles are available with a turret spray gun that can deliver sludge up to 165 feet and are specifically designed to negotiate the uneven terrain and steep slopes of forest sites. Research in western Washington has shown that dewatered sludge may be trucked to a site where it can be successfully rewatered and sprayed on the forest floor (Henry and Cole 1983). Only liquid sludge is recommended for application in forests. Surface-applied

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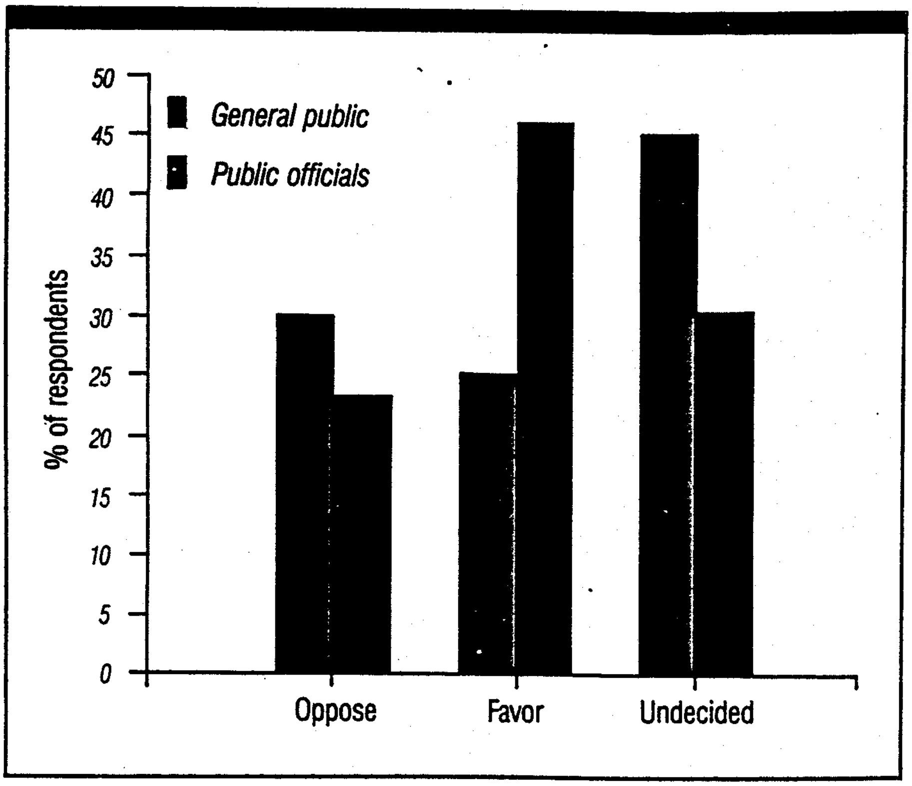

Figure 4. Public attitudes toward forestland application of sludge (Gigliotti and Peyton 1986).

dewatered sludge cake often remains on the forest litter and thus makes poor contact with the most biologically active portion of the forest floor. This prolongs the period of incorporation by natural processes and extends the period of potential direct contact with forest users (Richter et al. 1982).

Costs. Major costs for sludge fertilization of forests are stand preparation, which is typically paid by the land owner, and sludge transport and application, normally paid by the sludge generator (Brockway and Nguyen 1986). In stands of unmerchantable trees, access trail development may be a net cost to the land manager. Costs for bulldozing trails through aspen sprouts in Michigan averaged $66 per acre. When trees are of sufficient size and quality, net income may be realized by harvesting timber growing in proposed access trails. Financial return to the land manager ranged from $6 to $15 per acre on northern hardwoods, oak, and pine sites prepared for access. The cost to a sludge generator for transporting 1 million gallons of sludge a distance of 50 miles and applying it to 44 acres of forestland was $48,576 in 1981, approximately 4.9 cents per gallon or $275.94 per dry ton. This cost compares favorably with applying sludge on agricultural land, where shorter transportation distances (less than 15 miles) are typical.

The economic justification for applying sludge on land has most often been addressed in management planning as a least-cost alternative when compared to traditional options such as landfilling, which does not beneficially recycle the nutrients contained in sludge. Based upon the median nutrient and microelement content of sludges and current commercial fertilizer prices, the value of the sludge resource in Michigan is estimated at $23.76 per ton or $5,327,775 per year. At recommended application rates (Urie and Brockway 1986), the value added to a forest site may range from $75 to $160 per acre. Because all costs for sludge transportation and application are normally incurred by the generator, the economic benefits of sludge fertilization in the forest are readily apparent to the land manager.

Sociological Considerations

Public opinion. Public opinion surveys conducted in the forested counties of northern Michigan indicated that while two-thirds of residents believe sludge generation is a significant problem for cities and industry, the majority of residents are undecided *(fig. 4)* about the practice of sludge application on forestland (Gigliotti and Peyton 1986). Very little technical information on the risks and benefits of various sludge management alternatives was available to the general public, and this lack accounted for the absence of strong opinions. The task in developing effective public involvement is to supplement deficient knowledge rather than remediate inaccurate knowledge. A large segment of the public (87 percent) indicates an interest in learning more about sludge management practices.

Human health and environmental quality are of greatest concern, and economics and esthetics of least concern, to residents considering sludge management options *(fig. 5)*. Public preference is a direct result of the perceived impact each option will have, first on human health and second on environmental quality (Gigliotti and Peyton 1986). Forestland application is the second most preferred sludge management alternative *(fig. 6)*. 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 in sludge incineration, forestland application will become an increasingly attractive option.

Forestland application of sludge is an emerging natural-resource issue that has not prompted such public controversy and strongly polarized interest groups that consensus-building is not possible (Gigliotti and Peyton 1986). To minimize the opportunity for development of disruptive levels of controversy, forestland application proposals must not be introduced into the planning process as preformed alternatives to be accepted or rejected. Rather, citizens must recognize that no decision will be made until they have had an opportunity to learn about and evaluate the full range of options and influence the final selection.

Public education. Members of environmental organizations and public officials are substantially more favorable toward forestland application than is the general public *(fig. 4)*. Recreationists who anticipate a loss in the quality of their outdoor experience are much less favorable (Gigliotti and Peyton 1986). 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.

Educational materials to improve public understanding of sludge management practices will be most useful if the risks and benefits of all options are explained (Gigliotti and Peyton 1986). These materials should also encourage and teach members of the public how to

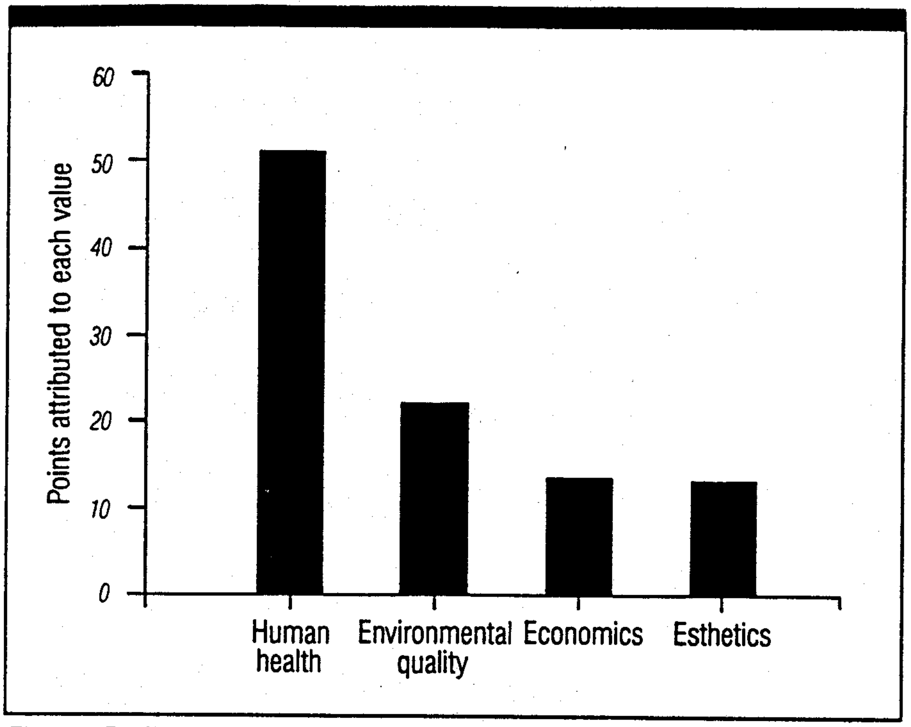

Figure 5. Public priority of concerns about sludge management practices (Gigliotti and Peyton 1986).

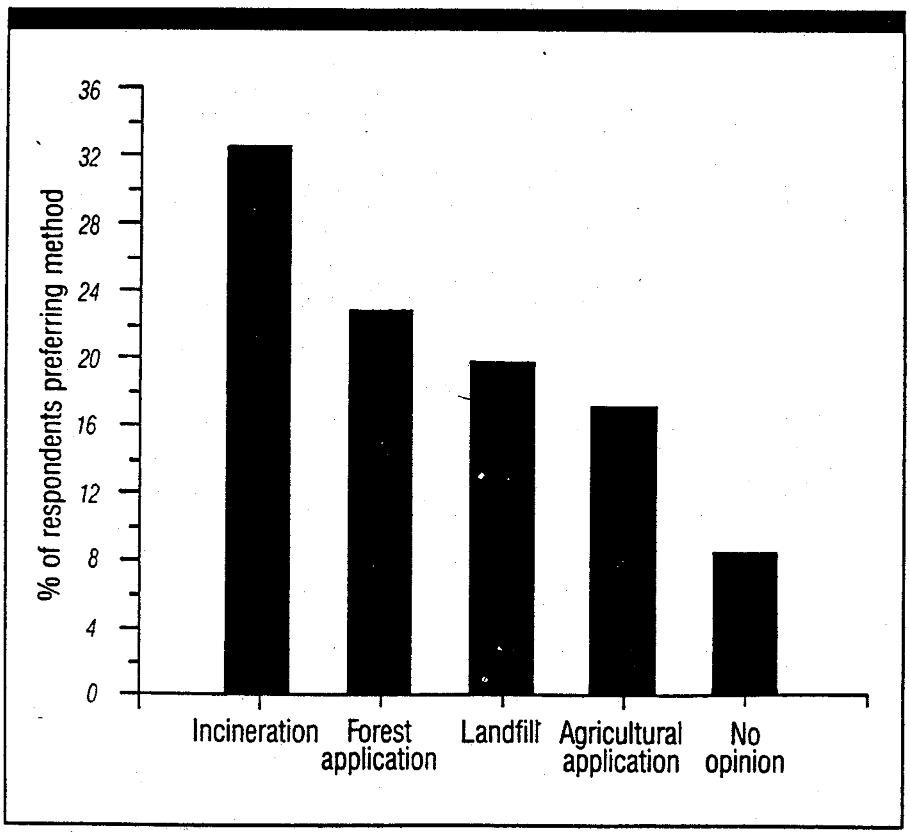

Figure 6. Public preference for sludge management alternatives (Gigliotti and Peyton 1986).

become effectively involved in project planning. To increase perceived influence as well as to familiarize individuals with new technology, the public should be provided with constant feedback before, during, and after forestland application programs are developed and implemented.

Because forestland 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 percent) do not wish to have their locale become a dumping site for distant communities (Gigliotti and Peyton 1986). Because of this prevailing view, forestland application programs should initially be limited to use of sludge from local sources. This attitude may change as education programs persuade the public to perceive sludge as a resource rather than waste.

Summary and Recommendation

In Michigan, sludge-applied nutrients substantially enhanced nutrient cycling, tree growth, wildlife habitat, and nutritional quality of forage plants in the forest. At appropriate application rates, these benefits were obtained while avoiding groundwater contamination and toxicant transmission in the food chain. Forestland application methods were shown to be technologically feasible and cost effective, providing the land manager with a valuable silvicultural option.

Forestland application of wastewater sludge represents an important land management opportunity that also addresses an essential environmental need. We recommend that silvicultural use of wastewater sludge be considered by land managers to not only benefit tree growth and wildlife habitat but also highlight the participation of forestry professionals in publicly supported environmental protection programs. ■

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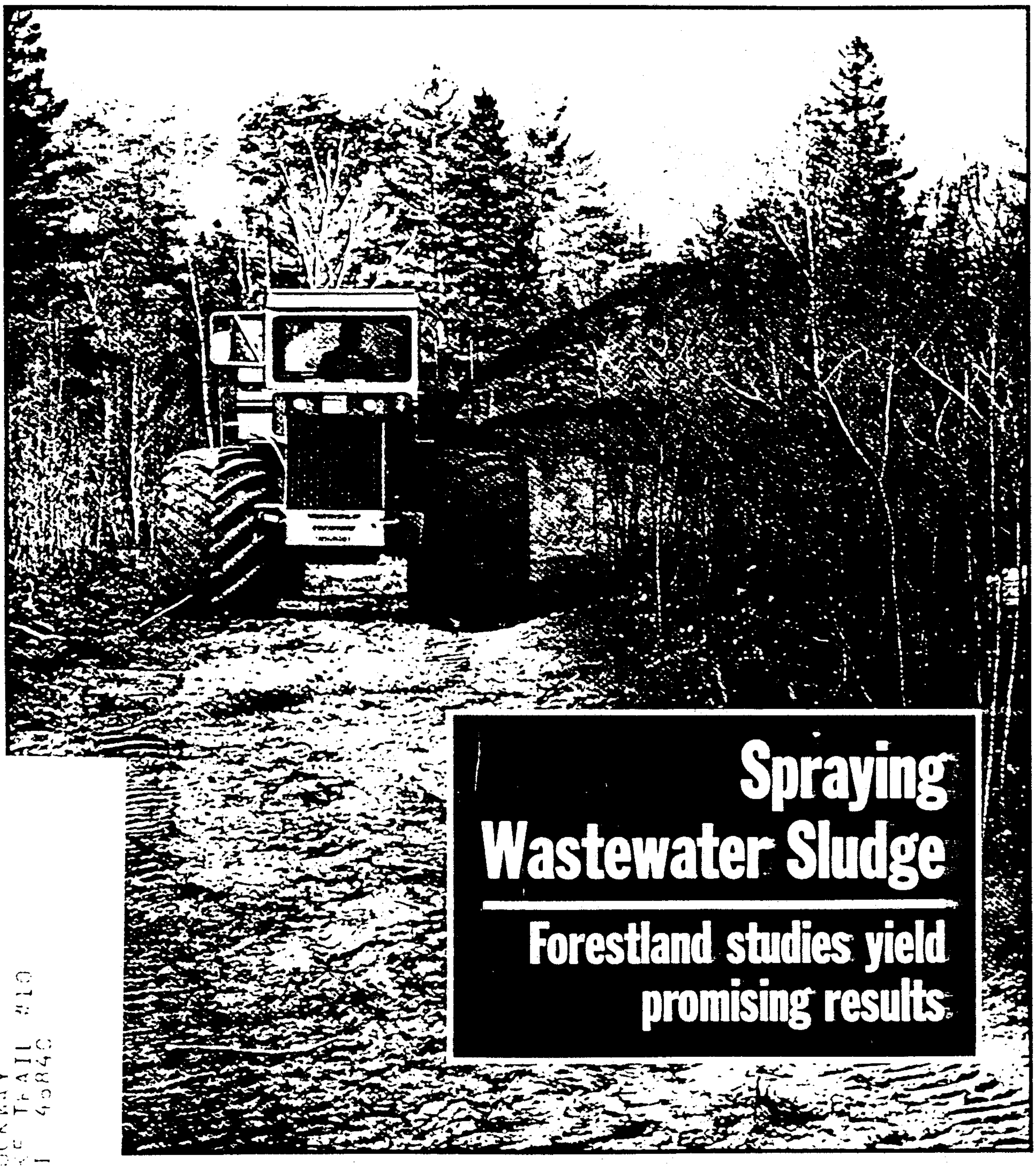

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