Wastewater and Sludge Nutrient Utilization in Forest Ecosystems

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ABSTRACT Although forest ecosystems have evolved efficient mechanisms to assimilate and retain modest levels of annual geochemical input, their productivity is frequently limited by low levels of available nutrients. A review of research studies conducted in the major U.S. forest regions indicates that the nutrients and organic matter in wastewater and sludge represent a resource of substantial potential benefit to augment site nutrient capital and ameliorate the environment for plant growth. Wastewater irrigation provides phosphorus that is strongly held in upper layers of mineral soil and cations (potassium, calcium, sodium) that accumulate but are subject to loss with leaching anions (sulfate, nitrate, chloride) during periods of groundwater recharge. Applied nitrogen that is not lost to the atmosphere by volatilization or denitification accelerates forest floor decomposition, accumulates in soil in association with organic matter, is taken up by plants, or, following nitrification, is leached as nitrate to groundwater. Nitrogen utilization is greatest in young poplar forests growing in association with understory vegetation. Sludge applications provide phosphorus, potassium, and calcium that largely remain in the forest floor and upper layers of mineral soil. Calcium and potassium are subject to loss by leaching with anions (principally nitrate) during recharge periods. Applied nitrogen that is not lost through volatilization or denitrification is initially stored in the forest floor, where the resulting decrease in C:N ratio accelerates the decomposition of organic matter, and eventually the nitrogen is assimilated by vegetation or leached to groundwater as nitrate. Nitrogen uptake is highest on sites occupied by young poplar (200 to 400 kg/ha-yr) and somewhat less in middle-aged stands of Douglas-fir (90 kg/ha·yr) and loblolly pine (105 kg/ha·yr). Nitrogen application rates of 400 to 500 kg/ha have been associated with tree growth increases of up to 40% without producing soil leachate concentrations of nitrate that exceed the 10 mg/l U.S. EPA standard. Repeated sludge applications should provide a cumulative positive effect on forest site quality that could lead to permanent increases in productivity.

In the United States, disposal of waste effluent and sludge has become an increasing problem in recent decades because of expanding industrialization, population growth in urban and suburban areas, and legislation requiring a higher standard for wastewater treatment. Walsh (1976) estimated 1970 sludge production at 3.6 million Mg (4 million tons) and projected a doubling by 1985. Total 1975 discharge of domestic sewage was 90.5 billion liters (24 billion gallons), containing approximately 733 million kg (1.6 billion lb) of nitrogen, 674 million kg of phosphorus, and 428 million kg of potassium (Freshman 1977). The value of these nutrients amounted to $561 million.

With adoption of the Federal Water Pollution Control Act Amendments (PL 92-500) in 1972, land application of waste effluent and sludge was cited as a major alternative for eliminating nutrient-rich discharges into navigable waters (Morris and Jewel1 1977). Preliminary research and experience have shown land application to be an innovative, cost-effective technology for environmentally sound waste treatment (Forster et al. 1977). Although agricultural land 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).

In application of wastewater and sludge to forest land, as with other lands, the main goal is to deliver nutrients to the site at a rate that does not exceed the assimilation capacity of the ecosystem. In so doing, deleterious side effects such as contamination of groundwater, impairment of biological production, and degradation of environmental aesthetics are avoided. However, forest ecosystems differ in their manner of and capacity for nutrient cycling.

Diverse research endeavors have been under way in the major U.S. forest regions in the hope of more precisely calibrating rates of waste-borne nutrient assimilation, loss, and cycling in the forest types of commercial importance (Sopper and Kerr 1979, Bledsoe 1981, Brockway 1983, Henry and Cole 1983, Urie et al. 1984, Nutter and Red 1984, Wells et al. 1984). This work is important for improved understanding of how wastewater and sludge application to forest land can become operationally useful in completing the nutrient cycle. Before examining these studies in detail, a brief review of nutrient cycling in natural, undisturbed forests will provide an ecosystem prospective for further discussion of the utilization of nutrient additions.

NUTRIENT CYCLING IN FOREST ECOSYSTEMS

Nutrient utilization in forest ecosystems is the extent to which and how nutrients are used (Winburne 1962) on the forest site. Although thousands of physical, chemical, and biological processes are involved in forest nutrient cycles, an examination of the dynamic interaction among ecosystem components within the "geochemical nutrient cycle" and "biological nutrient cycle" provides a concise overview.

Forests are systems bounded by atmosphere,. geologic strata, and adjacent environments (Figure 1). Water, energy, and nutrients may cross their boundaries through various input and output mechanisms and accumulate in numerous ecosystem components: overstory trees, understory vegetation, forest floor, mineral soil, and saturated groundwater zone or geologic strata within the plant rooting zone. The magnitude of nutrient inputs from external environments and the efficiency of nutrient storage in ecosystem components largely determine the degree of nutrient loss from a forest site. Over time, the levels of site nutrients may increase, decrease, or remain unchanged, depending on the relative rates of nutrient input and output.

Within the forest ecosystem, nutrients are cycled on a seasonal basis among the numerous components present (Figure 2). Nutrients available in the soil and forest floor are taken up by plants (uptake) and used in growth and metabolism. Some of these nutrients are used in production of plant structures (retention) and others are cycled back either through crown wash or in litterfall to the forest floor (return). Decomposition and incorporation of organic matter in the forest floor and soil make these returned nutrients available for another turn of the annual nutrient cycle.

The relative magnitude of nutrient flux in temperate forest ecosystems is shown in Table 1, constructed from data compiled by Pritchett (1979). While by no means exhaustive, the information provides a range of values measured by numerous studies in recent

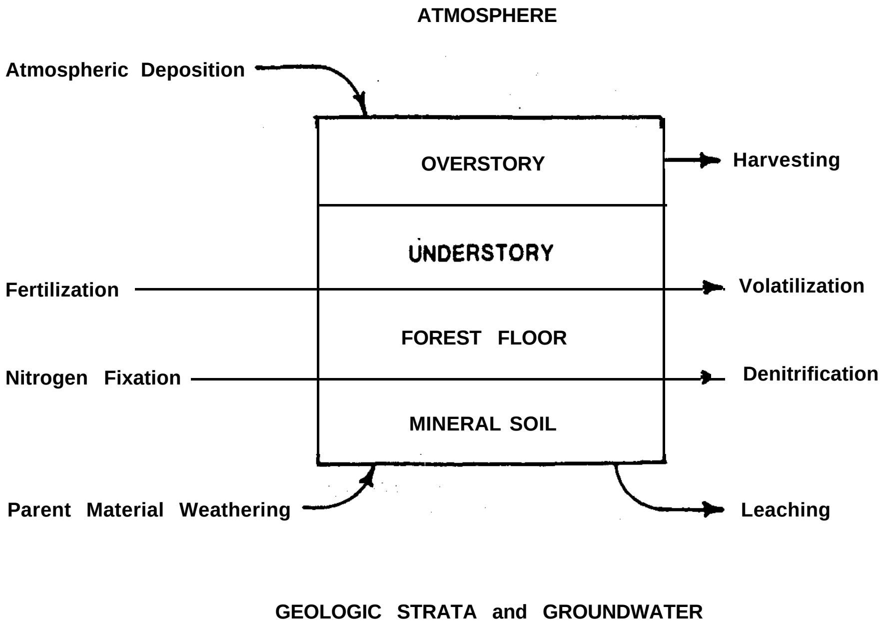

Figure 1. The geochemical nutrient cycle.

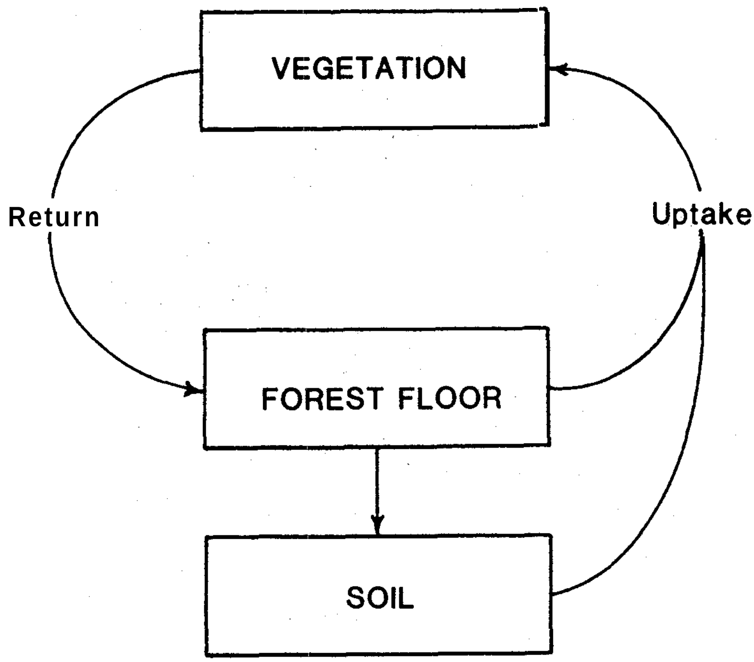

Figure 2. The biological nutrient cycle.

TABLE 1. Nutrient dynamics of temperate forest ecosystems.

	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium
			(kg/ha·yr)		
Geochemical Inputs	13-26	0.1-0.5	8-20	19-40	5-11
Atmospheric	3-13	0.1-0.5	0.8-4.6	2-15	0.5-3.0
Dinitrogen fixation					
Nonsymbiotic	0.3-3.0				
Symbiotic	9-10				
Geologic weathering	--	--	7-15	17-25	4-8
Geochemical Outputs	1-5	0.1-0.5	1-4	4-11	3-12
Leaching and runoff	0.4-4.8	0.1-0.5	1-4	4.5-11.4	3.2-12.4
Volatilization	Negligible without fire				
Exports	Negligible without harvesting				
Net Geochemical Change	12-21	0	7-16	15-29	0-2
Ecosystem Internal Cycling					
Uptake	34-61	4-12	6-29	--	--
Retention	12-24	1-10	2-14	--	--
Return	22-40	3-10	4-10	--	--

decades. These data reflect rates of nutrient input to and output from ecosystems and rates of nutrient cycling within ecosystems.

In examining the net geochemical change (inputs minus outputs) of the forest ecosystem, more nutrients are input than output each season. As this balance is maintained year after year, large nutrient amounts accumulate until an event such as wildfire or timber harvest occurs, resulting in a massive nutrient loss. Mortality of individual or groups of trees from natural aging, insects, disease, or atmospheric causes and their subsequent decomposition and release of stored nutrients may also result in high outputs of nutrients.

Annual geochemical nutrient gains are largely assimilated by vegetation. Although lower nutrient quantities in the forest ecosystem are retained each year by plants than are returned to the forest floor, nutrients accumulated in plant biomass can reach substantial proportions over forty to fifty years. Much smaller nutrient quantities are accumulated in the forest floor and soil over the long term. While younger forest ecosystems may accumulate nutrients in the forest floor, such accretions are not present in middle-aged and mature forests, where the rate of litterfall addition approximates that of decomposition. Nutrient accumulation in soils is even less, being largely associated with living roots, organisms, and soil organic matter.

FERTILIZER ADDITIONS

Forest fertilization is a carefully controlled geochemical input to a forest ecosystem which is typically conducted when tree growth is limited by a deficiency of one or two plant nutrients. In the Pacific Northwest, where nitrogen is often limiting, nitrogen fertilizer applications of 100 kg/ha (89 lb/acre) every four years or 150 kg/ha every five years are commonly used (Miller and Webster 1979). In the Southeast, where phosphorus may be limiting, phosphorus fertilizer additions of 40 kg/ha are applied every twenty years (Pritchett and Smith 1975). These rates, equivalent to 25 to 30 kg N/ha and 2 kg P/ha per year, are very similar to natural nitrogen and phosphorus inputs in temperate forest ecosystems.

The addition of fertilizer increases the level of available nutrients in the forest floor and soil and increases nutrient uptake, nutrient retention, and tree growth. Fertilizer nitrogen is rapidly incorporated into the forest floor and soil, from where it is taken up by plants and retained in association with increased biomass production or returned to the forest floor by leaching and litterfall. After four to six years, the rate of nitrogen cycling declines to pretreatment levels, indicating the need for another application. Fertilizer phosphorus also enters the nutrient cycle to enhance growth, but most of it forms insoluble iron and aluminum compounds in the soil. Slow resolution of these compounds over an extended period provides small annual inputs of available phosphorus, similar to those from geologic weathering, to the forest ecosystem. Because of the economic considerations in conducting a forest fertilization program, fertilizer application rates are controlled to levels that promote tree growth but do not result in leaching losses great enough to degrade groundwater quality.

WASTEWATER ADDITIONS

Wastewater application to forest land provides the ecosystem with nutrients that improve soil fertility and enhance vegetation growth (Nutter and Red 1984). Of these, nitrogen and phosphorus are of greatest concern, because they are most limiting to production in aquatic ecosystems. Characteristic fertilizer nutrient concentrations found in various waste effluents are listed in Table 2. As is obvious, the chemical form of each element is quite variable and yet has a profound influence on its overall fate in each plant-soil system.

Nitrogen, for example, may be present as organically bound or in one or more of its mineralized forms, ammonia or nitrate. Biological wastewater treatment plants often discharge effluent that is higher in the mineralized forms of nitrogen, while sewage lagoon systems may be managed to convert most effluent nitrogen to organic forms. If sewage is stored in lagoons prior to land application, nitrate may become an important effluent constituent, because ammonia-N is typically lost as a volatilized gas. This process of “ammonia stripping” may be useful in lowering effluent nitrogen content so as to enable use of higher hydraulic application rates. The average concentrations for the various forms of nitrogen reported in effluents used in several forest application studies are

TABLE 2. Nitrogen and phosphorus concentrations in domestic wastewater (U.S. EPA 1981).

	Wastewater Nutrient Level		
Component	High (mg/l)	Medium (mg/l)	Low (mg/l)
Nitrogen	85	40	20
Organic	35	15	8
Ammonia	50	25	12
Nitrate	0	0	0
Phosphorus	15	8	4
Organic	5	3	1
Inorganic	10	5	3

shown in Table 3. The high degree of variation directly influences nutrient loading rates and highlights the need to evaluate study results in terms of the nutrient dynamics unique to each locale.

TABLE 3. Concentrations of nitrogen in wastewater used in forest irrigation studies (Hook and Kardos 1978, Brockway et al. 1979, Schiess and Cole 1981, Harris and Urie 1983, Nutter and Red 1984, Urie et al. 1984).

Study Site	Total N (mg/l)	Mineralized N (mg/l)	Organic N (mg/l)
Unicoi State Park, Georgia	18.0	7.6	10.4
Pennsylvania State University	27	21	6
Pack Forest, Washington	18.6	17.1	1.5
Harbor Springs, Michigan	5.4	2.1	3.3
Middleville, Michigan	12.6	7.6	5.0
East Lansing, Michigan	13.8	10.6	3.2

Renovation Capacity

The ability of a forest ecosystem to renovate wastewater is dependent on processes such as nutrient uptake by plants and nutrient accumulation in the soil. Renovation efficiency is commonly expressed as the ratio of the nutrient amount applied in irrigation water and the amount leaving in water drained from the site. Renovation capacities for nitrogen are listed in Table 4 for numerous forest ecosystems. In general, renovation capacities in juvenile forests exceed those of established stands because of the higher growth rate and nutrient uptake of young trees and associated herbaceous cover (Urie et al. 1978).

Over time, the ability of a forest site to renovate wastewater becomes progressively diminished. The vegetation can be managed so that site longevity is only limited by the assimilative capacity of the soil (McKim et al. 1982), but the ability of the soil to adsorb nutrients in solution is dependent on the amount of organic matter and clay it contains. Approximately 4 to 6% organic matter and clay has been suggested as a minimum to maintain soil renovation capacity for wastewater (Murrman and Koutz 1972). Forest ecosystem longevity is, as yet, not fully predictable (McKim et al. 1982). Longevity estimates for phosphorus removal through chemical precipitation and adsorption exceeding 100 years have been reported for wastewater sites in Washington, Michigan, and Pennsylvania. One may, nonetheless, expect disparity between empirical data and such predictions based on theory.

Phosphorus. Phosphorus applied to forest sites in irrigated wastewater is predominantly orthophosphate accompanied by lesser amounts of organically bound forms. These organic forms become available, also as orthophosphate, as soil organic matter decomposition proceeds. Phosphates entering the soil are adsorbed onto the surfaces of clay minerals and precipitated with iron and aluminum hydrous oxides. At typical slow-rate wastewater applications to forest ecosystems, nearly complete retention of phosphorus can be anticipated, leading to high renovation efficiency (McKim et al. 1982).

Wastewater-applied phosphorus is largely retained in the surface mineral soil (Harris 1979). As much as 34% of that applied has been reported to have been taken up by poplar plantations in the Pacific Northwest (Cole and Schiess 1978) and Great Lakes regions (Urie 1979). Soil phosphorus tends to become less soluble over time. This process, in addition to plant uptake, tends to increase the period during which a forest site may function as an effective renovator for phosphorus.

Potassium. Potassium applied to forest soils during wastewater irrigation is adsorbed by clay minerals and can be leached from the profile under an expanded presence of sodium and ammonium cations (McKim et al. 1982). The magnitude of leaching loss may be related to irrigation rate. In Pennsylvania, exchangeable potassium levels decreased in the upper meter of soil beneath an old field and a mixed hardwood forest that were irrigated for eight growing seasons with 5 cm (2 inches) of waste effluent per week. Beneath a nearby red pine stand and mixed hardwood forest irrigated with 2.5 cm of waste effluent per week, soil exchangeable potassium levels either increased or remained unchanged from controls (Sopper and Kardos 1973). In northern Michigan, exchangeable potassium levels increased in the sandy soil where a northern hardwoods forest was irrigated for five growing seasons with 7.5 cm of stabilization pond effluent per week (Harris and Urie 1983). In this study, the effluent contained an equivalent ratio of total N to total K, and the overall nutrient loading rate was relatively low. However, soil leachate samples collected at a depth of 120 cm (4 ft) contained elevated potassium concentrations.

Potassium depletion on sites irrigated with wastewater may be a problem where plant uptake of potassium increases or when effluent nitrogen concentrations greatly exceed those of potassium. Forage grass irrigated with wastewater has been shown to assimilate

TABLE 4. Nitrogen renovation capacities for numerous forest ecosystems.

Vegetation	Soil	State	Effluent Treatment	Irrigation Rate (cm/wk)	Nitrogen Loaded (kg/ha·yr)	Nitrogen Leached (kg/ha·yr)	Renovation (%)
Established Forests							
Douglas-fir	grav. sand	WA	secondary	5	327	75	77'
Northern hardwoods	sand	MI	lagoon	7	a2	15	a2
Red pine	sand	MI	lagoon	8	131	40	70
Maple	loam	MI	secondary	5	217	200	a
Maple	loam	MI	secondary and lagoon	5	40	40	0
Red pine	loam	PA	secondary	5	728	250	66
Mixed hardwoods	loam	PA	secondary	5	726	100	86
Pine and hardwoods	loam	GA	lagoon	7.6	703	233	67
Juvenile Forests							
Douglas-fir	grav. sand	WA	secondary	5	484	20	96
Poplar	grav. sand	WA	secondary	5	484	20	96
Mixed conifer	loamy sand	MI	lagoon	7	105	12	a9
Hardwood-Conifer	loam	MI	secondary	5	117	30	74

greater amounts of potassium than that supplied in the applied effluent (Palazzo and Jenkins 1979). Analysis of tree foliage indicates that leaves typically accumulate less than half as much potassium as nitrogen, suggesting that potassium deficiencies induced by imbalanced wastewater nutrient composition are quite unlikely.

Cations. Sodium, calcium, and magnesium delivered to forest sites with irrigated waste effluent will tend to exchange with cations in the soil exchange complex. The wastewater levels of those cations will influence establishment of a new equilibrium of soil cations, the solution leached from soil being adjusted accordingly. Renovation efficiencies of 85% and 24%, respectively, for calcium and sodium reflect the tenacity with which each is held in the soil (McKim et al. 1982). Like potassium, calcium and mag nesium are increasingly leached from the profile under the expanded presence of sodium and ammonium ions. Total dissolved salts remain relatively unchanged in the soil solution, normally at concentrations that do not adversely affect plants or soils in the humid climates of forested regions.

Anions. Sulfate in irrigation-applied wastewater is weakly adsorbed by hydrous iron oxides present in forest soils, but the amount of sulfate thus retained in relation to that applied is generally negligible. Chloride and nitrate are not adsorbed in mineral soils, generally passing rapidly through the profile during periods of recharge to groundwater. Levels of chloride, nitrate, and sulfate found in soil leachate may be expected to approximate those in applied effluent minus adjustments for plant uptake and denitrification of nitrate.

Nitrogen. Under high rates of nitrogen application with irrigated waste effluent, the biological decomposition rates of litter and humus have been increased in eastern mixed hardwood forests (Richenderfer and Sopper 1979). Nitrogen accumulation in wastewater-irrigated forest soils has also been reported. At weekly irrigation rates up to 88 mm which supplied as much as 550 kg N/ha over five seasons, the upper 10 cm of loamy sand beneath a red pine stand accumulated approximately 600 kg N/ha (Harris 1979). This increase was related to increases in soil organic matter ranging from 50 to 100%, presumably including decomposed forest floor materials. Ammonia adsorption onto clay minerals may also contribute to increases in soil nitrogen.

Wastewater-supplied ammonia may be subject to volatilization loss directly to the atmosphere but is largely converted to nitrate under well-aerated, acidic soil conditions. Nitrate is then susceptible to denitrification or leaching during periods of excess soil moisture. Nitrate leaching and nitrogen gas diffusion have been suggested as the primary means of nitrogen assimilation in forest land treatment systems in the Southeast (Nutter and Red 1984). However, studies in the Pacific Northwest have assumed denitrification loss to be of little consequence (Schiess and Cole 1981). In most studies, only applied nitrogen and leached nitrogen have been directly measured.

Wastewater irrigation of forests has, with minor exceptions, universally stimulated increased production of vegetation and a concomitant increase in nitrogen uptake. Significant increases in nitrogen levels in bark, twigs, and leaves were reported for effluent-irrigated conifers and hardwoods in Georgia (Brister and Schultz 1981). Increased crown biomass and nitrogen assimilation of red pine in Michigan were linearly related to rate of wastewater irrigation (White et al. 1975). Increases in foliar nitrogen concentrations for numerous effluent-irrigated forests are shown in Table 5. Values are similar to those associated with maximum growth rates in mineral fertilizer studies.

Nitrogen uptake by waste effluent-irrigated forests may reach substantial proportions

TABLE 5. Foliar nitrogen levels in forests irrigated with wastewater.

Vegetation	State	Total Kjeldahl Nitrogen (%) Control	Irrigated
Conifer seedlings	MI	2.4	2.9
Hardwood seedlings	MI	2.1	2.2
Hybrid poplar cuttings	MI	1.9	2.3
Northern hardwoods, mature	MI	1.6	2.2
Northern hardwoods, understory	MI	2.0	2.6
Mixed hardwoods	PA	2.2	3:o
Red pine	PA	1.3	2.2
White spruce	PA	1.5	2.2
Mixed hardwoods	GA	1.6	2.0
Mixed pine	GA	1.1	1.6
Hardwood-pine, understory	GA	1.2	1.6

TABLE 6. Nitrogen uptake by vegetation irrigated with wastewater.

Vegetation	State	Irrigation Period (years)	Applied (kg N/ha)	Assimilated (kg N/ha)	Efficiency (%)
Grass	WA	5	2,215	627	28
Douglas-fir seedlings	WA	5	1,811	893	49
Poplar	WA	5	2,171	1,247	57
Hybrid poplar	MI	4	500	400	80
Old field	MI	1	150	128	85
Old field	PA	9	208	195	94
Pine and hardwoods	GA	6	703	470	67
Hardwood seedlings with grass	GA	1	521	152	29

(Table 6). Although the highest nitrogen uptake efficiencies appear in systems dominated by herbaceous cover, the greatest total uptake is observed on sites with young, rapidly growing stands. Douglas-fir and poplar seedlings in the Pacific Northwest can reportedly assimilate as much as 893 and 1,247 kg N/ha, respectively, over a five-year period of irrigation that supplied about 2,000 kg N/ha (Schiess and Cole 1981). Nitrogen uptake by hybrid poplar in Michigan was 400 kg/ha over a four-year irrigation period during which approximately 500 kg N/ha were loaded on the site (Cooley 1979). A mature mixed hardwood and pine forest in Georgia assimilated 470 kg N/ha, some of which was no doubt denitrification, during one irrigation year in which over 700 kg N/ha were applied (Nutter and Red 1984). A pole-sized red pine plantation in Michigan took up as much as 70% of the nitrogen applied to the site during the first three years of effluent irrigation (White et al. 1975). However, nitrogen removal rates of only 20% were measured in an effluent-irrigated mature mixed hardwood stand in the same locale (Burton and Hook 1979).

Harvesting trees is a useful means of removing accumulated nitrogen from an effluent-irrigated forest site. The storage of nitrogen in aboveground vegetation can be substantial, ranging from 112 to 224 kg/ha per year in established eastern forests to rates approaching 300 kg/ha per year in rapidly growing jwvenile stands (McKim et al. 1982). Nitrogen is known to accumulate differentially within tree tissues, concentrating most in foliage and least in xylem and phloem of branches and stems (Ralston and Prince 1963). Therefore, the type as well as the timing of harvest may be a major management concern. If only stemwood is harvested in a young hybrid poplar stand, one-third as much nitrogen would be removed from the site as when whole trees containing foliage are taken. As the proportion of stemwood increases with age, the importance of short rotations to maximize nitrogen removal becomes evident. Whole tree harvest at five to eight year intervals could remove over 80% of the nitrogen stored in the aboveground biomass of an irrigated poplar plantation (Cooley 1978).

In juvenile stands, understory vegetation constitutes an important sink for nitrogen, The grass component in young Douglas-fir and poplar stands accounted for 57 and 37% of the nitrogen uptake, respectively, on effluent-irrigated sites in the Pacific Northwest (Schiess and Cole 1981). With crown closure the importance of understory vegetation declines. Ground cover has also been established as a component instrumental in abating nitrate leaching in young plantations.

Models of Nitrogen Utilization

Study results from the major forest regions have been compiled to assess ecosystem nitrogen utilization trends (Table 7). Direct measurements have been made of nitrogen applied, taken up, and leached. Values for soil storage and volatilization loss were estimates inferred from other measures.

Nitrogen application rates have typically been moderate, ranging from 40 to over 500 kg/ha annually, and produced nitrate discharges to groundwater generally less than the 10 mg/l US. EPA **standaid.** With minor exception, this standard was not exceeded until applied inorganic nitrogen approached 200 kg/ha per year. High rates of effluent irrigation and nitrogen application resulted in higher concentrations of nitrate in leachate and increased rates of overall loss of nitrate-N from the site.

Generally, younger forests capable of substantial rates of nitrogen uptake have shown the best on-site retention of this nutrient. Older forests that have shifted their mode of nutrient cycling, from rapid assimilation of exogenous nutrients to conservation and recycling of endogenous nutrients, were less efficient sites for wastewater renovation. Although forest soils offered some increased storage for nitrogen, greater storage generally resulted from increases in site organic matter following irrigation. Volatilization and denitrification losses, while discounted by some studies, are believed important in others.

The fragmentary nature of these data does not allow for an integrated overview of each of the regions. Proper system selection and management will remain an exercise of balancing nitrogen application rates with volatilization, denitrification and leaching losses, plant uptake, and soil storage. Further studies will no doubt be required before a comprehensive construct of nitrogen utilization in various wastewater-irrigated forest ecosystems becomes available.

SLUDGE ADDITIONS

As previous research has indicated, the major benefit of nutrient additions in forest ecosystems is to remediate natural nutrient deficiencies (Cunningham 1976), increase foliar efficiency (Brix and Mitchell 1980), enhance foliage production, accelerate crown closure, and shorten the overall rotation period (Miller 1981). However, when large

TABLE 7. Nitrogen transformation and utilization in waste effluent-irrigated forests.

Vegetation	Application Rates: Wastewater (mm/wk)	Application Rates: Organic N (kg/ha·yr)	Application Rates: Inorganic N (kg/ha·yr)	Volatilized N (kg/ha·yr)	Soil Storage (kg/ha·yr)	Plant Uptake (kg/ha-yr)	Leached Nitrate-N (kg/ha·yr)	Leachate Nitrate-N (mg/l)
Pacific Northwest Region								
Poplar	50	100	200	134		200-300	50	10
Douglas-fir, young	50	100	200	96		150-200	87	14
Douglas-fir, mature	50	100	200	--	--	175	125	8
Great Lakes Region								
Poplar	35	25	30	--	--	100	25	12
Poplar	70	50	60	--	--	100	50	25
Mixed hardwoods	50	48	32	30		--	51	2
Mixed hardwoods	72	48	147	50		--	146	5
Mixed hardwoods		90	20	20		40	20	2
Red pine	25	35	5	--	--	--	5	1
Red pine	50	120	20	--	--	60	50	5
Northeastern Region								
White spruce Mixed hardwoods Mixed hardwoods Mixed hardwoods	50 50 25	548	241	30		200 84 --	200 -- 50	15 210
Southeastern Region								
Mixed hardwoods	76	150	150	50		50	200	9

quantities of nutrients are added to a site, as in the application of wastewater sludge, substantial improvement of site quality can be effected (Miller 1981) through a change in moisture relations and the cycling of nutrients, and this may lead to permanent increases in productivity (Zasoski et al. 1983). Organic matter additions with sludge may also be instrumental in promoting site aggradation; the importance of the forest humus in nutrient storage and supply is well documented (Foster and Morrison 1983). Growth responses to sludge additions in Pacific Northwest Douglas-fir forests are reportedly of greater magnitude and longer duration than the average 23% response obtained from applications of commercial fertilizer (Zasoski et al. 1983).

The potential nutritional and growth benefits of sludge applications in forests appear to be intuitively clear, but environmental concerns persist about the possible enrichment of groundwater by sludge-borne nutrients that leach from the rooting zone (Koterba et al. 1979, Sidle and Kardos.1979, Riekerk 1981, Urie et al. 1984). While nitrogen loss to surface and groundwaters is generally less than 3% of the total applied as commercial fertilizer (Groman 1972), several researchers have measured higher rates of nitrate-N leaching below the rooting zone following applications of wastewater sludge (Riekerk and Zasoski 1979, Sidle and Kardos 1979, Vogt et al. 1981, Brockway and Urie 1983). This large flush of nitrate anions has been associated with a reduction of exchangeable cations in lower soil horizons (Riekerk 1978, Wells et al. 1984). Adjustment of sludge nutrient application rates to those suited for the particular combination of sludge, site, and vegetation characteristics has been shown to abate nutrient leaching losses (Riekerk 1982, Brockway and Urie 1983).

Fate of Applied Nutrients

The nutrients of major concern in forest ecosystems (nitrogen, phosphorus, potassium, and calcium) are, with the exception of potassium, found in good supply in wastewater sludges. Nitrogen may typically range from 2 to 7%, phosphorus from 1 to 4%, potassium from 0.2 to 1%, and calcium from 0.4 to 2%. The nutrient composition of three sludges applied to forests in the Pacific Northwest, Great Lakes, and Southeast is presented in Table 8. If a 20 Mg/ha (9 tons/acre) sludge application rate were assumed, individual nutrient application rates would result as shown in Table 9. As is obvious, sludges are highly variable in nutrient content.

Nutrients reaching the forest floor through sludge application are subject to numerous processes of transformation and translocation. Nitrogen is perhaps the most studied of the major nutrients, having been identified as an element that most often limits vegetation growth (Cunningham 1976, Edmonds and Mayer 1981). It may be found in sludge primarily in organic forms, but is also present in soluble forms as ammonia and, at lower concentrations, as nitrate. Nitrogen added to a forest site characteristically undergoes volatilization, mineralization, nitrification, denitrification, uptake by plants, leaching as nitrate, and storage in the forest floor and soil (Cole et al. 1983). Other nutrients-phosphorus, -potassium, and calcium-are somewhat less dynamic and have received less attention in sludge application studies.

Phosphorus. Sludge applications have typically resulted in significant increases of phosphorus levels in the forest floor (Brockway 1983, Wells et al. 1984). Although a portion may be present as orthophosphate, most of the phosphorus is organically bound and slowly released as the humus and sludge slowly degrade (Edmonds and Mayer 1981). Phosphorus entering the soil was largely retained in the upper profile (Stednick

TABLE 8. Nutrient composition of three wastewater sludges applied to forest land, (Zasoski 1981, Cole et al. 1983, Brockway 1983, Wells et al. 1984).

	Seattle, WA (%)	Cadillac, MI (%)	Augusta, GA (%)
Total nitrogen	4.3	6.0	7.2
Ammonia-N	0.9	1.7	3.0
Nitrate-N	--	0.002	0.01
Phosphorus	1.5	7.8	1.6
Potassium	0.16	1.54	0.27
Calcium	0.4	1.4	1.5

TABLE 9. Nutrient application rates of three wastewater sludges applied to forest land, assuming a 20 Mg/ha sludge application.

	Seattle, WA (kg/ha)	Cadillac, MI (kg/ha)	Augusta, GA (kg/ha)
Total nitrogen	860	1,200	1,400
Ammonia-N	180	340	600
Nitrate-N	--	0.4	2
Phosphorus	300	1,560	320
Potassium	32	308	54
Calcium	80	280	300

and Wooldridge 1979, Richter et al. 1982, Urie et al. 1984), where fixation with free iron oxides caused increases (from 0.06 to 1.5%), up to 13-fold (Riekerk 1978), which were capable of substantially altering soil chemical properties (Zasoski 1981). Phosphorus concentrations in understory vegetation have reportedly doubled following sludge application (Richter et al. 1982, Brockway 1983), indicating increased levels of plant uptake. Phosphorus increases in foliage of loblolly pine have been less, though significant (Wells et al. 1984). Leaching losses of this nutrient have been consistently reported as minimal (Urie et al. 1978, Riekerk and Zasoski 1797, Hornbeck et al. 1979, Richter et al. 1982). Many forest ecosystems appear to accommodate sludge-borne phosphorus additions and store this nutrient in a manner of benefit to short- and long-term site quality.

Potassium. Potassium additions with sludge application are, because of lower concentrations, generally of lesser magnitude than those of other major nutrients (Bledsoe and Zasoski 1979). These smaller additions reportedly show minor changes in forest floor (Brockway 1983) and soil (Hornbeck et al. 1979) potassium levels. A very soluble nutrient, potassium is observed to move readily from sludge into the upper soil profile (Stednick and Wooldridge 1979), where it is presumably retained through exchange. Increased plant uptake of potassium following sludge application has been infrequently reported (Brockway 1979). However, potassium losses through leaching have been noted (Riekerk 1978, Urie et al. 1984, Wells et al. 1984) to accompany major intervals of nitrate leaching which cause cation stripping in the soil profile (Riekerk 1981, 1982). This interaction between leachable anions and potassium may result in induced nutrient deficiencies in certain potassium limited soils (Bledsoe and Zasoski 1979). Following sludge application, this stripping phenomenon is observed in the soils of several forest ecosystems.

Calcium. Additions of calcium at rates as high as 1,600 kg/ha have produced watershed level changes, which were relatively small and of short duration (Hornbeck et al. 1979). Calcium from sludge applications is largely held in the forest floor (Brockway 1979) and moves into the upper soil profile (Urie et al. 1984), where it is retained (Stednick and Wooldridge 1979) by cation exchange. Although increases in plant uptake of calcium following sludge application are not reported, several studies have identified calcium leaching losses in forest ecosystems (Riekerk 1978, Koterba et al. 1979, Riekerk and Zasoski 1979, Wells et al. 1984). These losses are temporarily associated with anion leaching occurring during periods of groundwater recharge.

Nitrogen Transformation and Translocation

Aside from potential toxicants, nitrogen is generally the most important element that limits land application rates of sludge (Sommers and Nelson 1981). This is true largely because nitrogen levels in sludges are high relative to other nutrients present, and nitrogen may be transformed into soluble forms, such as nitrate, that would represent a potential risk to environmental quality and public health if they were to enter groundwater in sufficient quantity. In addition, nitrogen is the element that appears as most frequently limiting in the nutrition and growth of tree species in a number of forest ecosystems (Edmonds and Mayer 1981). Nitrogen applied in forests with applications of wastewater sludge may undergo several different biological or chemical changes once it is delivered to the surface of the forest floor.

Volatilization. Surface applications of liquid sludge are normally subject to drying conditions wherein that portion of the supernatant that does not immediately infiltrate the soil begins to evaporate. During this period, much of the nitrogen present in the sludge as soluble ammonia is transformed to ammonia gas, which readily volatilizes into the atmosphere when sludge conditions exceed pH 7, as is commonly the case (Cole and Henry 1983). Ammonia loss by volatilization may range from 20 to 60% of that present (Sommers and Nelson 1981) depending on temperature, relative humidity, infiltration rate, and pH of sludge and soil. Typically, about 50% of the available nitrogen in a surface-applied sludge is volatilized as ammonia gas (Cole et al. 1984), most of it lost in the first three days following application (Sommers and Nelson 1981).

Mineralization. Nitrogen not lost through volatilization consists of mostly organic nitrogen and lesser amounts of more soluble forms. Through various biological decomposition processes, organic nitrogen is mineralized to form ammonia-N. In assessing the nitrogen mineralization rate for sludge, various studies have assumed a rate of 20% of the organic nitrogen as becoming available during the first year following application (Cole and Henry 1983, Urie et al. 1984). However, studies (Sommers and Nelson 1981, Parker and Sommers 1983) have shown that the nitrogen mineralization rate varies from 3 to 42% as a function of the biological process used in sludge treatment (Table 10). Also, experiences with incorporated (Richter et al. 1982) and surface-applied (Wells et al. 1984) dewatered sludge cake indicate that mineralization rates for these are much lower than those of liquid sludges. It appears then that mineralization of sludge-borne nitrogen is dependent on the nature of the sludge as well as the physical, chemical, and biological characteristics of the forest environment.

Nitrification and Denitrification. These two processes are of major importance in considering sludge nutrient utilization, because they both result in nitrogen losses from the application site. Nitrification occurs in nearly all adequately drained forest soils and is

TABLE 10. Nitrogen mineralization rates in the first year following sludge application (Sommers and Nelson 1981, Parker and Sommers 1983).

Sludge Type	Nitrogen Mineralization Rate (%)
Waste activated	42
Primary	29
Primary plus CaO	28
Aerobic digested	25
Anaerobic digested	15
Composted	9
Primary, wet-air oxidized	3

responsible for converting ammonia-N to nitrite and then nitrate-N. Nitrification is a biochemical process that occurs in a substrate dependent manner where, other factors remaining constant, rates of nitrate production will increase as ammonia availability increases, until the on-site microbial populations have become saturated. This largely accounts for the progressive abundance of nitrate produced under increasing application rates of nitrogen-rich sludge (Sidle and Kardos 1979, Cole et al. 1983, Brockway and Urie 1983). Nitrate enrichment of surface and groundwater is a frequently noted environmental and public health concern.

Nitrogen losses through denitrification may reach 20% of that available (Cole et al. 1984) when nitrate-N is abundant under reducing conditions in the soil. Such conditions were reported when perched water tables temporarily formed above lenses of fine sand in a coarse-textured outwash soil (Brockway and Urie 1983). Denitrification losses of nitrogen gases may, under certain circumstances, be an added measure of protection for phreatic aquifers which may become threatened by nitrate leaching from the rooting zone.

Forest Floor and *Soil Storage.* A portion of the nitrogen added to the forest floor during sludge application soon becomes indistinguishable from native nitrogen. Much of this supplemental nitrogen rapidly enters the surface soil, resulting in significant increases of this nutrient (Zasoski 1981, Brockway 1983). Soil nitrogen increases as high as threefold have been reported (Riekerk 1978), from approximately 700 to 2,000 kg N/ha in the A horizon and from 2,000 to 5,800 kg N/ha in the B horizon of a soil receiving nearly 5,600 kg N/ha with an anaerobically digested sludge application in the Pacific Northwest. Smaller increases in soil nitrogen were noted in soils treated with approximately half the above nitrogen application rate in the Great Lakes (Urie et al. 1978).

Most of the nitrogen contained in applied sludge is initially retained in the forest floor, where it is slowly released as degradation of organic matter ensues (Brockway 1983, Wells et al. 1984, Urie et al. 1984). Studies in the Pacific Northwest have shown that approximately 80% of the total nitrogen initially contained in sludge applied to Douglas-fir forests remains in the sludge after one year (Mayer 1980) and 71% is still present at the end of two years (Edmonds and Mayer 1981). The impact of this nitrogen on the forest floor is a measurable narrowing of the carbon to nitrogen (C:N) ratio, from values of 60:1 and 80:1 to ratios of 23:1 and 42:1 (Brockway 1979, Stednick and Wooldridge 1979). This has typically resulted in an accelerated rate of humus decomposition (Harris 1979, Stednick and Wooldridge 1979, Edmonds and Mayer 1981, Brockway 1983) and an enhanced availability of on-site nutrients. Sludge applications to loblolly pine plantations have resulted in an increased mass of litterfall needles that had higher nitrogen (and phosphorus) concentrations, and this has produced a doubling in nitrogen transfer rates in that ecosystem (Wells et al. 1984). Little evidence of microbial immobilization of nitrogen on sites receiving sludge applications has been reported (Edmonds and Mayer 1981).

Plant Uptake. Mineralized nitrogen not lost from the application site is available for uptake as ammonia or nitrate. Indeed, a prominent result of sludge applications in forests has been a dramatic increase in foliar nitrogen levels in understory and overstory plant species (Wells et al. 1984, Cole et al. 1984, Urie et al. 1984). Nitrogen additions with sludge application to Douglas-fir seedlings grown in native soils of western Washington have resulted in foliar nitrogen increases from background levels near 1.4 to 2.4% to concentrations ranging from 2.5 to 3.5% (Chapman 1983). Apparently 2.5% foliar nitrogen is optimal for growth of Douglas-fir, and increases beyond this level were of questionable benefit to tree growth. In northern Michigan, sludge applications increased foliar nitrogen levels from values near 1.1% to levels approaching 1.7% in red and white pines (Brockway 1983). The increased nitrogen levels facilitated optimization of the N:P ratio in the pines from 5:1 to 10:1 (van den Driessche 1974), thereby promoting an overall increase in canopy weight and photosynthetic capacity in the plantations (Brockway 1979). Similar increases have been reported for sludge-treated loblolly pines in South Carolina, where foliar nitrogen levels rose from 1.26 to 1.45% following applications as low as 400 kg N/ha (Wells et al. 1984). These increases in foliar nitrogen were associated with volume increases of approximately 40% in 9- and 28-year-old stands.

The uptake of nitrogen by forests can often be as great as that of agricultural crops (Cole et al. 1984) and, as can be seen in Table 11, is highly variable depending on factors such as climate, species, stand age, and rate and form of nitrogen addition. The greatest assimilators of nitrogen appear to be various poplars. Their rates of nitrogen assimilation

TABLE 11. Nitrogen uptake rates of various forests receiving waste-effluent or sludge applications.

Species	Age (years)	Uptake Rate (kg/ha·yr)	Reference
Pacific Northwest			
Poplar	seedlings	300 to 400*	Schiess and Cole 1981
Douglas-fir	seedlings	150 to 250*	Schiess and Cole 1981
Douglas-fir	young stands	up to 225	Cole and Henry 1983
Douglas-fir	55	90	Cole and Henry 1983
Douglas-fir	conceptual	112 to 168	Cole and Henry 1983
Great Lakes			
Hybrid poplar	young stands	up to 200	Cooley 1979
Aspen	less than 10	60 to 166	Urie et al. 1978
Mixed hardwoods	50	100*	McKim et al. 1982
Northeast			
Mixed hardwoods	--	95 to 224*	McKim et al. 1982
Red pine	--	112*	McKim et al. 1982
Southeast			
Mixed hardwoods	40 to 60	140 to 220*	McKim et al. 1982
Loblolly pine	20	220 to 330*	McKim et al. 1982
Loblolly pine	28	105	Wells et al. 1984

*Uptake rate with waste-effluent irrigation.

range from near 200 to 400 kg/ha per year in seedlings and young stands (Cooley 1979, Schiess and Cole 1981). Middle-aged mixed hardwood and loblolly pine forests also approach this range when nitrogen is supplied with waste effluent irrigation (McKim et al. 1982). Sludge-treated Douglas-fir of the Pacific Northwest is thought to assimilate up to 225 kg N/ha per year in young stands and has been reported to take up 90 kg N/ha per year in 55-year-old stands (Cole and Henry 1983). Aspen and mixed hardwoods in the Great Lakes region approximate this latter value, ranging from 60 to 166 kg N/ha per year (Urie et al. 1978). Nitrogen uptake of sludge-amended loblolly pine in the Southeast, estimated at 105 kg/ha annually, is similar (Wells et al. 1984). Because of the large biomass accumulation on forest sites during stand rotation, a substantial potential exists to store nitrogen in overstory trees.

Nitrogen uptake by understory vegetation has been reported to increase nitrogen levels from background near 1% to values approaching 3% (Brockway 1983). Although such increases are beneficial in understory growth, leading to biomass increments ranging from 50 to 100%, total assimilation is limited to less than 1% of the nitrogen applied during sludge application. Because many understory species annually return their nutrients to the forest floor, they can be useful in nitrogen cycling and leaching abatement but may not be effective long-term accumulators.

Leaching Losses. Nitrate losses from the rooting zone to groundwater following sludge applications in forests have been a major environmental and health concern. Available nitrogen that is not taken up by plants or immobilized by microbes is readily converted to the nitrate form, thus susceptible to leaching (Cole et al. 1984). Groundwater nitrate enrichment may be the most prominent factor limiting nitrogen additions with sludge applications to forest sites (Zasoski et al. 1984), as water yielded by forested watersheds is normally expected to be of high quality (Brockway and Urie 1983).

In the mild climate of the Pacific Northwest the opportunity for year-round nitrogen assimilation poses a reduced risk of nitrate leaching beneath evergreen forests (Zasoski et al. 1984). Rates of ammonia (McKane 1982) and nitrate (Vogt et al. 1981) leaching are nonetheless closely related to sludge application rates, suggesting that caution be used in prescribing high rate applications. Sludge applied at 1,080 Mg/ha (4,800 kg N/ha) in a 45-year-old Douglas-fir stand in western Washington resulted in nitrate concentrations peaking near 120 mg/l in groundwater and remaining elevated for several years following a single application (Riekerk 1981). Nitrogen losses from a cleared Douglas-fir forest soil amended with 247 Mg of anaerobically digested sludge per ha (5,750 kg N/ha) totaled 8% from nitrate leaching (Riekerk 1978). Though a small proportion of the total applied nitrogen, this value of 460 kg N/ha lost through leaching did acutely affect groundwater quality, producing nitrate peaks near 30 mg/l.

Excessive nitrate leaching need not always result from sludge application. Liquid sludge additions at 5.5 dry Mg/ha (402 kg N/ha) and dewatered sludge applications of 50 Mg/ha (632 kg N/ha) and 275 Mg/ha (1,500 kg N/ha) in loblolly pine plantations produced leachate nitrate levels that did not exceed the 10 mg/l drinking water standard (Richter et al. 1982, Wells et al. 1984). On northern hardwoods sites in New Hampshire, sludge additions up to 25 Mg/ha (477 kg N/ha) resulted in soil water nitrate increases of only 3 mg/l (Hornbeck et al. 1979). However, the more typical result of sludge-borne nitrogen applications is a rapid production of nitrate in well-aerated forest soils and subsequent leaching during periods of groundwater recharge. In groundwater 3 m below a 40-year-old red pine plantation growing on a coarse-textured sandy outwash soil in Michigan, nitrate peaks of 49 mg/l were recorded nearly two years after a single sludge application of 32 Mg/ha containing 2,260 kg N/ha (Brockway and Urie 1983). In Pennsylvania, sludge applications of 27 Mg/ha (3,034 kg N/ha) to mixed hardwood stands produced peak nitrate flushes as high as 290 mg/l in soil percolate (Sidle and Kardos 1979). Peak nitrate levels near 60 mg/l were measured beneath loblolly pine plantations that received sludge applications of 11 Mg/ha containing 804 kg N/ha (Wells et al. 1984). Sludge applications of 512 Mg/ha which added 20,750 kg N/ha (3,250 kg available N/ha) to a 42-year-old Douglas-fir stand growing on gravelly outwash resulted in peak nitrate concentrations of 420 mg/l in leachate moving immediately below the soil surface (Zasoski et al. 1984). When three parts sawdust were added to one part sludge, the C:N ratio of the amend. ment was increased from 10:1 to over 19:1, thus encouraging nitrogen immobilization by microbial action and a resulting decrease in nitrate leaching losses (Vogt et al. 1979, 1981). It should be noted that soil percolate is yet in the biologically active zone of the ecosystem and that high percolate nitrate values do not necessarily translate into high groundwater nitrate levels.

Soil structure and texture of the sludge application site may also have a major effect on the amount of nitrate leached to groundwater. High nitrate levels found percolating below a mixed hardwood stand growing on a clay loam soil were largely a result of solute channeling through macropores present in the soil (Sidle and Kardos 1979). On pine plantations in Michigan, higher nitrate levels were recorded in leachate collected from sands without textural bands than from soil containing lenses of finer sand and clay (Brockway and Urie 1983). These finer-textured bands served as denitrification sites during seasonal periods of moisture saturation. In western Washington greater nitrate losses from the rooting zone were observed in ascoarse-textured, gravelly outwash than from a finer-textured, loamy residual soil (Riekerk and Zasoski 1979).

The temporary soil storage capacity for nitrogen is quite variable, ranging from 450 to 1,350 kg/ha (Cole and Henry 1983), depending on numerous characteristics of the particular forest site. Leaching of excess nitrate should theoretically not occur until the storage limits are exceeded, but nitrate leaching is observable once nitrogen reaches 50% of these maximums. Studies in Michigan have related sludge applications to the magnitude of nitrate leaching, in an effort to establish rates of nitrogen addition that were compatible with maintaining soil leachate and groundwater nitrate levels below the 10 mg/l potable water standard (Brockway and Urie 1983). While various site characteristics such as soil and vegetation type and age were of importance in determining the nitrogen storage capacity of each ecosystem, the chemical characteristics and mineralization potential of each sludge type were also germane.

If nitrogen additions with sludge application in forests are limited to 400 to 500 kg/ha per year, significant leaching of nitrate below the rooting zone can be avoided (Riekerk 1981, 1982). Other studies in the Pacific Northwest support this conclusion, finding very little nitrate leaching resulting from sludge applications of 21 Mg/ha, which supplied 400 kg N/ha to forest sites. In addition, sludge applications at rates as high as 40 to 47 Mg/ha have also been proposed as minimizing nitrate loss to groundwater (Stednick and Wooldridge 1979, Cole et al. 1983, 1984). Concern has been noted that sludge applications of no more than 40 Mg/ha may be of little benefit to increasing Douglas-fir growth (Cole et al. 1983). However, sludge nitrogen applications exceeding 400 kg/ha appear to be of no added benefit to growth of loblolly pine (Wells et al. 1984). In the Great Lakes region, sludge application rates ranging from 10 to 19 Mg/ha (670 to 1,140 kg N/ha) have been identified as maximums for pine and aspen forests, beyond which nitrate leaching to groundwater will become excessive (Brockway and Urie 1983). In this region, however, sludge application rates greater than 10 Mg/ha have proved of no added benefit to aspen growth (Urie et al. 1978).

Regional Conceptual Models of Nitrogen Utilization

In an effort to summarize the nutrient utilization characteristics of various forest ecosystems, conceptual models of nitrogen dynamics following sludge application have been constructed for three major forest regions (Table 12). Sludges used in each model are typical of those applied in each locale and, as such, are somewhat variable in their composition. Although all sludges are anaerobically digested, that applied to Douglas-fir forests in the Pacific Northwest has been dewatered and is therefore lower in ammonia-N than those applied to Great Lakes aspen and southeastern loblolly pine, which were applied as liquid slurries. The general correspondence between sludge application rates and overall nitrogen additions is generally similar.

Mineralization rates of organic nitrogen are, from the literature, assumed to be 15% in the first year (Sommers and Nelson 1981) in the aspen and pine forests; however, a rate of 25% was reportedly assumed for Douglas-fir stands (Cole et al. 1983). Although this value may be somewhat overestimated for a dewatered anaerobically digested sludge, the abundant moisture and moderate climatic conditions of the Pacific Northwest may justify such an assumption. Plant uptake rates, though variable, appear to fall into a range that does not differ radically. Nitrogen uptake in aspen and pine was estimated to vary with corresponding changes in sludge-supplied available nitrogen.

In examining these models, the most apparent regional difference is the variation in the threshold sludge application rate that produces leachate nitrate concentrations that exceed the 10 mg/l U.S. EPA standard. The threshold rate is near 40 Mg/ha (715 kg available N/ha) in the Pacific Northwest, 19 Mg/ha (466 kg available N/ha) in the Great Lakes region, and 9 Mg/ha (334 kg available N/ha) in the Southeast. From these calculations one might conclude that Pacific Northwest forest ecosystems possess inherently greater nitrogen assimilation capacities. than those in the Great Lakes and Southeast. However, although these models may be useful starting points for comparative discussion, they are based on assumptions and data that must, at best, be considered only preliminary. Further studies will undoubtedly be required before a complete construct of sludge nitrogen utilization in various forest ecosystems becomes available.

SUMMARY OF MANAGEMENT CONSIDERATIONS

Forest ecosystems have evolved efficient mechanisms to assimilate and retain modest levels of annual geochemical input. As inputs exceed outputs over time, a slow, but progressive, process of nutrient accumulation leads to a natural aggradation of forest site quality. Nutrients accumulated on site are largely stored in association with an expanding plant biomass and to a lesser degree with forest floor and soil.

Fertilizer additions are carefully controlled geochemical inputs that are intended to alleviate deficiencies on sites where one or two nutrients limit plant growth. Increases in available nutrient levels in the forest floor and soil, nutrient uptake and retention, and tree growth are typical results of fertilization. Because of economic considerations, fer-

TABLE 12. Nitrogen transformation and utilization during first year following sludge application (conceptual models by region).

Application Rate (Mg/ha)	Organic N (kg/ha)	Ammonia-N (kg/ha)	Mineralized N (kg/ha)	Volatilized N (kg/ha)	Forest Floor Storage (kg/ha)	Soil Storage (kg/ha)	Plant Uptake (kg/ha)	Leached Nitrate-N (kg/ha)	Leachate Nitrate-N (mg/l)
Douglas-fir in Pacific Northwest Region									
23	784	224	196	168	588	140	112	0	0
47								84	15
93	1,568	448	392	420	1,176	224	112	213	42
140	4,704 3,136	1,344 896	1,176 784	1,445 907	3,528 2,352	448 560	112 112	403	79
187	6,272	1,792	1,568	1,982	4,704	672	112	594	117
467 280	9,408	2,688	2,352	3,058	7,056	896	112	974	192
	15,680	4,480	3,920	5,208	11,760	1,344	112	1.736	341
Aspen in Great Lakes Region									
5									
10	300 150	200 100	23	123 62	255 127	131	60	0	0
			45				89	20	4
20	600	400	90	245	510	78	111	56	11
40	1.200	800	180	490	1,020	171	166	153	30
Loblolly Pine in Southeastern Region									
6						10		12	3
11	466 233	338 169	35 70	204 102	396 198	19	105 80	80	20

Assumptions:

1. Anaerobically digested sludges (analyses in Table 1) applied as 18.4%, 5.5%, and 2.5% solids in PNW, GL, and SE, respectively.
2. Organic nitrogen mineralized in first year is 25% in PNW and 15% in GL and SE (Sommers and Nelson 1991).
3. Volatilization loss is 50% of available nitrogen (Sommers and Nelson 1981).
4. Forest floor storage is unmineralized organic nitrogen remaining in sludge and 0 horizons.
5. Soil storage is the residual of available nitrogen inputs and losses in the short term. Long-term changes are unknown.
6. Plant uptake is estimated from field studies (Cole et al. 1983, Urie et al. 1978, Wells et al. 1984, Powers 1976).
7. Average nitrogen leached is based on regional precipitation and evapotranspiration: 114, 96, and 144 cm of precipitation and 64, 46, and 104 cm of evapotranspiration for the PNW, GL, and SE, respectively.

tilizers are applied at rates that simulate natural geochemical inputs and enhance tree growth but do not result in leaching losses that would degrade groundwater quality.

Wastewater additions provide forest sites with rates of soluble nutrients that generally exceed rates by natural input. Phosphorus is retained well by mineral soil, and cations (potassium, sodium, calcium) may also accumulate to some extent. However, anions (sulfate, nitrate, chloride) are quite subject to leaching from the soil and are accompanied by cations during periods of groundwater recharge. The chemical composition of waste effluent may influence the relative balance of cations and anions in the soil, often leading to a new equilibrium in the soil solution. Irrigation-applied nitrogen accelerates forest floor decomposition and may accumulate in soil in association with increases in organic matter. Volatilization of ammonia and denitrification of nitrate may be important avenues of nitrogen loss from sites irrigated with wastewater.

Two universal results of waste effluent irrigation are increased nitrogen uptake and retention by vegetation and increased rates of nitrate-N leaching below the rooting zone. Nitrogen utilization is greatest in young forests of poplar that are rapidly growing in association with understory vegetation. Mature forests are less efficient in assimilating and retaining wastewater-applied nitrogen. Substantial leaching of nitrate from waste effluent-irrigated forests has been reported where rates of soluble nitrogen application exceeded site assimilation capacities. Generally, rates approaching 200 kg of available N/ha per year lead to nitrate-N concentrations in leachate that exceed the 10 mg/l U.S. EPA standard.

Although not fully predictable, forest site renovation capacity for wastewater appears to diminish over time. Given that wastewater provides a high proportion of soluble nutrients and little organic matter, effluent irrigation remains limited in promoting forest site aggradation. Wastewater irrigation can be an effective means of recycling nutrients back into the ecosystem. However, nutrient application rates (especially nitrogen) should be adjusted to the assimilation capacity of the forest site, if unacceptable leaching losses and groundwater degradation are to be avoided.

Sludge applications provide forest sites with rates of nutrient addition that exceed those of wastewater, fertilizer, or natural inputs. Applied phosphorus, potassium, and calcium are largely retained in the forest floor and upper layers of mineral soil. While leaching of phosphorus is nil, potassium and calcium losses are reported to accompany leaching of anions (primarily nitrate) during periods of groundwater recharge.. Sludge nitrogen is initially stored in the forest floor, where it becomes slowly available as organic matter degrades. A lowering of the C:N ratio in the forest floor results in an accelerated rate of decomposition. Volatilization of ammonia following surface application of liquid sludge and denitrification during periods of excess soil moisture represent two potential pathways of nitrogen loss from a treated forest site.

Increased nitrogen uptake and rates of nitrate leaching are two widespread results of sludge application to forest land. Nitrogen assimilation is greatest on sites occupied by young, rapidly growing poplar (200 to 400 kg/ha·yr) and somewhat less in middle-aged stands of Douglas-fir (90 kg/ha·yr) and loblolly pine (105 kg/ha·yr). While foliar nitrogen increases in both overstory and understory vegetation following sludge application, the nitrogen storage capacity is substantially greater in the larger biomass of overstory trees. Increases in tree growth rates up to 40% have been associated with sludge nitrogen applications of 400 kg/ha. Excessive nitrate-N leaching losses have been related to high rates of sludge application, However, when sludge nitrogen additions were limited to

400 or 500 kg/ha, nitrate concentrations in soil leachate did not exceed the 10 mg/l U.S. EPA water quality standard.

The addition of nutrients and organic matter with wastewater sludge applications may produce a substantial beneficial effect on overall site quality. Organic matter, in addition to nutrients, may prove a significant modifier of forest floor and soil characteristics, changing moisture relations and the manner in which nutrients are stored and Cycled on the site. Short-term transfer rates for nitrogen and phosphorus are known to double within one year of sludge applications on pine sites. Abundant evidence has been noted in regard to the enhanced site nutrient relations and vegetation growth resulting soon after application of sludge to forest ecosystems. In the long term, repeated sludge applications should provide a cumulative positive effect on site quality. Although the prospect is quite speculative at this juncture, one would anticipate a continued buildup of site nutrient capital and development of a rich forest humus, resulting in a greatly ameliorated environment for plant growth. This process of accelerated site aggradation could lead to permanent increases in forest production.

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