

Nitrogen Fertilizers: Fates and Environmental Effects in Forests

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ABSTRACT. The main nitrogen sources used in forest fertilization are urea and ammonium nitrate, which differ in their chemical behavior. Rapid hydrolysis of urea in forest soil releases ammonium and generates alkalinity, which can lead to an evolution of ammonia from the soil surface that may reach 40% of applied nitrogen. Volatilized ammonia may be partly retained by foliar uptake. Since soil pH is not raised by ammonium nitrate, volatilization of ammonia does not occur. Ammonium is strongly retained in forest soils by processes of cation exchange, immobilization, and plant uptake. Nitrate, either from ammonium nitrate or nitrification of ammonium, is more easily leached because of weak chemisorption and lower rates of immobilization. Plant uptake of nitrate can be efficient due to advective transport and favorable kinetics of absorption by roots. Provided that poorly drained sites are avoided, denitrification is not normally a significant pathway in fertilized forests. If conditions favoring volatilization or leaching are avoided, ecosystem retention of applied nitrogen is high—typically over 80%. Bioavailability of nitrogen is high initially, but typically declines exponentially to near background within six months. Uptake efficiency is usually in the range of only 20-30%, but nitrogen is recycled actively within the tree, enhancing growth over about five to ten years. The bulk of applied nitrogen is immobilized in surface horizons—as much as 50% in the forest floor. Immobilized nitrogen appears relatively stable, and therefore poorly available to trees. Larger growth responses to ammonium nitrate, compared to urea, probably are related to lower immobilization rates. Single nitrogen applications appear to have minimal long-term effects on ecosystem properties or functioning. Multiple applications have been reported to increase nitrification and nitrogen leaching, alter abundance and speciation of understory plants, and decrease community respiration and decomposition. Research is needed to assess the prevalence of long-term effects reported for serial fertilizations.

Coniferous forests of western North America often increase their aboveground growth when nutrient elements are added to the soil. Screening trials and detailed dose-response studies have shown that the range of nutrient element deficiencies is narrow. Deficiencies of phosphorus occur in highly acidic, podzolic, coastal landscapes (Weetman et al. 1989); phosphorus and sulfur limitations occur in soils formed from certain types of volcanic ejecta, especially rhyolitic ash (Cochran 1978; Turner et al. 1979). The preponderant deficiency, however, is nitrogen, and the remainder of this chapter deals with that element.

Additions of nitrogen may be made through use of N_2 -fixing plants, application of municipal or industrial wastes, or use of synthetic fertilizers. Of these, synthetic fertilizers have dominated.

Nitrogen is usually applied to forest stands near the time of crown closure, which corresponds to peak nitrogen demand. In the Pacific Northwest, Douglas-fir (*Pseudotsuga menziesii*) has been the main species fertilized. Fertilizer is most often aerially applied in pelleted form at a dosage of 150-250 kg N/ha as urea ($[NH_2]_2CO$) or ammonium nitrate (NH_4NO_3). Efficiency of fertilization in forests, defined as the percentage of applied nitrogen recovered in the target trees, is low compared to cereal grains, in which 50% uptake is common. Depending on weather, site, stand, and fertilizer factors, efficiency in the first few growing seasons can range from less than 10% (Preston et al. 1990) to approximately 30% (Heilman et al. 1982a; Nason 1989). This means that from 70 to 90% of applied nitrogen is either retained by nontree components or transmitted through the ecosystem. The fate and effects of this "residual N" will be a major focus of this chapter.

Fertilization affects a broad range of ecosystem attributes, from levels of chemical species in tree tissues to

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respiration rates of decomposer organisms. The forest fertilization literature is large and this chapter is not an exhaustive review. Rather we emphasize fates of nitrogen in soil and trees, and effects on the soil microbiota.

Properties of Nitrogen Fertilizers

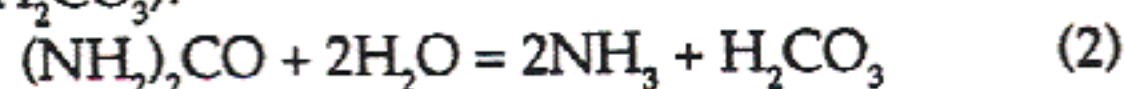
Nitrogen sources differ in chemical and physical properties (Table 1), and these cause differences in their fates and effects, particularly in the first few days after application. The nitrogen percentage is important from the standpoint of minimizing the total mass of fertilizer handled, and this favors use of melamine and urea over the ammonium salts: ammonium nitrate (AN) and ammonium sulfate (AS). Other properties affecting fertilizer efficiency, however, tend to override nitrogen analysis considerations. Urea, AS, and AN dissolve rapidly and usually penetrate the forest floor over a few hours to a few days depending on availability of moisture. Ammonium nitrate and ammonium sulfate ($[\text{NH}_4]_2\text{SO}_4$) are salts of strong acids, and dissolution is accompanied by ionization. The mobility of ions released decreases in the order $\text{NO}_3^- > \text{SO}_4^{2-} > \text{NH}_4^+$, in accordance with the ion exchange properties of soil organic matter. Urea is both highly soluble and uncharged, which would suggest high mobility. Urea mobility in forest soils is in fact very limited because of rapid hydrolysis by urease (Overrein 1968), which releases NH_4^+ and HCO_3^- ions. Melamine (67% N) has low solubility, and this, coupled with chemical stability, probably accounts for the generally poor results obtained in forest applications (Rinehart 1983).

With the exception of urea, nitrogen fertilizers common in forest management are mildly acidifying (Table 1). Ammonium released from nonurea sources thus remains protonated and dissolved in the soil solution:



Alkalinity increases when urea (Table 1) is hydrolyzed by soil urease, because two equivalents of ammo-

nia (NH_3) are released for each equivalent of carbonic acid (H_2CO_3):



In agricultural use, urea is normally incorporated to a depth of several centimeters, where soil minerals and organic matter provide buffering that keeps released nitrogen in the ammonium form. Broadcast application, as in forest practice, relies on precipitation and stored soil moisture to redistribute urea and its hydrolysis products. Many studies show that, under restricted moisture conditions, pH will rise sufficiently to allow volatilization of ammonia from the forest floor. Volatilization losses range up to greater than 40% of applied nitrogen (Marshall and DeBell 1980; Watkins et al. 1972). Because volatilized nitrogen is assumed lost from the site, much effort has gone into identifying and controlling factors that regulate volatilization.

Fates of Applied Nitrogen

The major fates of fertilizer nitrogen in forests are volatilization as ammonia, immobilization, nitrification, denitrification, leaching, and plant uptake (Figure 1). With the exception of volatilization, these are normal processes of the forest nitrogen cycle.

Volatilization

Volatilization of ammonia from urea-fertilized forest soils is positively correlated with temperature, wind speed, pH (Watkins et al. 1972), and application dosage of nitrogen (Overrein 1968). Nõmmik (1973) reported a complex relationship between fertilizer pellet size and volatilization that seemed to be mediated by dissolution rate and soil moisture. A simulated rainfall of 12 mm reduced ammonia volatilization by 8 to 31%, depending on method of measurement (Marshall and DeBell 1980). Craig and Wollum (1982) reported that ammonia volatilization after application of urea to loblolly pine (*Pinus taeda*) forest floor was related more to precipitation timing and amount than to season of application. Using

Table 1—Properties of fertilizer nitrogen sources used in forestry.

Property	Urea ($[\text{NH}_2]_2\text{CO}$)	Ammonium Nitrate (NH_4NO_3)	Ammonium Sulfate ($[\text{NH}_4]_2\text{SO}_4$)	Melamine ²
Melting point, °C	D	170	D, 235	>300
% Nitrogen	46	34	21	67
pH of 1M solution	>10 ¹	4.6	4.6	~5.8
Solubility in water	High	High	High	Low

¹After hydrolysis.

²(2,4,6-triamino-1,3,5-triazine).

D = decomposes.

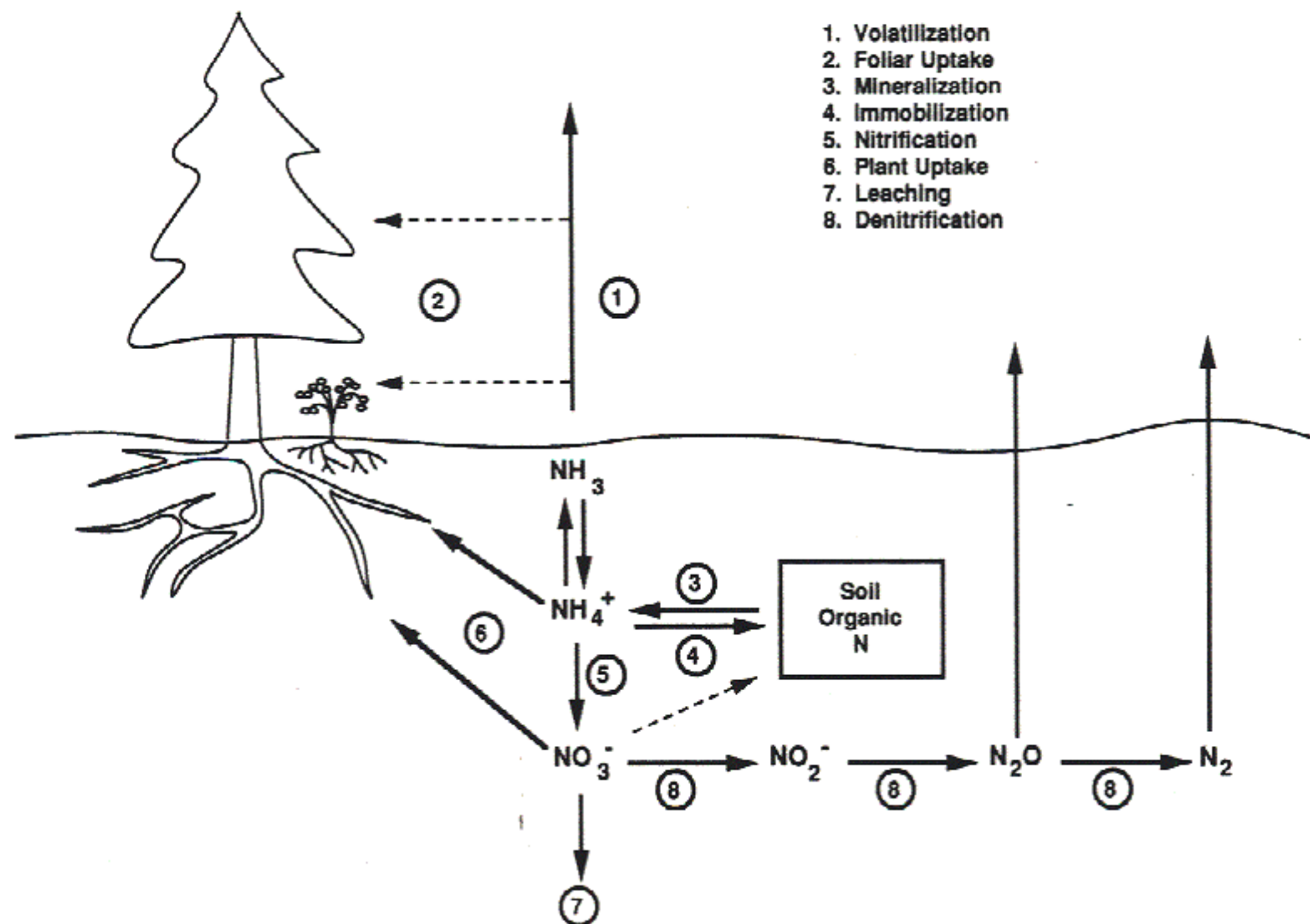


Figure 1. Forest nitrogen cycling processes representing major fates and effects of nitrogen fertilizers.

^{15}N , Nason et al. (1988) showed that the amount and proportion of fertilizer-derived ammonia volatilized depended on the intensity of rainfall, which apparently regulates access between dissolved urea and urease on the one hand, and dispersion and buffering of ureolytic products on the other (Eq. 2). Overall, small precipitation events tend to promote volatilization whereas larger events (>1 cm) reduce losses.

Managers can thus minimize volatilization by timing applications to coincide with cool, calm weather with a high probability of significant, but not torrential, rainfall. In the Pacific Northwest, such conditions are most likely to occur in the fall. Another option is to apply urea in winter directly to snow. Preston et al. (1990) recorded volatilization equivalent to less than 1% of urea-N applied to snow-covered soil of interior lodgepole pine (*Pinus contorta*) and coastal Douglas-fir stands. This practice, however, is largely untested and other nitrogen loss mechanisms such as leaching and loss in runoff may be unfavorable.

It is often assumed that volatilized nitrogen is entirely lost from the ecosystem. This is probably incorrect. Pang (1984) showed that excised foliage of Douglas-fir exposed to $^{15}\text{NH}_3$ in a closed chamber incorporated ^{15}N in a nonextractable form. Nason et al. (1988) found that potted Douglas-fir seedlings positioned above a forest soil fertilized with ^{15}N -urea incorporated volatil-

ized ^{15}N , and allocated nitrogen to tissues in the normal way. But captured ammonia declined quickly with elevation of the seedling above the forest floor, and the authors concluded that understory species would be the main beneficiaries in practice.

Immobilization

Immobilization includes, in the broad definition used here, all processes that lead to change of soil inorganic nitrogen into organic forms (Figure 1).

Studies with ^{15}N have shown that immobilization is the major fate of ammoniacal fertilizer nitrogen in a wide range of coniferous forest types. The first ^{15}N report of fertilizer nitrogen fate within a forest stand (Nõmmik and Popovic 1971) showed marked differences in immobilization related to chemical source of nitrogen (Table 2). Both ammoniacal N sources, urea and ammonium sulfate, resulted in $\approx 70\%$ immobilization at six months, whereas less than half this amount was immobilized from calcium nitrate ($\text{Ca}[\text{NO}_3]_2$). Similar differences between ammonium- and nitrate-based N sources were reported by Melin and Nõmmik (1988) in Scots pine/Norway spruce (*P. sylvestris/Picea abies*) and lodgepole pine (Preston et al. 1990). Overall, in the first year after fertilizer application, immobilization has averaged 60 and 20% for ammonium-based and nitrate-based fertilizers, respectively.

Table 2—Immobilization of fertilizer nitrogen in ^{15}N field experiments. Modified from Preston et al. (1990).

System	Nitrogen Source	Application Dosage (kg N/ha)	Time after Application (months)	% Recovery as Organic N ¹	Reference
Scots pine	$\text{Ca}(\text{NO}_3)_2$	100	6, 12	28, 19	Nõmmik and Popovic (1971)
	$(\text{NH}_4)_2\text{SO}_4$	100	6, 12	70, 57	
	Urea	100	6, 12	71, 70	
Scots pine	$\text{Ca}(\text{NO}_3)_2$	150	6, 15	19, 17	Melin and Nõmmik (1988)
	$^{15}\text{NH}_4\text{NO}_3$	150	6, 15	44, 47	
	$^{15}\text{NH}_4^{15}\text{NO}_3$	150	6, 15	34, 35	
	Urea	150	6, 15	58, 61	
Slash pine	$(\text{NH}_4)_2\text{SO}_4$	56	7	34 ²	Mead and Pritchett (1975)
	Urea	224	7	20 ²	
Lodgepole pine	Urea	100	9	64	Preston et al. (1990)
	$^{15}\text{NH}_4\text{NO}_3$	100	9	73	
	$\text{NH}_4^{15}\text{NO}_3$	100	9	31	
Douglas-fir	Urea	224	6, 12	53, 44 ²	Heilman et al. (1982b)
Douglas-fir	Urea	200	6, 12	58, 54	Nason (1989)
Douglas-fir	Urea	200	9	33	Preston et al. (1990)

¹Data pairs indicate recovery at times shown in column to the left.

²Forest floor plus 0-10 cm increment only.

Reasons for differences in ammonium and nitrate immobilization rates seen in stand-level studies have been explored in field microplots (Jones and Richards 1977; Overrein 1971) and laboratory experiments (Jansson 1958; Schimel and Firestone 1989). A general concept, based largely on Jansson's (1958) work, holds that autotrophs control production (nitrifiers) and consumption (plants) of nitrate, whereas production and consumption of ammonium is regulated by heterotrophs. Microbial energy necessary for assimilation of ammonium is less than for nitrate, which must be reduced, so higher microbial uptake rates for the former (Schimel and Firestone 1989) seem logical. Conversely, for nitrate, low rates of immobilization by heterotrophs and weak sorption to colloids promote transport to roots.

The magnitude of immobilization of ammonium-based fertilizers is a concern for fertilizer efficiency. The few data available from field experiments indicate that the immobilization process is rapid. Heilman et al. (1982a) followed inorganic and organic forms of nitrogen from three days to two years after application of urea-N at 224 kg/ha to 7 to 9-year-old Douglas-fir. Immobilization increased hyperbolically to a maximum of 53% at six months (Table 2). In contrast, Nason (1989), working in a 38-year-old stand of Douglas-fir, found that 50% of a 200 kg/ha application of urea-N was immobilized within three weeks. The vertical distribution of immobilized N may play an important role in availability of nitrogen to trees. In both the above studies, season of application was found to have little effect on

the amount of ^{15}N immobilized. However, distribution of immobilized N was skewed to greater depth when fertilizers were applied in fall, and this was associated with greater growth response (Heilman et al. 1982b; Nason 1989). These growth response differences may be a function of different initial distributions of fertilizer nitrogen, different potentials for remineralization of immobilized N from mineral soil or forest floor materials, or both.

Fertilization efficiency is increased by minimizing immobilization, especially in forest floor materials. This objective can be met through use of nitrate-based fertilizers or, if ammonium-based sources are used, timing fertilizer applications to coincide with periods of cool, moist weather, which minimize immobilization in the forest floor.

Plant Uptake

Fertilizer nitrogen partitions between understory and overstory species. Unfortunately, accounting of fertilizer nitrogen among vegetative layers has been attempted in only a few studies.

Understory. Fertilization with nitrogen generally increases the concentration of nitrogen in tissues of understory species. Stanek et al. (1979) showed significant increases in nitrogen content of both salal (*Gaultheria shallon*) and bracken fern (*Pteridium aquilinum*) after urea fertilization. Recovery of fertilizer ^{15}N in understory plants has been below 11% of applied in all studies save two in Scandinavia, where unusually low nitrogen dosages were used (Table 3). In most cases uptake by

Table 3—Recovery of fertilizer ¹⁵N in plant biomass reported in field experiments. Modified from Preston et al. (1990).

Species/ Age (yr)	Duration (seasons)	Fertilization		% Recovery		Reference
		Dosage (kg N/ha)	Chemical source	Tree	Understory	
Scots pine						
11	2	50	(NH ₄) ₂ SO ₄	5		Nõmmik (1966)
11	2	50	Ca(NO ₃) ₂	9		
15	1	60	(NH ₄) ₂ SO ₄	12.9 ¹	7.9	Björkman et al. (1967)
15	1	60	Ca(NO ₃) ₂	11.7 ¹	21.6	
70-90	1	53	Urea	2.3	19.4	Paavilainen (1973)
120	2	100	¹⁵ NH ₄ NO ₃	23 ²		Melin et al. (1983)
120	2	100	NH ₄ ¹⁵ NO ₃	29 ²	9	
50	2	150	Urea	20 ³	1	Melin and Nõmmik (1988)
50	2	150	Ca(NO ₃) ₂	44 ³	1	
50	2	150	¹⁵ NH ₄ NO ₃	31 ³	1	
50	2	150	¹⁵ NH ₄ ¹⁵ NO ₃	33 ³	1	
50	2	50	¹⁵ NH ₄ ¹⁵ NO ₃	28 ³	2	
Black spruce						
5-6	1	56	Urea	8.2		Knowles and Lefebvre (1972)
Slash pine						
11	2	56	(NH ₄) ₂ SO ₄	24.6 ⁴	0.1	Mead and Pritchett (1975)
11	2	224	(NH ₄) ₂ SO ₄	26.6 ⁴	0	
Douglas-fir						
7, 9	2	224	Urea	30		Heilman et al. (1982a)
12	1	200	Urea	5.5	10.8	Preston et al. (1990)
38	3	200	Urea	23 ⁵		Nason (1989)
Lodgepole pine						
11	1	100	Urea	10.1	2.4	Preston et al. (1990)
11	1	100	¹⁵ NH ₄ NO ₃	5.3	2.9	
11	1	100	NH ₄ ¹⁵ NO ₃	1.9	3.4	
Sitka spruce						
20	2	160	Urea	13		Hulm and Killham (1990)
Radiata pine						
1	4	236	(NH ₄) ₂ SO ₄	18		Nambiar and Bowen (1986)

¹Aboveground parts only.

²Including understory roots.

³Tree biomass includes roots > 20 mm; stand includes 30% Norway spruce.

⁴Ninety-three percent of foliage was shed after first growing season; tree uptake includes surrounding trees.

⁵Includes branches, twigs, and foliage only.

understory is less than 5% of applied and, from the standpoint of efficiency, is of little concern to the manager. Normally, fertilizer nitrogen is partitioned strongly to the overstory (Table 3), as expected from the lower biomass and growth rate of the understory. Exceptions to this rule are likely to occur when stand density is low or leaf area has been sharply reduced by pests, disease, or fire.

The fate of fertilizer nitrogen immobilized in understory plant tissues has not yet been reported. Whether this nitrogen becomes available to crop trees in amounts capable of affecting growth, particularly in cases where understory uptake is high, is worthy of study.

Overstory. Aboveground growth of coniferous trees is closely related to the nitrogen content of the foliage (Brix 1981b). The obvious and desirable aim of nitrogen ferti-

zation is to increase the nitrogen status of crop trees, and only a few studies have failed to show an increase in foliar N concentration (Heilman 1971; Powers and Jackson 1978; Radwan et al. 1991). Foliar N concentrations in Douglas-fir have been increased through fertilization from deficiency levels of 0.9 to 1.2% to over 2% (Brix 1981a; Miller et al. 1986), but applications in the 150 to 250 kg N/ha range most often raise foliar N to the 1.3 to 1.5% range (Brix 1981a; Heilman and Gessel 1963; Nason et al. 1990). Brix (1981a) showed that maximum photosynthetic efficiency occurs at a foliar N concentration of about 1.7%, but efficiency falls by less than 5% in the foliar N range of 1.4 to 2.1%.

Translating these concentration increases into uptake estimates requires information on the distribution of fertilizer nitrogen within the tree as well as detailed allometric relationships. Root systems are often ex-

cluded from uptake estimates. When roots are included, it is usually only large, structural roots. Only two ^{15}N studies provide information on fertilizer nitrogen assimilation into roots under 3 cm diameter (Melin and Nõmmik 1983, 1988), so conclusions on the magnitude of this sink are tentative.

Recoveries of ^{15}N fertilizer in target conifers have varied between 1.9 and 44% of applied nitrogen, with a mean of 18% (Table 3). But recoveries are not normally distributed. A cluster of low recoveries is associated with studies where one or more of the following conditions existed: (1) application dosages were well below operational convention (<100 kg N/ha); (2) fertilizers were applied to snow (Preston et al. 1990); or (3) organic soils were involved (Knowles and Lefebvre 1972; Paavilainen 1973). Deletion of these studies gives a recovery range of 13 to 44%, with a mean of 26.4%. Even within this restricted range, generalizations on recovery are difficult with respect to site, species, and application factors. In head-to-head comparisons, nitrate sources have given greater recoveries than ammoniacal sources (Dangerfield and Brix 1981; Melin and Nõmmik 1988; Melin et al. 1983), and, within the latter, differences between urea and ammonium salts have been minimal.

Nitrogen fertilizer uptake by conifers in the range of 20 to 30% of applied is often described as "low" in the literature, and this is justified in relation to efficiencies of 50% or greater for annual crops. Alternatively, uptake of fertilizer nitrogen may be compared to nitrogen uptake in control trees, which for candidate Douglas-fir stands has been estimated at about 25-40 kg/ha (Gessel et al. 1973; Heilman and Gessel 1963; Cole 1981). Thus a 25% recovery of a 200 kg/ha N application in the first year represents more than a doubling of the annual uptake.

Low recoveries in trees of ammonium-based fertilizer nitrogen coincide with low application dosages or organic soil types (Table 3). Both of these conditions would lower the ratio of fertilizer nitrogen to microbial biomass. This observation, taken with the relative efficacy of fertilizer nitrate (in the absence of strong leaching conditions), suggests that competition for ammonium between tree roots and microbes is a key factor regulating short-term fertilizer response.

Distribution Within Trees. In this and the following section, "percentage of fertilizer nitrogen taken up" refers to the proportions of nitrogen *in trees* that can be assigned a fertilizer source by means of ^{15}N labeling—this is not synonymous with fertilizer efficiency or proportion of applied nitrogen taken up.

Initially, maximum ^{15}N enrichments occur in current foliage, and this is consistent with the higher photosyn-

thetic capacities of these tissues when compared to older foliage (Brix 1983). Foliar ^{15}N enrichment usually reaches a maximum throughout the crown in the second growing season after fertilization (Hulm and Killham 1990; Nõmmik 1966; Nason 1989). Nõmmik (1966) showed that, at this time, about 65% of fertilizer nitrogen taken up by Scots pine and Norway spruce was in foliage, and distribution among tree components was not influenced by source of nitrogen. Mead and Pritchett (1975), working with ^{15}N in a young slash pine (*Pinus elliotii* var. *elliotii*) plantation, showed that distribution patterns of fertilizer nitrogen were unaffected by nitrogen dosage in the range of 56 to 224 kg/ha. In this latter study, only 40% of fertilizer nitrogen taken up was found in foliage two years after application, but this lower figure is affected by the short needle retention of slash pine. Melin and Nõmmik (1988) reported that, after two years, 70-72% of fertilizer nitrogen taken up by 50-year-old Scots pine resided in crowns, irrespective of nitrogen source.

Heilman et al. (1982b) found that two years after ^{15}N -urea fertilization of 7 and 9-year-old Douglas-fir, nitrogen concentrations exceeded those of unfertilized controls only for older needles and bolewood. Nine years after fertilization of 25-year-old Douglas-fir at a dosage of 448 kg/ha, urea-N concentrations of nitrogen in bolewood and branches were significantly less than in controls (Pang et al. 1987). Due to increased growth, however, the net gain in mass of nitrogen in trees over the nine-year period had increased by 25 and 50% over control for unthinned and thinned stands respectively (Pang et al. 1987). The increased mass of nitrogen in this study was mainly in crowns, which had expanded significantly in response to fertilization. Accretion of nitrogen in branches and needles was, in part, at the expense of nitrogen in boles. More information on long-term fate of fertilizer nitrogen in trees is needed before generalizations can be made.

Internal Redistribution. Studies with ^{15}N have shown that newly acquired fertilizer nitrogen is highly mobile. For example, declines of needle ^{15}N abundance in needles without nitrogen loss (i.e., nitrogen concentration of the needle does not change) have been recorded by a number of investigators and provide clear evidence of a flux of nitrogen through the needle.

Quantitative treatments of redistribution of needle N are scarce. Nambiar and Bowen (1986) estimated that 72% of ^{15}N in needles of radiata pine (*Pinus radiata*) at 12 months after fertilization was retranslocated in the following three years. Nason (1989) estimated "annual turnover of N" to average 52% in one-year-old needles

of 38-year-old Douglas-fir in the second year after fertilization. Hulm and Killham (1990) showed very large retranslocations of nitrogen one year after spring application of ^{15}N -urea to Sitka spruce (*Picea sitchensis*). Assuming an approximate steady state and a potentially mobile pool of one-half of needle N, it may be estimated that April to May retranslocation in this latter study amounted to 106% of total needle N.

Fluxes of nitrogen through needles probably represent turnover of cellular proteins and export of nitrogen-rich compounds to other tissues. The detailed, monthly sampling approach of Hulm and Killham (1990) needs to be applied in future studies to test for the existence of such retranslocations in other systems and clarify the relationship between the magnitude of retranslocation and nutrition.

Nitrification and Leaching

Nitrification is the biological oxidation of reduced forms of nitrogen to nitrite (NO_2^-) or nitrate (NO_3^-) (Figure 1) and is therefore a potential fate only for ammonium-based fertilizers. The mobility of nitrate in soils is well known, and therefore nitrification is usually considered the gateway to nitrogen losses through leaching.

Nitrogen fertilizers applied to forest soil can establish or increase nitrification potential, but where, when, and to what extent have been difficult to predict. Nitrification did not occur in some or all fertilizer treatments reported by Heilman (1974), Heilman et al. (1982b), Martikainen (1984), and Nason (1989). Only one of four previously fertilized Douglas-fir soils had increased nitrification when incubated without amendments (Heilman 1974). However, three of these four soils, including the one mentioned above, nitrified the equivalent of 25-45% of a 400 ppm urea-N amendment within 28 days. In time-course studies of soils that were urea amended but not previously fertilized, Heilman (1974) reported lags of two to six weeks for the onset of nitrate production. Delayed nitrification after nitrogen fertilization of forest soils has also been described by Roberge and Knowles (1966), Otchere-Boateng and Ballard (1978), and Heilman et al. (1982b).

Many studies have sought causes for differences in nitrification patterns in forest soils. The principal regulators identified are: (1) size and speciation of the nitrifying population, (2) availability of ammonium, and (3) pH. Low pH exerts selective pressure on species of nitrifiers (Martikainen and Nurmiäho-Lassilla 1985) and maximum energy yields (Schmidt 1982; Martikainen 1984). Persistent elevation of ammonium availability promotes development of an active nitrifying popula-

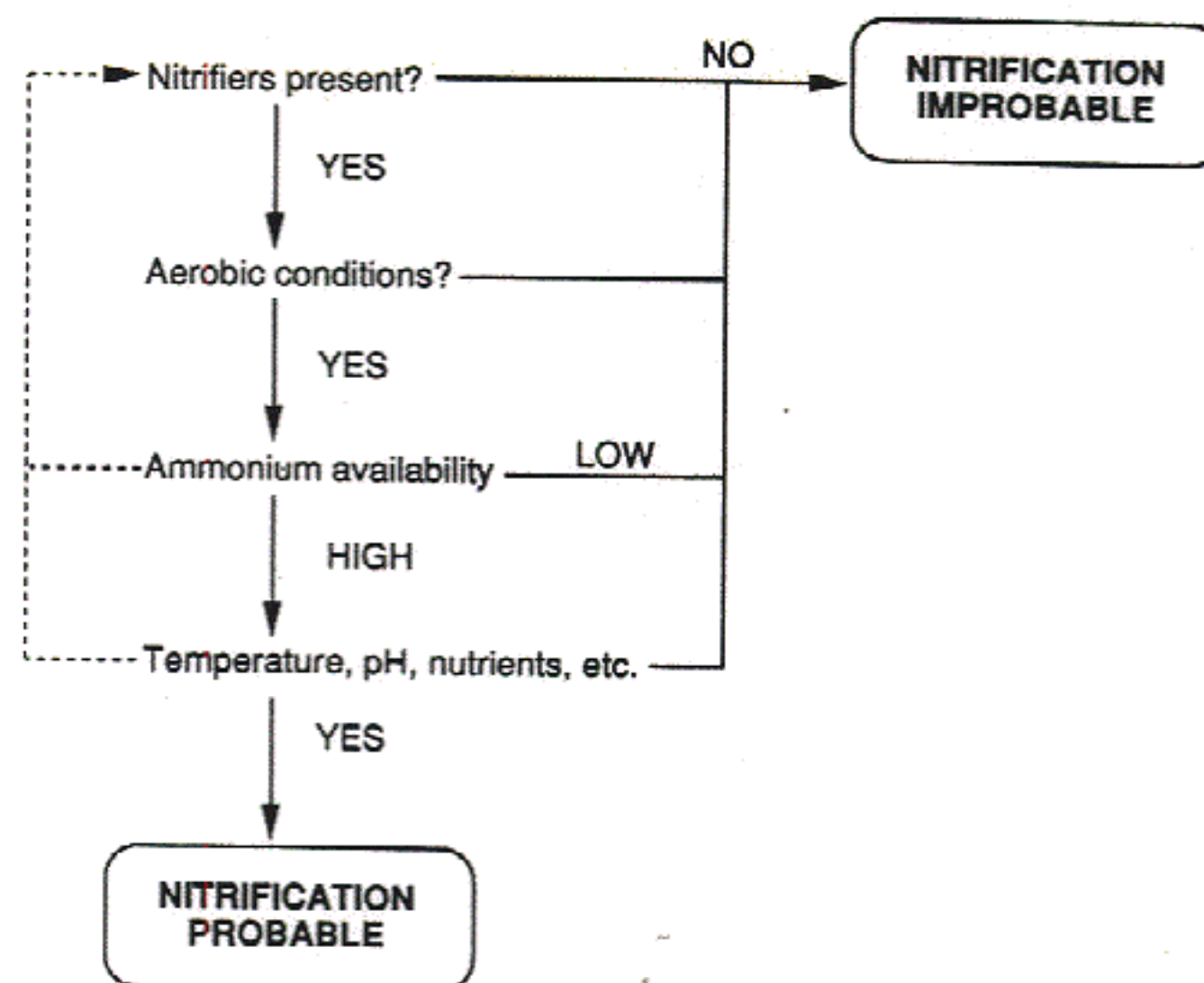


Figure 2. Hierarchy of factors regulating nitrification in nitrogen-fertilized forest soil.

tion even in soils strongly acidified by vegetative type (Van Miegroet et al. 1990) or acidic deposition (Nilsson et al. 1988; Van Breemen and Van Dijk 1988). A hierarchical, conceptual framework for evaluating nitrification after fertilization is proposed in Figure 2. Additional feedback control (represented by broken lines in Figure 2) is contributed by the interaction of ammonium availability and pH with nitrifier populations.

Fertilization with ammonium-based fertilizers raises ammonium availability and is expected to increase nitrification. However, no nitrification may result due to the lack of a nitrifying population. Assuming viable cells are present, a nitrifying population may develop, provided ammonium availability persists. The duration of elevated nitrogen availability following fertilization can be short, often less than six months, as affected by the activities of heterotrophic microbes and plant roots (Johnson et al. 1980; Johnson and Todd 1988; Riha et al. 1986; Nason 1989).

If an increase in ammonium availability is of sufficient magnitude and duration to induce nitrification, a nitrogen-leaching potential is generated. Whether this will lead to significant loss of nitrogen from the ecosystem will depend on the intensity of, and degree of synchrony between, nitrification and plant uptake (Johnson and Todd 1988; Vitousek et al. 1982). Whole watershed nitrogen budgets suggest that the linkage between nitrification and plant uptake in Pacific Northwest forests remains tight after a single nitrogen fertilization because losses as nitrate are typically less than 1% of applied urea-N (Moore 1975). Multiple applications,

however, can result in substantial losses of nitrogen as nitrate. Hetherington (1985) reported up to 14% of applied nitrogen lost as nitrate in stream water draining a Douglas-fir forest that had been fertilized two and seven years previously.

Prediction of the duration of nitrogen fertilization-induced nitrification capacity is important from a standpoint of management of refertilization and harvest activities. In the absence of accurate prediction, managers should consider testing for nitrification rate and capacity in situations suggested by the hierarchical framework outlined in Figure 2.

Denitrification

Denitrification (Figure 1) is the biological reduction of nitrate to nitrous oxide (N_2O) or dinitrogen (N_2). The process is carried out by bacteria when availability of oxygen, required as an electron acceptor for respiration, is restricted. Estimation of denitrification rate is difficult because of technical problems in the detection of products and very high spatial variability (Burton and Beauchamp 1984). There are few data on the magnitude of this process in fertilized forest soils.

Overrein (1972) reported a "substantial evolution" of $^{15}N_2$ from ^{15}N -urea amended humus maintained under a helium atmosphere. In field lysimeter experiments, however, N-oxides were not detected after applications of urea-, ammonium-, and nitrate-N in the range of 10 to 1,000 kg/ha (Overrein 1969). Pluth and Nõmmik (1981) found that denitrification potentials of a Swedish forest soil were affected by the chemical source of nitrogen used in a fertilization four years previously. Recovery of $^{15}NO_3^-$ was only 40% after a 17 day anaerobic incubation of urea-treated soil, whereas recoveries in control and ammonium nitrate-fertilized soils were 80 and 88%, respectively. A nitrogen source effect on potential denitrification was also noted by Melin and Nõmmik (1983) in a laboratory core study where evolution of nitrous oxide ranged from 0.02 to 0.39 kg N/ha per day. Urea fertilization effects on potential denitrification (Melin and Nõmmik 1983; Pluth and Nõmmik 1981) probably stem from increases in both pH and availability of ammonium, which promote the activity of nitrifiers, and subsequently, perhaps, development of a denitrifying population.

Denitrification potential measurements optimize conditions for the process and therefore can be used as an index of field denitrification rates *only where all necessary conditions were met*. The only field study quantifying denitrification following forest fertilization showed that losses were low—0.05% of a 160 kg/ha dosage

applied to Sitka spruce (Hulm and Killham 1988). Based on the low frequency with which all requisite conditions for denitrification will be met in fertilized forests, it appears that this pathway would normally be a negligible component of the nitrogen fertilizer balance sheet.

Effects of Nitrogen Fertilizers

Soil Processes and Properties

Respiration and Decomposition. Nitrogen fertilizers have been reported to both increase and decrease soil respiration. Chemical source of nitrogen and time after application are factors affecting respiratory response. Foster et al. (1985) reported a 100 to 200% increase in oxygen consumption in a 17 day incubation when urea was broadcast at 25 to 300 kg N/ha to jack pine (*Pinus banksiana*) humus. These, and other authors, have attributed such respiratory flushes to an increase in carbon availability induced by the rise in pH accompanying ureolysis. Respiratory flushes have not been observed when forest soils have been fertilized with other nitrogen sources.

Söderstrom et al. (1983), working with podzolic soils from Sweden, found a sustained depression in carbon dioxide evolution resulted from applications of ammonium nitrate (Figure 3). Urea initially stimulated microbial activity but, after three months of incubation, respiration had returned to background. These effects were induced by heavy nitrogen applications in the laboratory, but the authors also reported an approximate 10% reduction in respiration of soils field-fertilized at only 150 kg N/ha. Martikainen et al. (1989) also

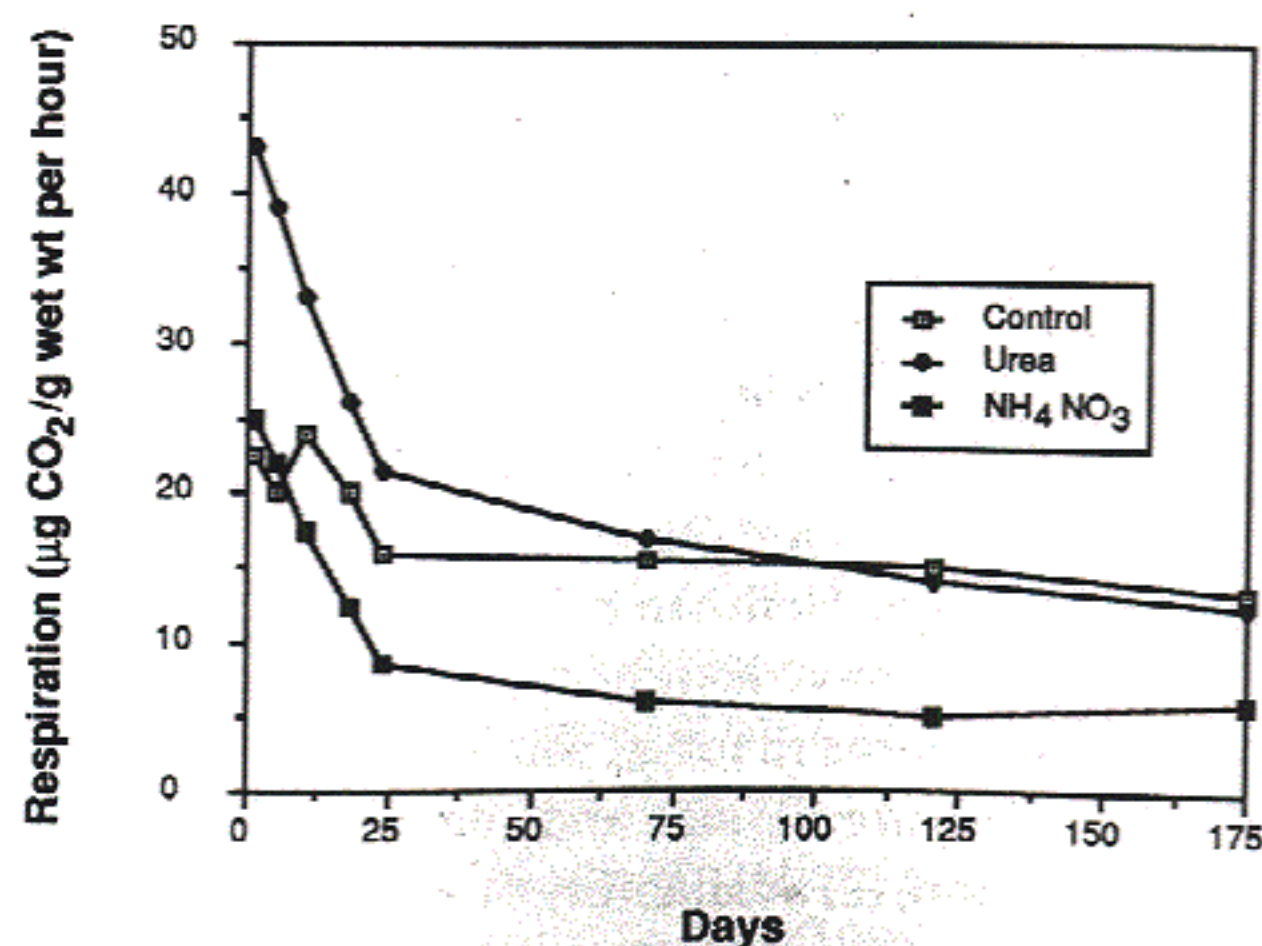


Figure 3. Carbon dioxide evolution from Scots pine forest soil after application of nitrogen fertilizers at 2 µg/g wet soil. After Söderstrom et al. (1983).

reported long-term depressions in respiration rate of nitrogen-fertilized, low fertility soils (*Empetrum-Calluna* type) but found no significant differences in the more productive *Vaccinium myrtillus* type.

Hypotheses advanced to account for fertilizer-induced respiratory declines include depressions in pH or toxic osmotic potentials (Söderstrom et al. 1983), inhibition of fungal ligninolytic enzymes (Leatham and Kirk 1983), and a reduction in carbon availability (Titus and Malcolm 1987). Evidence in support of the pH hypothesis is weak, as little correlation exists between changes in pH and respiration rates following fertilization. Toxic osmotic potentials also seem incapable of explaining nitrogen-induced respiratory depressions, because additions of non-N salts have produced both positive and negative effects (Söderstrom et al. 1983). Evidence for carbon availability effects is given by Titus and Malcolm (1987) and Nohrstedt et al. (1989).

Titus and Malcolm (1987) measured decomposition of spruce litter with and without additions of NPK fertilizer. Over a three-year period decomposition in fertilized litter was retarded by 45% (Figure 4). Nohrstedt et al. (1989) reported that 11 years after fertilization with urea or ammonium nitrate, a significant accretion of forest floor carbon had occurred that could not be explained by a computed increase in annual litterfall caused by fertilization. Measurements of microbial biomass and activity, and respiration, showed only slight, nonstatistical differences when expressed on an area basis, but when expressed per unit of soil carbon, declines from control near 50% were observed for respiration and biomass in H and A1 horizons of soils fertilized with ammonium nitrate. Nohrstedt et al. (1989)

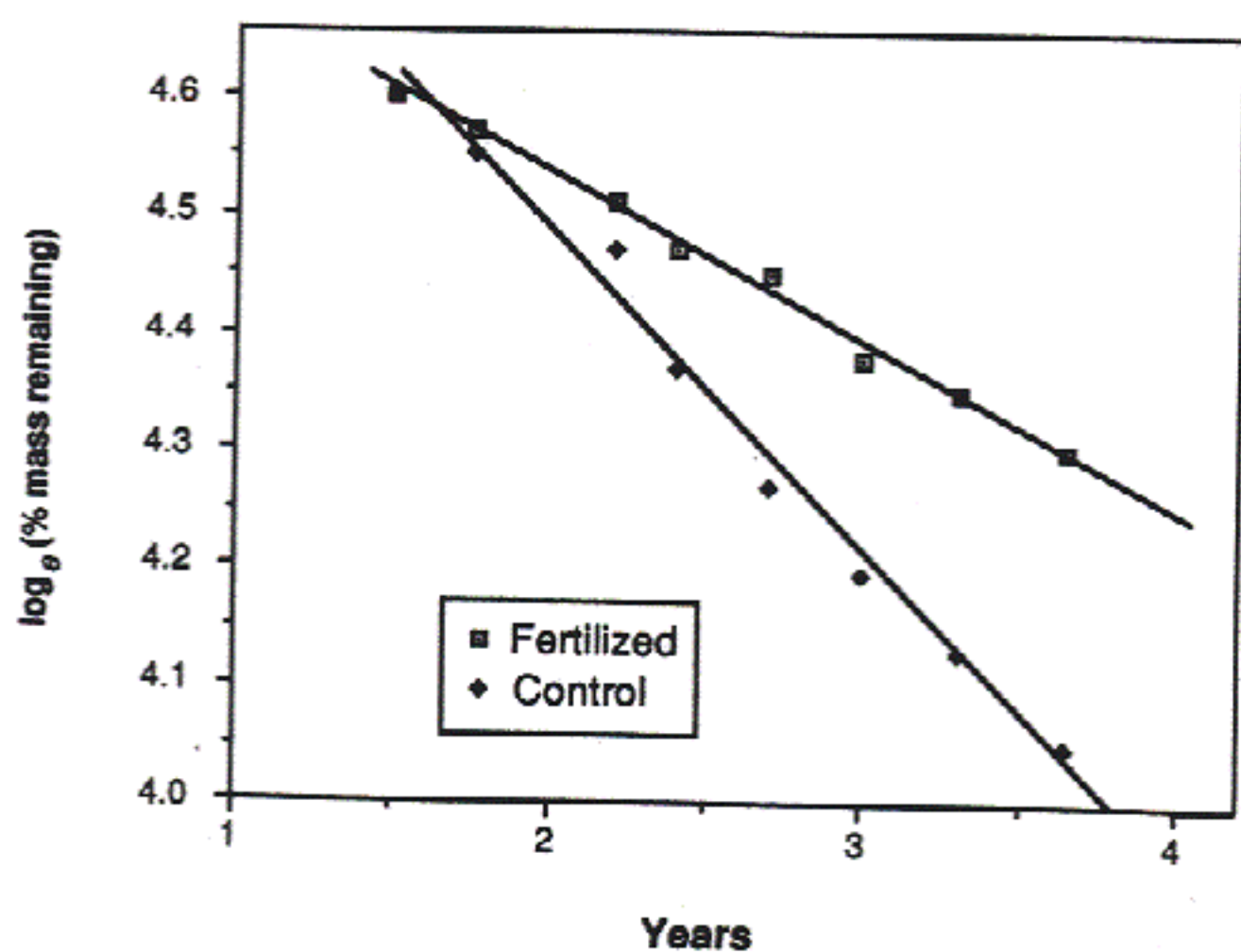


Figure 4. Mass loss of litter in cleared Sitka spruce forest with and without addition of NPK fertilizer. After Titus and Malcolm (1987).

hypothesized that the absence of a decline in tree growth predicted from the above changes in microbial activity was likely obviated by the greater mass of forest floor organic matter after fertilization.

A possible explanation to account for reduction of carbon availability lies in the classical theory of humus formation. Condensation of ammoniacal N with various organic compounds underlies a variety of mechanisms proposed for the formation of humic substances (Stevenson 1982). Ammonium or other reduced forms of nitrogen that increase as a result of fertilization may accelerate the stabilization of available carbon to forms more physically or chemically resistant to microbial attack.

Fungal Ecology. Arnebrandt et al. (1990) examined distribution and abundance of filamentous fungi at the sites studied previously by Söderstrom et al. (1983) and Nohrstedt et al. (1989). Although speciation in fertilized and control plots was similar, several significant differences from control were found in fungal abundance. Further, urea and ammonium nitrate produced different changes. A principal components analysis showed that community structures in control and AN- and urea-fertilized soils were different (Arnebrandt et al. 1990). Arnebrandt et al. (1990) speculated that community structure changes might be related to differences in soil reaction caused by the two nitrogen sources (see "Properties of Nitrogen Fertilizers" above).

At the same site, Arnebrandt and Söderstrom (1989) studied the effects of nitrogen fertilization on mycorrhizal infection of Scots pine seedlings. Unlike other investigations that have shown a reduction in infection frequency, Arnebrandt and Söderstrom (1989) found no significant differences from control, perhaps due to the time elapsed since fertilization—13 years. Distinct differences in species composition were detected, however. For example, *Cenococcum graniforme* was present in both control and urea treated plots but not AN-treated plots. The ecological significance of these changes in mycorrhizal community is unknown.

Nitrogen Cycling - Mineralization. Effects of nitrogen fertilization on immobilization and nitrification were discussed above as fates for applied nitrogen. The following discussion deals mainly with mineralization.

The obvious and desirable effect of fertilizer on soil is to increase the availability of the applied nutrient(s). Although a great number of reports describe availability of nitrogen for the first few months after fertilization, little information has been published on long-term effects. Miller (1981) contends, based on experiments with

Corsican pine (*Pinus nigra* var. *maritima*) in Scotland, that nitrogen fertilization has an ephemeral impact on nitrogen availability and that tree growth responses should not be expected to last beyond a few years. This is consistent with the brief duration of increased nitrogen availability reported after nitrogen fertilization (Johnson et al. 1980; Radwan et al. 1984; Nason 1989). In contrast, Binkley and Reid (1985) described extended nitrogen fertilization response by Douglas-fir coincident with a sustained increase in nitrogen availability. Laboratory incubations of fertilized forest soils often show modest increases in mineralization rate (Robertson 1982), but the significance of this in tree nutrition is not known at present.

Nason (1989) found that movement and transformations of ^{15}N -urea in a Douglas-fir soil could be described by a three-compartment system consisting of active and stabilized forms of organic N and ammonium (Figure 5). During the first few weeks after fertilization, expansion of the active nitrogen fraction had the effect of increasing mineralization rate; however, as stabilization drew fertilizer nitrogen to less active forms, the effect on gross mineralization rate subsided. The compartment model of Nason (1989) is consistent with the short-term increases in nitrogen availability reported by Johnson et al. (1980) and Miller (1981). More work is needed, however, to confirm: (1) that trends in postfertilization nitrogen mineralization reported to date are typical, and (2) that the kinetic, compartmental approach to

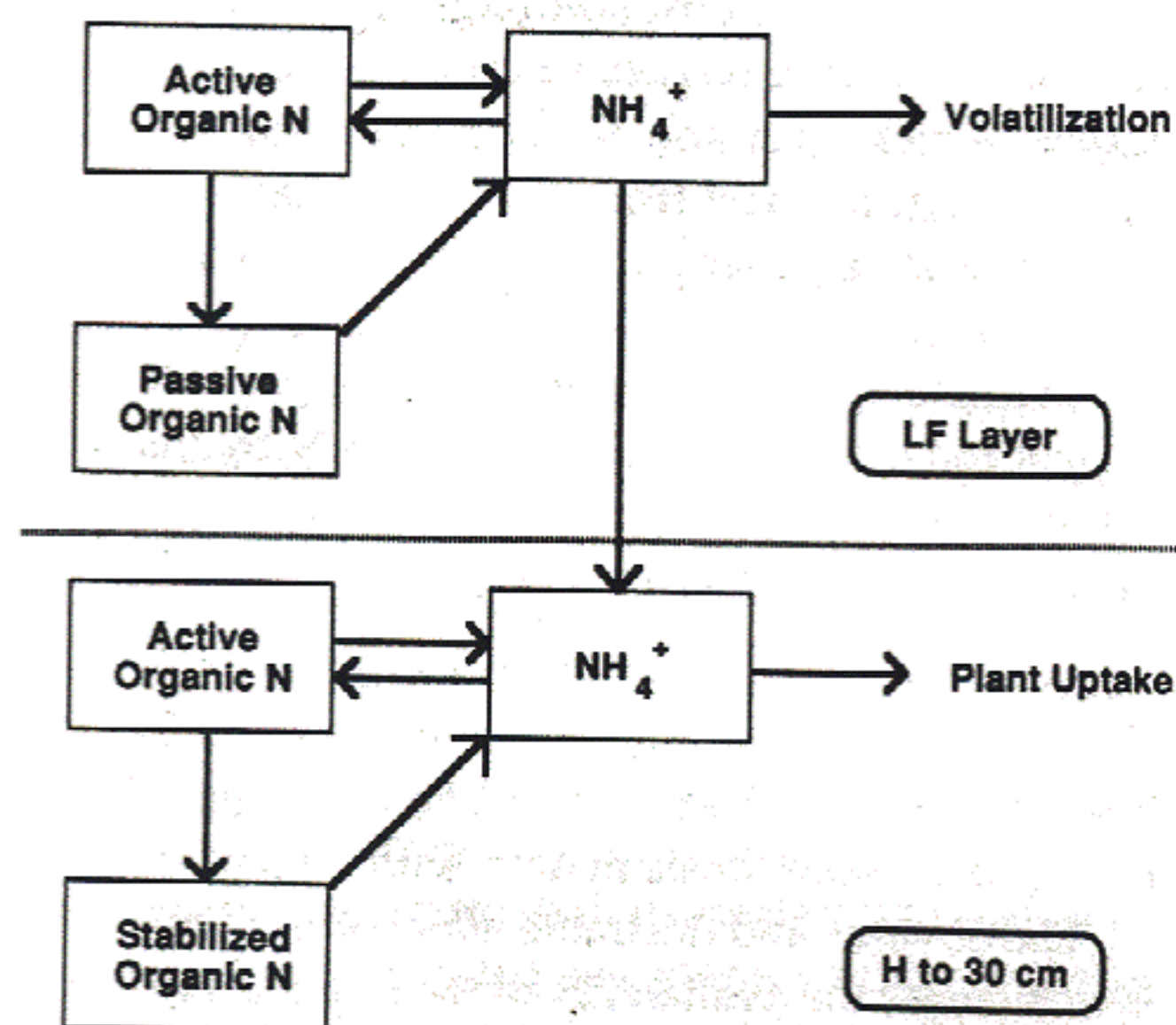


Figure 5. Proposed model for nitrogen cycling in first year after fertilization of a Douglas-fir forest soil with ^{15}N -labeled urea at 200 kg N/ha. After Nason (1989).

nitrogen cycling is appropriate in a variety of forest soils.

Priming Effect. Much has been written on the "priming effect" of fertilizer nitrogen on mineralization processes. Jenkinson et al. (1985) and Hart et al. (1986) have provided clear explanations and demonstrations of how "added nitrogen interactions" (ANIs) may arise, and how most ANIs are essentially misinterpretations of ^{15}N data. We will not add to the discussion other than to point out that ANIs are predicted well by compartmental models of nitrogen cycles (Myrold and Tiedje 1986; Nason 1989), result in an underestimation of fertilizer nitrogen uptake, and should be expected in any experiment adding high levels of ammonium.

Soil Reaction. Acidifying effects of nitrogen fertilizers on agricultural soils have been known for some time and may serve as a basis for predicting forest soil behavior. The forest situation differs, however, in that (1) ambient pH is normally much lower, (2) nitrogen applications are relatively small, and (3) nitrification may be weak to absent.

Urea application initially increases soil pH (see "Properties of Nitrogen Fertilizers" above). Otchere-Boateng and Ballard (1978), Radwan et al. (1984), Nason (1989), and Radwan and DeBell (1989) all reported increases of about one pH unit in surface horizons for the first few months following urea fertilizations of Douglas-fir or western hemlock. Radwan and DeBell (1989) showed that the magnitude of alkalization could be reduced through use of sulfur-coated urea granules. Nitrification of ammonium derived from urea may result in acidification, however. Nitrification commencing three months after urea fertilization of Douglas-fir was accompanied by a pH decline below control of 0.5 in soil solution collected at 10 cm depth (Otchere-Boateng and Ballard 1978).

In addition to regulating retention of fertilizer nitrogen, nitrification plays a key role in potential acidification resulting from fertilization. Nitrification of one equivalent of ammonium releases two equivalents of protons, and thus acts as a *potential* source of acidity. However, Reuss and Johnson (1986) show that the net effect of nitrification may be less at the ecosystem level because one proton is neutralized by plant uptake. Thus nitrification followed by complete plant uptake is equivalent to uptake of the ammonium source from the standpoint of acidification. Theoretically, ammonium nitrate should not acidify at all provided plant uptake is complete. In practice, fertilizer efficiency is usually less

than 30% and the H⁺ balance will depend on fates other than plant uptake of the applied nitrogen.

Long-term nutrition experiments in Sweden provide some information on total system response. Tamm and Popovic (1974) reported that nitrogen additions to a Norway spruce forest up to 1,550 kg/ha did not affect pH in the 0-50 cm depth over a 12 to 14-year period. Addition of 3,900 kg N/ha, which more than doubled site nitrogen capital, caused a decline of approximately 0.5 pH unit. Nohrstedt (1990) showed that three cycles of a 7-year interval ammonium nitrate fertilization program of Scots pine did not affect the pH of the forest floor or eluvial horizon but resulted in a 0.2-0.3 unit decline in pH of the spodic horizon.

Fertilization of forest soils with nitrogen at conventional dosages has not been reported to result in measurable long-term acidification. Lack of a nitrifying potential is a factor in some cases; however, even where nitrifiers were active, pH effects were minimal (Tamm and Popovic 1974). Research in acidic deposition has shown that the pH stability of coniferous forest soils relies on the low ambient pH. Simulations suggest that, in the pH range of 4 to 5—common in coniferous forest soils—fixed additions of acidity (protons) result in very small changes in pH because of hydrolysis reactions of aluminum liberated from primary minerals and hydroxides (De Vries et al. 1989).

Consideration of (1) nitrogen loading rates in relation to site nitrogen, (2) the balance between nitrate generation and plant uptake, and (3) buffer systems of forest soils leads to the conclusion that current forest nitrogen fertilization practice is not likely to cause long-term acidification in western North American forest soils. Further investigation of the acidic components of waters draining fertilized watersheds may, however, be justified from the standpoint of protecting surface waters.

Vegetation

The growth response of target trees to nitrogen fertilizers is treated elsewhere in this volume. Here we restrict our discussion to understory species.

Successful fertilization increases the availability of the applied elements and may result initially in increased growth of understory species. However, a major component of target tree response is expansion of leaf area (Brix 1983), and this should decrease availability of light beneath the canopy. Thus it has often been reported that total understory biomass decreases (Wolters and Schmidting, 1975; Stanek et al. 1979; Gerhardt et al. 1986).

Overall, nitrogen fertilization can be expected to result in a transient increase in understory biomass

followed by a decline as overstory canopies expand and reduce illumination near the forest floor. Heavy or serial fertilizations may result in changes in understory species composition.

Summary and Conclusions

The principal nitrogen sources applied to forest soils are urea and ammonium nitrate. These differ in their chemical properties, primarily their acid-base chemistry, and this results in important differences in their behavior in soil/plant systems. Alkalinity generated during urea hydrolysis creates the potential for volatile loss of ammonia. This may be minimized by application of urea during cool, moist weather. Ammonium nitrate is a slightly acidic salt that dissociates completely in the soil solution. Nitrate so liberated may leach from the system if hydrologic fluxes are high and plant uptake capability low. Leaching of nitrate may be minimized by timing application to avoid saturated conditions and taking advantage of periods of high root biomass and activity—conditions most likely met in spring in the Pacific Northwest.

Soil recovery of ammonium-based fertilizers in temperate coniferous forest soils is usually high as a result of immobilization, which averages 50-60% in the first year after application. Plant uptake is the normal secondary fate of fertilizer nitrogen. Estimates vary with species, application dosage, chemical source, and other factors, but conventional nitrogen dosages applied to appropriate stands usually result in uptake equivalent to 20-30% of applied nitrogen. Nitrification of fertilizer ammonium is extremely variable; many soils do not nitrify, whereas nitrate may be the dominant inorganic form of nitrogen in others. The weight of evidence suggests that ammonium availability is the principal factor limiting nitrification response. Because increases in nitrogen availability following fertilization are usually short, a majority of soils that don't nitrify before fertilization will not establish this activity thereafter. Soils with nitrifying capacity likely will increase that capacity after application of ammonium-based fertilizers. Retention of a fertilizer-induced nitrification increase apparently may last several years. Particular care should be taken with respect to nitrification management when refertilization is planned. Denitrification does not appear to be a significant part of the fertilizer nitrogen balance sheet in coniferous forest soils.

Once in trees, fertilizer nitrogen moves mainly to the needles of highest photosynthetic capacity. From there nitrogen is distributed throughout all plant tis-

sues, but after two to four growing seasons 60 to 75% of fertilizer nitrogen is found in the crown. Studies with ^{15}N show that retranslocation of recent foliar N is considerable: estimates range from 50% annually to over 100% in one month.

Residual fertilizer nitrogen and reaction products have been reported to have long-term effects on microbial processes and speciation, particularly on low fertility sites. Effects noted include depressions in rates of respiration and decomposition, reductions in biomass size and activity, and changes in the abundance of both saprophytic and mycorrhizal fungi. More studies are needed to assess the frequency of these effects and their significance.

The role of fertilizers in the long-term nutrition of forests is a surprisingly sparse area of research. More information on long-term patterns of carbon and nitrogen cycling is needed to evaluate fully the economic and environmental implications of forest fertilization.

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Questions and Answers

Our practice has been to wait until fall rains start before fertilizing with urea. This is because of concerns over volatilization loss. Operators tell us it would be OK to apply it earlier, including warm clear autumn days. Please comment.

Your practice follows accepted principles of urea fertilizer management and we would recommend that you continue to follow it. Your operators might like to apply urea on warm, clear autumn days, but in doing so you risk higher losses from ammonia volatilization. Cool, moist weather may also serve to minimize short-term immobilization of fertilizer nitrogen.

Was the 40% ammonia volatilization from urea based upon actual field data, or was it based upon experimental laboratory conditions?

Ammonia losses from urea-fertilized forest soils of approximately 40% have been reported in two studies. Watkins et al. (1972) conducted their studies in the laboratory using an air sweep system. Marshall and DeBell (1980) used ^{15}N balance to estimate losses of about 40% in a field study, but their estimate included other unmeasured losses. Direct measurements of volatile loss in this latter study ranged from 13 to 17%. Field studies designed to minimize restrictions on air exchange and access of precipitation to applied urea (Craig and Wollum 1982; Nason et al. 1988) have generated volatilization estimates ranging from less than

1% under cool, moist conditions to about 14% under warm, dry conditions.

How significant to ammonia volatilization loss are short-term (one to three weeks) warm, dry spells during fertilization?

This type of weather, particularly if it is warm, is what enhances loss of urea-N by the ammonia volatilization process. Most volatilization studies show the greatest losses shortly after application, which subsequently decline fairly rapidly. An exact estimate of the effects of one to three weeks of dry weather on ammonia volatilization is difficult because of interactions between litter and soil moisture, relative humidity, temperature, and urease activity.

The literature indicates that ammonia volatilization requires over 80°F temperatures and 80% humidity. Are there any times in western Oregon or Washington that ammonia volatilization would be a significant problem? Also the pH of forest soils is generally 4.5 to 5.

Yes. Field experiments in Pacific Northwest forests have measured significant losses of urea-N from ammonia volatilization. For example, Nason et al. (1988) measured a 14% loss of urea-N applied in spring to a Douglas-fir stand on Vancouver Island. Measured ammonia volatilization losses are usually less in fall, however, because of cooler temperatures and the greater likelihood of heavy rainfall events. You are correct in assuming that once the urea dissolves and disperses in the soil solution, the buffering capacity of the soil maintains the pH at levels unfavorable for ammonia volatilization. But the pH immediately adjacent to a dissolving urea pellet is high enough (1M hydrolyzed urea has a pH of >10) for ammonia volatilization to occur.

What about forest tree response to urea application on snow versus no snow? Is depth of snow important?

The work of Preston et al. (1990) showed little loss of urea-N by ammonia volatilization when urea was ap-

plied on top of snow. Unfortunately, plant uptake of urea-N was low (5-10%). Ammonia volatilization should be less with more snow because of the greater amounts of water that the urea would dissolve into when the snow melts.

You stated that approximately 50% of the applied fertilizer nitrogen ends up in soil organic matter. What about when fertilizer is applied after a heavy thinning? Does a lot of the fertilizer nitrogen end up in the slash? Any practical considerations in the timing of fertilization after a thinning that leaves a lot of slash on the ground?

Although chemical immobilization of fertilizer-derived ammonium-N may be more important than generally recognized, it is useful to view the short-term fate of this nitrogen in the soil as depending on competition between plant (hopefully crop tree) roots and microorganisms. In this competition, the microbes seem to win—they wind up immobilizing about twice as much nitrogen as the trees take up. Microbial immobilization is favored in litter and soil that have a wide C:N ratio and when fertilizer nitrogen is present as ammonium rather than nitrate. The outcome of the competition is usually complete by the end of the first growing season following fertilization. Thinning slash is likely to have the greatest impact if it is in a position to be in intimate contact with the fertilizer during the first six months after application. Thus, if fertilizer is applied when slash is resting above the forest floor, it should have relatively little effect on the fate of fertilizer nitrogen that reaches the forest floor. If slash has been incorporated into the forest floor, then its effect on fertilizer nitrogen immobilization depends on its stage of decomposition. Fresh slash has a greater potential for immobilization than slash that is more decomposed, because the C:N ratio of the slash will narrow during decomposition. Nitrate-based fertilizers may be a more attractive choice than urea for this treatment, provided that leaching potential is not prohibitive.