FORMS OF NITROGEN FERTILIZER

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ABSTRACT

Forms of nitrogen fertilizer vary widely. Classifications that are important to foresters are the chemical, physical, economic, efficient, traditional, and environmentally acceptable forms. Chemical forms of nitrogen are ammonium, nitrate, and organic; there are many fertilizers in each of these classes. The first breakdown of the physical form is that of solid, suspension, liquid, and gaseous. Solid fertilizers can range in particle size from a fine powder to a granule, supergranule, or briquette. In the economic arena, a fertilizer expensive for one situation may be cheap for a different product or situation. Fertilizer efficiency can be high or low—and completely unrelated to growth response. Fortunately, fertilizer use in forested areas is still new enough that a traditional form of nitrogen fertilizer has not become established. Finally, there is a new consideration that is pertinent to the form of nitrogen fertilizer that can be used: whether or not the form is environmentally acceptable. Substantial progress has been made in the Pacific Northwest in evaluating the many combinations of forest products, nitrogen fertilizer forms, and modifying factors. Methods of improving the efficiency of fertilizer use, especially that of urea, should be of principal concern.

INTRODUCTION

The role of forestry has undergone drastic changes in the last few years. Clawson (1979), in his essay on "Forests in the Long Sweep of American History," clearly delineated this change. From the colonization of America until only a few years ago, forests were looked upon as sources of building materials and fuel, and as impediments to ready establishment of field crops. In more recent time, the forests have come to be more appreciated for their watershed, wildlife, recreation, wilderness, and esthetic values (Clawson 1979). A discussion of forms of N fertilizer for use in the forest industry must, then, include this wider role rather than be confined to the effects on timber production.

By the same polemic, "form" of N also must be considered in a context broader than heretofore considered by most forest fertilization researchers. In this paper form is classified in six ways. Unfortunately, research information is not available to exemplify each area; subjective discussion must suffice for some of them. The six areas to be considered are chemical, physical, economical, efficient, traditional, and environmentally acceptable.

CHEMICAL FORM

The literature on forest fertilization reports many comparisons of ammonium versus nitrate. Early investigators apparently hoped they could quickly resolve the question of whether ammonium or nitrate were the preferred form of N for all conifers (McFee and Stone 1968). As might be expected, the results were conflicting. At one of the early forest fertilization conferences, held at Gainesville, Florida, in April 1967, Hauck (1968) commented that it was difficult to prove preferential crop uptake of either ammonium or nitrate from the soil. Nutrient cultures and pot studies in greenhouses provide considerable information about chemical forms of N, but in the field a clear definition of crop preference is obscured by many unknown (and uncontrolled) variables. At this same conference, Gessel (1968) stated that form of N was not a significant factor in response to N in the Pacific Northwest. Despite this early advice, research continues and the results show the same disparity. Much of the ammonium-versus-nitrate work has been with seedlings and does not necessarily apply to mature stands, cone and seed production, nursery management, and the like.

Commercially available ammonium-type fertilizers include anhydrous ammonia, ammonium nitrate, ammonium sulfate, and N solutions. There are other fertilizers that contain ammonium such as the various ammonium phosphates, but these are not feasible for the Pacific Northwest where responses to P fertilization are quite rare. Commercially available nitrate-type fertilizers include only ammonium nitrate and N solutions. (For research purposes, there are additional sources of both ammonium and nitrate fertilizers. They are not discussed here.)

In the Pacific Northwest, as well as in other areas and countries, urea is a major source of N used in forest fertilization. Organic chemists classify urea as an organic compound, but fertilizer researchers normally consider it as an ammonium type. When urea hydrolyzes in aerobic soils, ammonia and carbon dioxide are formed. Urea decomposes differently in anaerobic soils and the reaction products include dinitrogen, nitrous oxide, nitric oxide, and nitrite.

Additional organic forms of N being tested in forested areas, including the Pacific Northwest, are solid and liquid municipal wastes. Such wastes contain low levels of essential plant nutrients, including N. Virtually all the N is in a form not quickly available to plants. This organic N must undergo microbial decomposition and conversion before it can be absorbed by plant roots. Thus there is a considerable delay, in comparison with the readily soluble commercial fertilizers, before the N is available. Once N enters into the plant system, however, it is entirely comparable to the inorganic forms. The delay in availability is not as serious in forest fertilization as it would be in an annual field crop or a fast-growing vegetable crop.

Nitrogen fertilizer reactions in soils have been studied extensively. As Hauck (1968) has pointed out, these reactions are controlled by a multitude of soil- and climate-related factors such as temperature, moisture, pH, texture, buffering capacity, and organic matter. All ammonium-type fertilizers commonly undergo a two-step nitrification process by soil microorganisms. Under some conditions, the second step is delayed and nitrites accumulate. This results in a reduction of fertilizer efficiency, in phytotoxicity, and possibly in loss of N as various gases.

Nitrite accumulation is a signal also for an accumulation of ammonium. Again fertilizer efficiency is reduced, phytotoxicity can occur, and so can loss of N as gaseous ammonia. The phytotoxicity probably is negligible under most forest-fertilization conditions, but it could be a problem in seedling nurseries. As has been pointed out above, anaerobic (such as high-moisture) conditions also cause urea fertilizers to decompose into gaseous forms of N. Loss of N as gaseous products thus is fairly common for ammonium-type fertilizers, but its seriousness in forest fertilization is not well documented.

A report by the Canadian Forest Service at this conference showed that ammonium nitrate was superior to urea on unthinned plots of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) in Victoria (Brix and Dangerfield, this volume). Several postulates for the difference were presented: The higher pH produced by hydrolysis of urea could have reduced N uptake, increased microbial activity from urea application could have immobilized N, or increase in pH produced by hydrolysis of urea could have resulted in volatilization of ammonia. Volk (1970), who measured gaseous loss of ammonia from urea applied to a pine forest, commented that the possibility of loss was high when the cation exchange capacity was deficient at the point where hydrolysis occurred. He found that volatilization losses were reduced by half in areas subjected to controlled burning, as compared with undisturbed organic residue. This was in keeping with the work of Overrein and Moe (1967), Roberge and Knowles (1968), and Shumakov et al. (1974), who have shown that the urease activity of forest litter is very high and that urea hydrolyzes rapidly under forest fertilization conditions.

Much of the urea applied by aerial broadcast to coniferous forests seems to be retained in the undecomposed or raw litter. Hydrolysis can be completed in as little as 3 days when temperatures are high and moisture is adequate (Carrier and Bernier 1976). Another factor affecting the rate of hydrolysis is the rate of urea application. Many workers have shown that increasing the rate of application increases the rate of hydrolysis—and exponentially increases the amount of ammonia volatilized (Bernier et al. 1972, Carrier and Bernier 1971, Overrein and Moe 1967, Volk 1970). Losses as high as 30% for an application of 267 lb N/acre (300 kg/ha) and of 18%–28% for an application of 200 lb N/acre (224 kg/ha) have been reported (Carrier and Bernier 1971, Morrison and Foster 1977).

Comparisons of urea with other N sources have not always been unfavorable to urea. van den Driessche and Webber (1975) reported that fertilization of Douglas-fir seedlings with urea significantly increased the concentration of guanidino compounds in twigs compared with those of seedlings fertilized with nitrate. Overrein (1969) found, as would be expected, very little leaching of urea in lysimeter experiments, but losses of nitrate were high and those of ammonium were significant. Nömmik and Popovic (1971) also found mobility of urea to be lower than that of calcium nitrate and ammonium sulfate when all were compared on a 90-yr-old stand of Scots pine (*Pinus silvestris* L.) on an iron-humus Podzol. Ammonium nitrate, because of its mixed composition of ammonium and nitrate, is difficult to study directly. The use of calcium nitrate and ammonium sulfate, as done by Nömmik and Popovic (1971), avoids confounding the ammonium and the nitrate effects.

Much has been learned about the factors that affect the efficiency of various N fertilizers. But, as Hauck (1968) has commented, it is much easier to delineate the conditions in which a particular N source should *not* be used than to tell how a particular source can be used most efficiently. There is an axiom that a pound of N is a pound of N, but this can be true only when each material is applied in a manner and under situations most favorable for its use. Frequently the user may be unable to select the most suitable source or to use the fertilizer in the most suitable manner. Some compromises are necessary. Compromise should not, however, be an excuse for ignorance or failure to learn the characteristics of various fertilizer products.

The fertilizers now available on the market are no longer simple, low-value products than can be used with impunity. As the complexity of fertilizers has increased, so also has the care that must be exercised to use them most advantageously. This in no way decreases the effectiveness or value of the newer materials, but it certainly requires that the user be more diligent in following the best techniques for use. Heilman et al.

(this volume) have amply illustrated the effects of transferring to urea the practices developed for ammonium sulfate and ammonium nitrate. It seems that there might be several practices that should be tested to determine if they would improve even further the effectiveness of urea.

Broadcast application of urea on the surface of the soil, especially a soil covered with trash that is high in urease activity, is not a satisfactory method of applying this fertilizer. Overrein and Moe (1967) showed that losses of volatile ammonia could be greatly reduced by incorporating the urea into soil as shallow as 0.5 cm. Although incorporation does not appear to be feasible for aerial applications of urea to large blocks of land, there are two methods that merit consideration. First, urea application could be timed to the rainy season. Carrier and Bernier (1976) found that the reduction of volatilization by artificial precipitation was significant and increased with increasing precipitation when the latter was applied soon after fertilization. Of course, equal caution should be exercised to not apply urea when soils are excessively wet and could be expected to stay wet. Denitrification under anaerobic conditions could lead to N losses even greater than the volatilization losses.

A second method of application should be tested. About 10 yr ago, Cominco American, Inc. developed a forestry-grade urea. As shown in Table 1, prilled urea is extremely light in weight, making it difficult to apply from the air. Granular urea is somewhat easier to apply, but forestry-grade urea granules are five to six times heavier than regular granules. Helicopter operators prefer the forestry-grade granules because they are less affected by air currents and swaths are wider and more uniform.

Table 1. Average weight of granules of various types of urea.

Type of urea	Granule wt (mg)
Prilled	2.3
Granular (TVA pan)	7.3
Granular (Cominco)	9.5
Forestry-grade (Cominco)	44.2
Supergranule	1000–3000
Briquette	>5000

Even larger granules have been developed. Supergranules, weighing 1–3 g each, and briquettes, weighing over 5 g each, are experimental materials intended for testing in rice paddies in tropical countries (International Fertilizer Development Center 1978). Supergranules applied aerially to forested soils, however, should penetrate the forest litter to a greater depth than forestry-grade granules, possibly to a depth sufficient to reduce volatilization losses. To date, there have been no trials of supergranules of urea on forested soils.

Carrier and Bernier (1971, 1976) have found that triple superphosphate or potassium-magnesium sulfate, applied at the same time as the urea, reduced volatilization losses. Although forest species in the Pacific Northwest are not known to respond to P, K, or Mg fertilization, the idea of an adjunct to urea to reduce losses deserves further consideration. In studies carried out at the National Fertilizer Development Center (NFDC) (1978) mixtures of urea and such materials as calcium nitrate, calcium chloride, and urea phosphate reduced volatilization losses to nil when the materials were placed on bare soils. Ammonium sulfate, potassium chloride, and ammonium polyphosphate were somewhat effective. Urea granules alone showed a 72% loss of N in 7 days.

Again, these adjuncts would not be feasible in the Pacific Northwest. The NFDC test also included urea ammonium nitrate solution containing 32% N. A urea solution applied to the soil volatilized of 64% of the N in 7 days when applied at a rate of 500 lb N/acre (560 kg/ha). The urea ammonium nitrate (UAN) solution showed no loss even at an application rate of 1115 lb N/acre (1250 kg/ha). The use of urea ammonium nitrate is discussed in a later section.

It has been pointed out that volatilization losses increase exponentially as the rate of urea application increases. The NFDC work described in the preceding paragraph showed a threefold increase in volatilization losses when the rate of N application was doubled. There are myriad tests with field crops showing that urea efficiency is markedly increased for crops responding to large quantities of N when the urea is applied in split doses. Equivalent research in forest fertilization generally is lacking. Steinbrenner (1968) reported data for comparisons of annual applications of 0, 100, and 300 lb N/acre (0, 112, and 336 kg/ha), as urea, with an application every 4 yr, in alternate years, and in 2 yr out of 4. The more frequent applications at the highest level of N increased diameter growth of 20-yr-old Douglas-fir by 12%. Unfortunately, because the response was still linear through the highest rate, it is impossible to determine whether additional increments of N would have caused the rate of yield to continue to rise, to plateau, or to drop.

Hohne and Fiedler (1977), working in the German Democratic Republic with pine stands, found that annual rates of 40 lb N/acre (45 kg/ha) and biennial rates of 80 lb N/acre (90 kg/ha) were superior to a rate of 120 lb N/acre (135 kg/ha) applied every 3 yr. The N source tested was calcium ammonium nitrate. On sites poor in nutrients, the recommended fertilizer program was 89 lb N/acre (100 kg/ha) applied every second year.

It seems appropriate to ask, then, whether the efficiency of urea applications in the Pacific Northwest could be improved by reducing the rate of application from 200 lb N/acre (100 kg/ha) to some lower rate. According to one commercial applicator, three passes over an area are needed for reasonably uniform application (Kvamme, this volume). Customarily, the three passes are made on the same day. Would not it be just as economical to make the three passes a year apart, especially if it resulted in increased utilization of the urea?

PHYSICAL FORM

The first classification of physical form is that of solid, suspension, liquid, and gas. The only gaseous N fertilizer is anhydrous ammonia, and even this fertilizer is usually refrigerated or maintained under pressure so that it is in the liquid form. Anhydrous ammonia is used extensively in the corn belt because of its extremely high analysis (82% N) and low cost per unit of N. There are few situations in the range of forest fertilization activities where anhydrous ammonia could be used advantageously, but it might be used in seedling nurseries or in certain areas that are being reforested. Another potential use is to ammoniate municipal wastes before they are applied in forested areas. Such wastes are low in N and probably could be ammoniated cheaply and easily.

Liquid forms of fertilizer, including liquid N, are popular in the United States. Nitrogen solution, containing 28%–32% N from urea and ammonium nitrate, makes up a very large proportion of the liquid N fertilizer. Also included in the statistics on liquid fertilizers are anhydrous ammonia and aqua ammonia, which is made from anhydrous ammonia. Nitrogen solution, and aqua ammonia in very low concentrations, can be applied through irrigation systems, thus they are appropriate for use in seedling nurseries.

Nitrogen solution also should be appropriate for aerial application. Miller (this volume) reported his experiments on the foliar application of urea ammonium nitrate to seedlings and established stands of Douglas-fir. Extensive osmotic burning was reported, but the effects may have been more inaesthetic than detrimental to growth. Eberhardt and Pritchett (1971) earlier made foliar applications of N to slash pine (*Pinus elliottii* Englem. var. *elliottii*). They also observed foliage burns when the concentration exceeded 3000 ppm N. They found much higher rates of N absorption from urea than from calcium nitrate or ammonium sulfate. This was in keeping with Michigan work that showed urea molecules could be absorbed intact into leaves (Wittwer et al. 1965).

There has been extensive work with foliar applications of fertilizers to agronomic crops especially in India, and more recently in the United States.

Opinions vary about the feasibility of foliar applications. Proponents claim greater utilization of N and thus a reduction in the total quantity of N that must be applied when compared with soil applications. Opponents call attention to the low concentrations that must be used and to the high cost of the frequent applications required to provide crops with an adequate supply of N. In the forest-fertilization arena, urea ammonium nitrate should be tested further before drawing conclusions about its utility. As pointed out earlier, urea ammonium nitrate solution that penetrates the canopy and falls to the soil may be more efficient than urea alone, either solid or liquid.

Suspensions are fluid fertilizers that also contain solids. They have most of the handling characteristics of fluids as well as other important advantages. They are higher in analysis than the clear liquid fertilizers and are ideally suited for application of the major nutrients plus other materials required in very small quantities such as micronutrients and pesticides. There have been experimental applications of suspension fertilizers to stands of timber, but use of suspensions is not yet an accepted practice in forest fertilization.

Solid fertilizers are, by far, the most commonly used form of fertilizer in the world, in the United States, and in forest fertilization. Among the various solid sources of N, urea, ammonium nitrate, and ammonium sulfate are the most likely to be commercially available.

Merely to specify that a fertilizer is a solid is not now an adequate description of the physical characteristics. At one time nearly all fertilizers were powders, and there were no particular problems when the powders were applied by hand at very low rates of application. With the advent of bulk handling, farmers found that powdery fertilizers drifted into their neighbors' fields, and aerial application was even less satisfactory. Granular fertilizers were a major improvement. Granulation produces large particles from powders or melts. Granules, as mentioned above, can be made in small, intermediate, large, or very large sizes. The larger the granule, generally, the easier it is to handle with a mechanical applicator.

ECONOMICAL FORM

For forest fertilization, a fertilizer that is expensive for one situation may be cheap for a different product or situation. As an example, almost any fertilizer that increases seed production would be economical to use, even if it had to be applied by hand, because of the high value of the seed (Table 2; Heid-

Table 2. Stimulating cone production in Ponderosa pine with TVA urea ammonium phosphate, 1978.

	Rate of 28–28–0 application (lb/acre)		
	0	500	1000
Cones/tree	17	30	73
Value of seed ($/acre)[a]	244	436	1065

[a]Seed valued at $23/pound.

mann et al. 1979, Heidmann pers. commun. 1979). For timber or pulp production, however, the cost of fertilizer, including the cost of application, must be scrutinized carefully. This often is not important to the researcher, who is interested principally in growth response.

To the commercial forester, costs are a significant consideration. He must know not only the increased growth that results from fertilization at any particular level of application, but also the effect of fertilizer on product quality, cost of fertilizer at the time of application, cost of application, carrying costs on fertilizer investment for the period between the date of application and date of harvest, and the value of the product when it is harvested 10, 20, or 50 yr later. Bengtson's (1979) calculations show that fertilization of Douglas-fir forests with urea is generally profitable for saw timber production, but only marginally profitable for pulp production.

EFFICIENT FORM

For many years, National Fertilizer Development Center scientists and others have sought a more efficient form of N fertilizer. There are many definitions for, and ways to measure, efficiency. One definition relates the rate at which N becomes available to a crop from applied fertilizer to the rate at which the crop needs N for growth. Most N fertilizers on the commercial market release all N within a few hours or days after application. Urea-formaldehydes, isobutylidene diurea, and a few other materials are slow-release sources of N. They are supposed to meter N to a crop at approximately the same rate that it is needed by the crop. Rothamsted Experimental Station workers have been interested in using these materials in English nurseries because the nurseries are typically located on light-textured soils with poor nutrient retention. Leaching of soluble N sources is a problem, but repeated small applications are costly (Benzain 1967, Benzain et al. 1971).

Mead et al. (1975) also used the nursery setting when testing sulfur-coated urea on *Pinus radiata* in New Zealand. They found that seedlings on strongly weathered clay soils cleared by slash burning responded more favorably to sulfur-coated urea than to ordinary urea. New Mexico workers, however, considered slow-release N sources potentially suitable for mature pecan trees (*Carya illinoensis* Koch). They tested both sulfur-coated urea and ammonium nitrate mixed with nitrapyrin, a nitrification inhibitor (Sullivan et al. 1976).

Sulfur-coated urea is one of the NFDC experimental fertilizers presently undergoing market development. This new fertilizer has been tested extensively in forest fertilization situations. In sulfur-coated urea tests in Montana with both subalpine fir and lodgepole pine, triple superphosphate (46 lb P_2O_5/acre, 52 kg P_2O_5/ha) and sulfur-coated urea (140 lb N/acre, 157 kg N/ha) were applied in the fall of 1974. Growth of lodgepole pine leaders for the last 3 yr was 122 cm compared with 48 cm for the nonfertilized pines. Subalpine fir also responded, but the response was not as dramatic.

In Oregon sulfur-coated urea was compared with ammonium nitrate sulfate on clearcut areas seeded to grass for game grazing. The sulfur-coated urea was comparable to the ammonium nitrate sulfate. Although sulfur-coated urea has been used as a broadcast application on the soil surface, it is more efficient when incorporated into the soil. It therefore suffers from some of the same application problems as granular urea. Sulfur-coated urea also has a higher cost than granular urea and is not yet recommended as a general forestry-type fertilizer.

The NFDC has other research in progress that uses entirely different approaches to N efficiency. It is hoped that some of this research will be useful in forest fertilization.

TRADITIONAL FORM

Traditional practices are difficult to change. In international programs designed to introduce fertilizers to farmers, and even in the United States when the fertilizer industry introduces new forms of fertilizers, there is a reluctance to accept new ideas. Fortunately, forest fertilization in the United States is a relatively new practice and few traditions have been developed (Bengston 1979). Fertilizer users are willing to try new sources in their attempts to improve production.

ENVIRONMENTALLY ACCEPTABLE FORM

There is a new consideration that is pertinent to the form of N fertilizer that can be used. This is whether or not the form is environmentally acceptable. A number of studies have been conducted in the Pacific Northwest to determine the effects of forest fertilization on water quality (see the Literature Cited sections in Moore 1975 and Tiedemann 1973 for a partial listing of published information). There is, however, another aspect that requires consideration: the disposal of municipal wastes in forested areas. Such wastes were considered earlier as low-level sources of plant nutrients. It would seem logical to use these wastes on crops with a higher value than forestry products, such as food and feed crops.

Unfortunately, municipal wastes often contain substantial concentrations of various heavy metals such as Pb, Cr, and Zn. These metals are readily absorbed by food and feed crops, thus they may be deleterious to human and animal health. Undoubtedly there will be limits imposed on the amounts of wastes that can be applied to croplands. Municipal wastes thus may be *more* environmentally acceptable in forested areas than in cropped or arable areas.

Soper (1971), working with white spruce, red pine, and other forest species, reported that municipal wastes could be disposed of on oak woodland and other hardwoods with beneficial effects on growth. Similarly, Bengston and Cornette (1973) reported that there was no adverse effect on slash pine when garbage compost was applied at rates as high as 20 tons/acre (44 t/ha). The Institute of Forest Resources (1979), University of Washington, is conducting somewhat similar research and the city of Bremerton, Washington, has contracted for the disposal of some of its wastes on forested lands. Such studies provide the data needed to determine the best mode(s) of utilizing municipal wastes.

CONCLUSIONS

There are several forms of N that are of concern in forest fertilization. There is the chemical form such as ammonium, nitrate, and organic. Urea, the leading N fertilizer for Pacific Northwest forests, is in the last class, but reacts in soils and forest litter as though it were an ammonium-type fertilizer. It poses many problems in application related to maximum efficiency.

The physical characteristics of fertilizers are just as important as the chemical characteristics. Fertilizers may be gases, liquids, suspensions, or solids, and each form has an effect on method of application and utility as a forest fertilizer. Solid fertilizers require further consideration because of the importance of particle or granule size in aerial application. Although forest fertilization does not require a large proportion of the fertilizers used in the United States, forestry has been the only practice that has warranted development of a specially sized granule. The forestry-grade granule is five to six times heavier than regular granules.

Cutting across the chemical and physical classifications is the economical form with all its connotations in the commercial area. The most economical form varies with cost of fertilizer, value of product, response to fertilizer, cost of application, and other considerations. Many research efforts are now focused on more efficient forms of N. Controlled-release sources have some specialty applications in forest fertilization but are not yet recommended for general use.

Newer research may result in an improvement in efficiency of forest fertilizers. Such improvements probably would be accepted readily by users because a traditional form of forest fertilizer has not been established in the United States. New fertilizers, and old ones too, must be environmentally acceptable. Research to study the relations of fertilizers to the forest environment is being conducted assiduously.

If only one point was to be garnered from this essay, it should be that of knowledge acquisition. Without knowledge about the chemical and physical characteristics of fertilizers, of how different fertilizers react under different soil and climatic conditions, and about cost relationships, it is impossible to conduct a satisfactory forest fertilization program.

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