ENVIRONMENTAL IMPACTS OF FOREST FERTILIZATION ON TERRESTRIAL ECOSYSTEMS

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ABSTRACT

Forest fertilization has obvious beneficial effects on the growth and vigor of trees on nutrient-deficient sites. Side effects such as improved tree resistance to damage by air pollution and, in some cases, insect and disease attack, should also be considered in any evaluation of fertilization impacts. Some intriguing possibilities for managing mycorrhizal communities by fertilization have also surfaced.

On the other hand, it is possible to sacrifice ecological optimums for physiological optimums in our quest for increased production. Fertilization is a drastic manipulation that is bound to produce negative as well as positive side effects, most notably in the case of excessive nitrification. While the prospects for managing mycorrhizal activity as well as controlling insect and disease outbreaks by fertilization are appealing, long-term ecological studies of forest fertilization effects on these as well as other ecosystem components are necessary before these goals can be achieved.

INTRODUCTION

Bengston (1979) reported that over 2 million acres (809,400 ha) of forest land have been fertilized in the United States, primarily in the Northwest and Southeast. He projects that an additional 750,000 acres (303,500 ha) will be fertilized annually in these regions during the next decade.

As forest fertilization becomes more common and widespread, environmental issues will no doubt be raised. Concern already has been expressed over water quality impacts (Reinhart 1973), a subject addressed by Moore (this volume). Weetman and Hill (1973) express less concern for water quality than for long-term ecological effects on forests. Long-term impacts are quite probable, given the conservative nature of forest nutrient cycles (Cole et al. 1968, Switzer and Nelson 1972, Henderson and Harris 1975). In contrast to agricultural systems, fertilizer is retained and cycled within forest ecosystems for many years (Heilman and Gessel 1963, Stone and Kszystyniak 1977). While this results in efficient fertilizer utilization by trees, the long-term side effects on the environment are not fully understood.

Weetman and Hill (1973) called for comprehensive, long-term ecological studies on forest fertilization and suggested that the alternative might involve not only environmental degradation but also "wide publicity of a few examples . . . [causing] public opinion to inhibit forest fertilization practice." That has certainly been the case with more visible management practices such as clearcutting and controlled burning.

Environmental assessments invariably involve value judgments as to what is positive and what is negative. Environmentalists interested in preserving a wilderness area may consider any impact, including increased growth and vigor of forests, to be negative. Fortunately, we are not discussing fertilizing wilderness areas here, but we are well-advised to keep in mind that such celibate philosophies often underlie environmental opposition to forest management practices as a whole. The effects of these philosophies on environmental research were eloquently described by Gessel (in press) in his keynote address to the Fifth North American Forest Soils Conference:

> The present environmental concern era, although the producer of many needed changes, has left us with several philosophies which often affect the direction and objectivity of forestry-related research. One is the "nature knows best" philosophy . . . . A similar concept is . . . that we should practice only "ecologically sound forestry." These general mottos . . . on the surface appear to be sound, but they suffer from the fact that ecological soundness and the state of nature are presently determined by the eyes of the beholder.
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> Another type of research philosophy which reduces usable output . . . is the focus on negative research and in so doing collect[ing] only data which serves to establish that a disaster is about to occur.

There is no scientific justification for assessing environmental impacts from an exclusively negative standpoint. Every management activity has some negative environmental aspects; the challenge to the environmental scientist is to objectively evaluate and project the impacts of man's activities on ecosystems before making judgments as to whether these impacts are to be defined as positive or negative. To concentrate solely on the negative is to run the risk of causing the elimination of management activities that not only increase forest production but also produce desirable changes in the ecosystem as a whole.

Likewise, we must not be totally blinded by desires to increase productivity as Odum (1969) points out:

> Many essential life-cycle resources, not to mention recreational and aesthetic needs, are best provided man by the less "productive" land-

scapes. In other words, the landscape is not just a supply depot but is also the *oikos*—the home—in which we must live . . . The "one problem, one solution" approach is no longer adequate and must be replaced by some form of ecosystem analysis that considers man as a part of, not apart from, the environment.

EFFECTS ON TARGET ORGANISMS: TREES

Fertilization can have several impacts upon trees in addition to the desired improvement in growth. Fertilization has been noted to increase the resistance of eastern white pine (*Pinus strobus*) to sulfur oxide injury (Cotrufo and Berry 1970, Will and Skelly 1974). This is an important consequence in view of the increasing toll taken by air pollution damage on this commercially important species. Linzon (1978) lists several commercially important tree species that are sensitive to sulfur oxide damage, and one might predict that large-scale fertilization will help minimize such damage (Table 1).

This may be particularly important with regard to Douglas-fir fertilization as atmospheric sulfur oxide emissions increase throughout the Pacific Northwest. In fact, increasing N fertilization may enable forests to utilize atmospheric sulfur oxide more efficiently because N fertilization creates increased S demands. Atmospheric sulfur oxide is an important source of S to plants even in cases where soil S supplies are adequate (Terman 1978).

The effects of fertilization on the health and vigor of trees are generally assumed to be positive, but there can be serious side effects as well. Tamm et al. (1974) found that, although fertilization generally increased growth, it also decreased tree hardness to "winter drought" in Sweden. This suggests that the normally N-deficient status of trees lends hardness to such climatic damage, and that fertilization effects in this case are "a good illustration of the difference between physiological optimum and ecological optimum."

NONTARGET ORGANISMS

Because of the conservation and cycling of nutrients in forest ecosystems, fertilization is bound to affect not only trees but also a range of other resident organisms, from bacteria to wildlife. Effects on wildlife are discussed in detail by Rochelle (this volume), and effects on understory vegetation are discussed by Turner (this volume). Here I will briefly review the effects of fertilization on invertebrates, fungi, and bacteria, including those regarded by foresters as pests and pathogens.

DECOMPOSER ORGANISMS

Many species of flora and fauna living in forest soils perform essential functions within forest nutrient cycles by facilitating litter decomposition. The effects of fertilization on these organisms are of obvious interest in terms of maintaining the integrity of nutrient cycles and long-term site productivity.

Kelly and Henderson (1978b) found increased bacterial activity but reduced invertebrate populations one year after fairly high levels of urea fertilization (550 and 1100 kg/ha) in a

Table 1. Sensitivity of some trees to sulfur dioxide (from Linzon 1978).

Sensitive	Intermediate	Tolerant
Douglas-fir (*Pseudotsuga menziesii*)	Balsam fir (*Abies balsamea*)	Balsam poplar (*Populus balsamifera*)
Eastern white pine (*Pinus strobus*)	Eastern cottonwood (*Populus deltoides*)	Grand fir (*Abies grandis*)
Jack pine (*Pinus banksiana*)	Engelmann spruce (*Picea engelmannii*)	Lodgepole pine (*Pinus contorta*)
Trembling aspen (*Populus tremuloides*)	Red pine (*Pinus resinosa*)	Red oak (*Quercus rubra*)
Western larch (*Larix laricina*)	Western hemlock (*Tsuga heterophylla*)	Sugar maple (*Acer saccharum*)
Ponderosa pine (*Pinus ponderosa*)	Western white pine (*Pinus monticola*)	Western redcedar (*Thuja plicata*)
		White cedar (*Chamaecyparis thyoides*)
White birch (*Betula papyrifera*)		
		White spruce (*Picea glauca*)

mixed deciduous forest in eastern Tennessee (Table 2). This change was regarded as important, because invertebrates play a major role in the initial breakdown of litter. In spite of decreased invertebrate populations, however, the authors found that urea additions had little effect on the decomposition rate of white oak (*Quercus alba*) leaves. Additions of superphosphate had quite different effects: decreased bacterial populations, no significant effect on invertebrate populations, and a slight but significant reduction in the decomposition rate of white oak leaves.

The authors attributed these results largely to changes in hydrogen ion concentration. Urea hydrolysis increases pH and thereby solubilizes humic material in litter (Ogner 1972, Crane 1972). This effect may have offset the effect of decreased invertebrate populations on the physical breakdown of litter to some extent. Superphosphate solubilization depresses soil pH, and since bacteria are sensitive to low pH conditions, a decrease in bacterial populations following superphosphate additions would be expected.

Kowalenko et al. (1978) found that fertilization with ammonium nitrate and potassium chloride caused a reduction in soil microbiological activity (as measured by carbon dioxide evolution) for at least 3 yr. Again, they attributed these results partly (but not entirely) to reductions in pH. Studies prior to those described above were thoroughly reviewed by Weetman and Hill (1973). In general, they concluded that fertilization has a lasting, mutually beneficial effect on soil microflora and fauna despite some short term toxic effects of fertilizer components (particularly ammonium).

MYCORRHIZAE

Nitrogen fertilization usually depresses mycorrhizal development (Weetman and Hill 1973, Menge et al. 1977). Because the mycorrhizal association is thought to be an adaptation to nutrient-deficient conditions (Harley 1963), suppression of mycorrhizae by fertilization might be expected. When other nutrients (especially P) are added, however, mycorrhizal growth is often stimulated (Shigo 1973, Menge et al. 1977). Menge et al. (1977) showed that species distribution of mycorrhizae can be changed by fertilization and suggest that it is feasible to manage mycorrhizal species to maintain a population adapted to fertilizer regimes. They further suggest that P fertilization could be used to stimulate mycorrhizae that lend drought resistance to loblolly pine (*Pinus taeda*).

INSECT AND DISEASE PESTS

Fertilization can affect tree resistance to insect and disease either positively or negatively. Several review papers have been written on this subject to which the reader is referred for details (Shigo 1973, Foster 1968, Weetman and Hill 1973). Only some general aspects will be considered here.

Weetman and Hill (1973) suggest that fertilization is likely to increase disease resistance if it improves tree nutrient status, but it will decrease resistance if it creates nutrient imbalances. On the other hand, improving tree nutrient status may also improve the palability of its tissues to insects and its susceptibility to pathogens. Nitrogenous fertilizers are known to reduce the production of phenols in plant tissues, thereby reducing resistance to infection by pathogenic fungi (Shigo 1973). Hollis et al. (1975) noted that additions of P as well as N to sites deficient in these elements increased the incidence of fusiform rust attack in slash pine. Correcting nutrient imbalances may in fact give the pest or parasite a greater advantage than it does the host. In addition to changes in tree physiology, fertilization produces changes in stand structure, which produces changes in understory composition and microclimate that could either increase or decrease the likelihood of insect or disease attack.

Despite some of the potential problems noted above, Shigo (1973) suggests that fertilization can be used as a tool for controlling insect and disease incidence in certain instances. Indiscriminate use of fertilizer could lead to serious damage not only to the forest environment but also to the timber industry, however, and the complex interactions between fertilizers and pathogens deserve close scrutiny as forest fertilization becomes more widespread.

NITRIFYING BACTERIA

The effects of fertilization on nitrifying bacteria deserve special attention because of potential problems with fertilizer loss, groundwater pollution, and native soil cation losses. In addition to these problems, there is now concern that nitrification followed by denitrification of fertilizers may cause global increases in nitrous oxide emission, which will in turn contribute to depletion of the earth's ozone layer (National Academy of

Table 2. Bacterial and invertebrate populations in litter one year after urea and superphosphate fertilization in a mixed deciduous forest in eastern Tennessee (from Kelly and Henderson 1978b).[a]

N added (lb/acre)	P added (lb/acre) 0	245	490
	Bacterial numbers (no. of isolates/oz litter × 10^{-6})		
0	1276	1332	1276
490	5018	3260	2352
980	6350	6549	5131
	Soil invertebrate population (no. of organisms/yd^2)		
0	565	537	338
490	390	357	370
980	288	359	384

[a]See appendix for conversion table.

Sciences 1978). Thus it is important from several standpoints to understand and regulate, if possible, the factors affecting nitrification following fertilization.

Nitrification is influenced by temperature, moisture, pH, oxide, and ammonium ion availability, and the presence of inhibitors (Alexander 1963). Temperature, moisture, pH, and ammonium ion supply are frequently suboptimal for nitrification in forest soils, and chemical inhibitors have been found in some cases (Rice and Pancholy 1972).

Fertilization with urea, the most commonly used nitrogenous fertilizer, causes increases in pH (Crane 1972) and enormous increases in soil ammonium ion concentration (Morrison and Foster 1977, Johnson 1979, Johnson and Edwards 1979). Although these changes should favor nitrification, several studies have shown little nitrate production and leaching following fertilization at normal levels (i.e., 100–300 kg/ha; Cole and Gessel 1965, Overrein 1971, Crane 1972, Wells et al. 1975, Cole et al. 1975, Morrison and Foster 1977). At higher rates of N fertilization, including wastewater and sludge application, nitrification can be substantial, however (Overrein 1971, Tamm and Popovic 1974, Cole et al. 1978, Riekerk 1978, Kelly and Henderson 1978a). Since nitrification produces $H+$ and a mobile anion, nitrate, cation leaching can be greatly accelerated by nitrification. Tamm and Popovic (1974) noted that nitrification resulted in as much as a 40% reduction in base saturation and a 0.5–unit reduction in soil pH following repeated, heavy fertilization in Sweden, for example.

Breuer (1978) found that repeated urea fertilization even at modest levels (200 kg/ha) at 5- to 8-yr intervals caused substantial increases in nitrification rates above those observed following the first application. He attributed this "refertilization effect" to a buildup in the populations of nitrifying bacteria.

Breuer's (1978) results corroborate laboratory studies conducted by Sabey et al. (1959) two decades previously. They showed that the activity of nitrifying organisms at a given temperature and moisture content was related to the initial population of nitrifiers and the amount of ammonium substrate available. During laboratory incubations, they noted that nitrate production in a given soil had a characteristic delay period (t) and maximum rate (R); (Figure 1). They found by independent means that the delay period was related to the initial population of nitrifying bacteria and the maximum rate was related to the supply of ammonium substrate.

Even modest levels of urea fertilization (~200 kg/ha) cause enormous increases in soil ammonium ion which should, according to Sabey's (1959) results, eventually produce a high rate of nitrification. What apparently prevents this from occurring in many cases is the relatively long delay period due to low initial populations of nitrifiers. During the delay period, heterotrophic soil organisms and plants rapidly take up fertilizer ammonium ion, often reducing levels by 95% within 6 mo (Morrison and Foster 1977, Johnson 1979, Johnson and Edwards 1979).

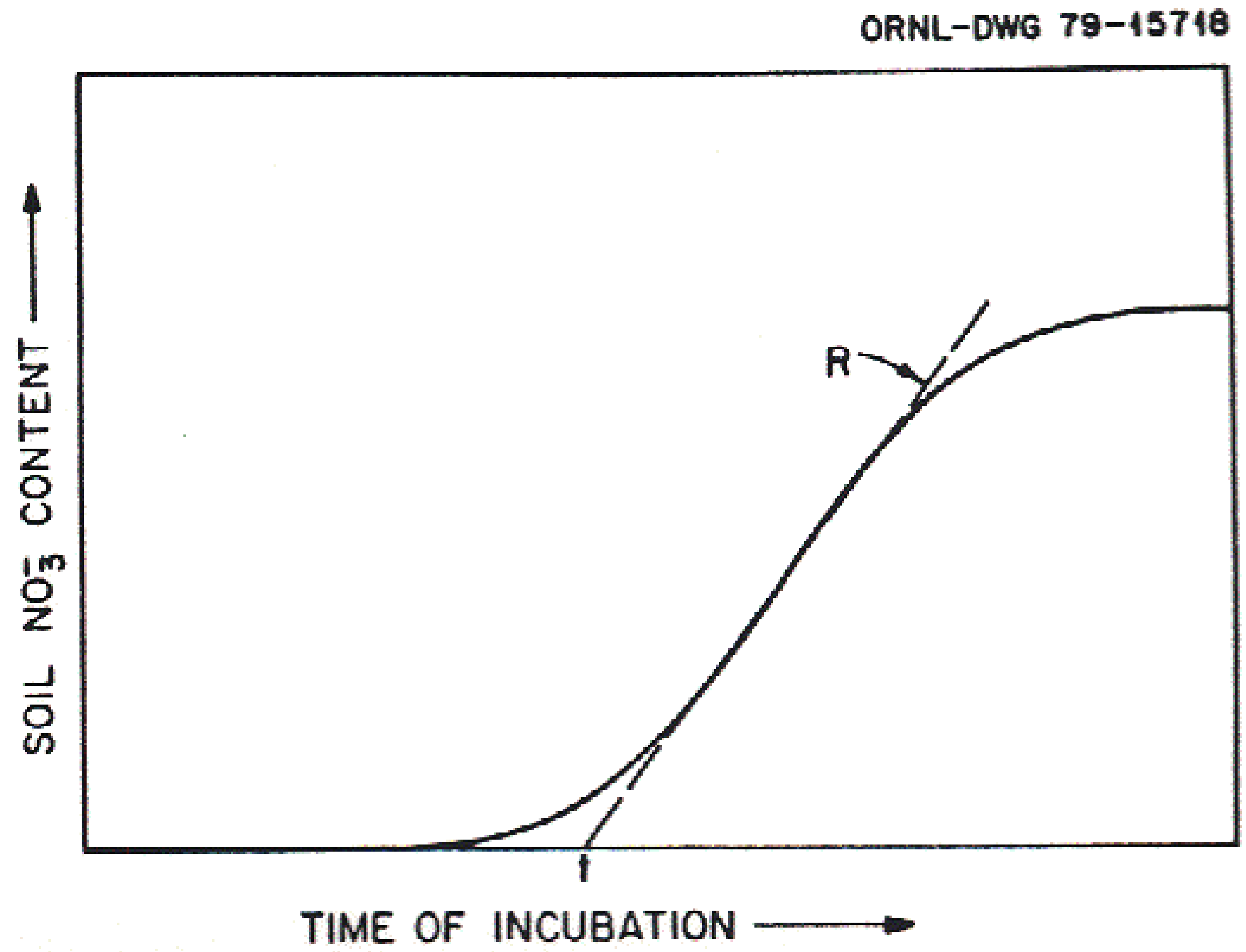
On the other hand, if nitrifier populations are initially high, the delay period is less, and substantial portions of fertilizer ammonium ion can be converted to nitrate. Johnson and Edwards (1979) found that even a 75-kg/ha application of N as ammonium sulfate resulted in substantial production of nitrate in an N-rich tulip poplar (*Liriodendron tulipifera*) site, for example. Presumably N-rich sites will not be fertilized, and problems with nitrification in those cases will be avoided; but if it is the delay period that is in fact the major factor preventing nitrification on N-poor sites, the results obtained by Breuer (1978) following refertilization of such sites deserve careful attention and further study.

CONCLUSIONS

Forest fertilization has obvious beneficial effects on the growth and vigor of trees on nutrient-deficient sites, and all other side effects must be weighed against these effects. It can also improve tree resistance to damage by air pollution and, in some cases, insect and disease attack. Some intriguing possibilities for managing mycorrhizal communities and controlling insect and disease attacks by fertilization have also been raised. Thus fertilization may be used to produce several beneficial effects in addition to increased wood production.

On the other hand, Tamm's concern for sacrificing ecological optimums for physiological optimums must also be heeded. Fertilization is a drastic manipulation that is bound to produce negative as well as positive side effects, most notably in the case of excessive nitrification. While the prospects for managing mycorrhizal and insect and disease outbreaks by fertilization are appealing, long-term ecological studies of forest fertilization effects on these as well as other ecosystem components will be necessary before we can hope to achieve these goals.

Figure 1. Hypothetical nitrate production curve during soil incubation showing delay period (+) and maximum rate (R) of nitrification (after Sabey et al. 1959).



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