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FOREST FERTILIZATION
(A State-of-the-Art Review and Description of Environmental Effects)

National Environmental Research Center
Office of Research and Monitoring
U.S. Environmental Protection Agency
Corvallis, Oregon 97330

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Abstract: The application of chemical fertilizers to forest soils for site amelioration is one of the newest and most promising methods for increasing production. Concern has risen over possible toxic and eutrophic effects of fertilization on water quality. The Environmental Protection Agency assembled data on the scope and trends of the practice throughout the world in order to determine the extent of actual or potential detrimental effects of forest fertilization, and to evaluate priority for grants. Definitive knowledge on the biological effects of forest fertilization is incomplete or lacking in many aspects of tree physiology and soil sciences, and in the long-term consequences of forest fertilization on toxic and/or eutrophic parameters of water quality. Toxic levels are usually not approached in natural water supplies and the total applied nutrient loss is inconsequential. Results of completed forest fertilization-water quality studies are summarized and evaluated, and the status of current water quality studies is described. Recommendations are given for reviews and new research efforts. (Knapp-USGS)

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ABSTRACT

Information pertaining to the concepts, scope, and methods of forest fertilization in various nations and regions of the world has been compiled from available sources Factors influencing development to present status, possible trends, and impacts on water quality are discussed

Results of completed forest fertilization-water quality studies have been summarized and evaluated, and the status of current water quality studies is described Recommendations for state of the art reviews and essential research efforts are presented

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SECTION I

CONCLUSIONS

1 The use of inorganic fertilizers is a forest cultural practice that has accelerated rapidly in certain sections of the world within the past ten years Although relatively small in terms of fertilizer production consumed and commercial forest area fertilized, the overall trend has been toward increased acceptance and use of inorganic chemicals to increase tree growth

2. An interrelationship of socioeconomic conditions, technologic advances, and scientific findings determine the rate and magnitude of forest fertilization operations in any area at any point in time

3. Definitive knowledge on the biological effects of forest fertilization is incomplete or lacking in many aspects of tree physiology and soil sciences, and in the long-term consequences of forest fertilization on toxic and/or eutrophic parameters of water quality

4. The few forest fertilization-water quality studies conducted to date indicate that toxic levels are not approached in natural water supplies and that the total applied nutrient lost is inconsequential. Numerous studies in progress or contemplated will provide more conclusive information on the real or potential hazards, if any, of forest fertilization on water quality

5. Increasing use of forest fertilization in certain areas, reapplication to previously fertilized forest lands, changes in application rates and fertilizer formulations, and new application methods could conceivably cause toxic or eutrophic consequences if predictive results and corrective procedures are not available

SECTION II

RECOMMENDATIONS

This report has reviewed the state of the art of forest fertilization and of water quality studies associated with the practice Although a relatively new and minor operation, the use of inorganic fertilizers to ameliorate forest soils has gained acceptance and expanded rapidly over the past several years Consequently, the concepts, methods, scope, and objectives of forest fertilization and of water quality studies are constantly changing As a result, much of the conclusive data essential for predicting tree growth and environmental quality parameters are incomplete or lacking

Two comprehensive and coordinated surveys are necessary to update and maintain contact with various phases of forest fertilization-water quality operations First, periodic compilation and summarization of national and regional data pertaining to the state of the art of forest fertilization should be conducted This information is vital for determining the scope, methods, and trends of forest fertilization and for assessing conditions that have the potential to affect water quality

Second, a continual process of collecting and evaluating forest-fertilization-water quality studies is required to supplement and refine current knowledge The few studies conducted to date indicate no substantial or long-term detrimental effects on the environment associated with the practice, however, the quantity and sophistication of water quality studies contemplated or being conducted should provide much needed definitive and predictive information

The following research areas should receive prime attention in the immediate future.

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1 The most significant and practicable proportional reduction of applied nutrient loss at this time can be accomplished through avoiding direct application of inorganic fertilizers to surface waters and riparian zones The minimum stream channel size to be avoided and width of an effective riparian zone are currently speculative. The numerous variables influencing conditions unique to each forest stand must be investigated, analyzed, and correlated

2. As the practice of forest fertilization expands both in area and in quantity of fertilizers utilized through reapplication to previously fertilized lands, new environmental considerations may appear

Monitoring of nutrient loss on forest lands has indicated that a very small percentage of the total applied elements enter the drainage system Nutrient concentrations have remained well below acceptable levels, but the ultimate fate of accumulations of these nutrients in streams, rivers, and impoundments has not been thoroughly investigated The amount of introduced nutrients that an individual forested water system can assimilate without deleterious consequences on the aquatic ecosystem must be determined

3 Losses of applied fertilizers through leaching and volatilization are largely dependent upon rate, timing, and fertilizer formulation Research efforts directed toward finding the most desirable interactions of these components to minimize losses should be undertaken

SECTION III

INTRODUCTION

Various socioeconomic factors have resulted in acceleration of intensive cultural practices on forest lands for the purpose of increasing wood fiber production Projected worldwide and national wood requirements indicate deficits within the next several decades, primarily due to the needs of an expanding population and the lack of additional productive forest lands to supplement existing sources (30) (40) (44)

The application of chemical fertilizers to forest soils for site amelioration is one of the newest and most promising methods for increasing unit growth increment (14) Although not a new concept, the main body of forest soil fertility and tree nutrition research has occurred since the late 1940's, the operational phase was initiated approximately one decade ago as advancing fertilizer technology, improved application methods, and favorable economic conditions enhanced its feasibility Research and practice of forest fertilization have progressed exponentially, with practice generally empirical and preceding conclusive or predictive research results

Within the past several years, concern has risen over possible toxic and/or eutrophic effects on water quality from fertilization of agricultural lands. Because of apparent similarities between agricultural and forest fertilization, the latter is also liable for criticism under a blanket indictment In addition, forest fertilization must undergo scrutiny for possible detrimental alteration of soil, watershed, and recreation values and as a potential disruptive agent in the forest ecosystem.

Realizing the concern of participants and observers on the effects of forest fertilization on water quality, the Environmental Protection Agency has assembled data on the scope and trends of the practice throughout the world in order to determine the extent of actual or potential detrimental effects of forest fertilization, and to evaluate priority for related grants

Prior participation in forest fertilization-water quality studies by the Environmental Protection Agency has included monitoring of two fertilized watersheds. One study was in cooperation with a forest industry firm and the other with the U S Forest Service In addition, grant support is pending for fiscal year 1972 with a forest industry research organization to determine the extent of volatilization and leaching of urea, and to investigate fertilizer formulations best suited to minimize these losses

The brief period during which forest fertilization has been practiced, and the relatively small magnitude of the operation in total annual tonnage of fertilizers applied and forested acreage involved present a unique opportunity to study forest fertilization-water quality relationships as the program expands.

Research efforts in this area have been conducted and are intensifying Therefore, as knowledge accumulates, situations which have potential to degrade the environment may be observed and corrected before they become widespread and irreversible

Purpose and Scope

The material presented in this report has been compiled through literature surveys, correspondence, and personal contacts The intent is to provide a current and comprehensive description of various aspects of forest fertilization and of related water quality studies throughout the world. Restrictions on completeness are imposed by available information and by rapidly changing knowledge and conditions.

The first section of the report reviews the development and current status of forest fertilization. The factors influencing possible trends are also delineated and assessed The second portion summarizes the results of completed forest fertilization-water quality studies and briefly describes the status of current or proposed research efforts

Aerial application of nitrogenous fertilizers receives the main attention throughout the report, inasmuch as this method currently dominates operational forest fertilization The use of other application techniques, essential elements (notably phosphates), and special purpose and product objectives separate from increased wood fiber increment are discussed where applicable

Excluded Practices

Operational forest fertilization has been defined as "that carried out on commercial forests as part of a management plan with profit motive, i e , as opposed to fertilization for purely research purposes" (32). This definition connotes application of chemical amendments to sizable areas of commercial forest lands in order to stimulate growth on new plantations or established stands

However, fertilizer usage under the control of forest land managers or occurring on forest lands for purposes other than operational fertilization is practiced These operations will be excluded from consideration and discussio Some are more closely related to agronomy than to forestry, others are highly controlled and/or involve small areas and application rates and, in certain instances, the growth benefits derived through fertilization are sub-ordinate to other objectives.

Exclusion from consideration does not imply that none of these practices has the potential for affecting water quality, but rather that they do not fit the definition of operational forest fertilization . A summary of specific purpose and special product uses of fertilizers in forestry follows.

1. Seed Production Areas. Specific purpose - to increase the production of seed on selected trees within a forest stand Highly controlled Small area.

2 Seed Orchards Specific purpose - to increase the production of seed from genetically selected clones Similar to horticultural practices. Highly controlled Small area

3 Christmas Tree Plantations. Special product - to improve color, needle retention, and growth qualities Highly controlled Relatively small area or portion generally involved

4 Forest Nurseries Specific purpose - to improve germination, vigor, and survival potential of seedlings Highly controlled Generally small area or portion involved

5. Individual Tree Planting Specific purpose - to aid survival and initial growth. Fertilizer applied to planting hole Highly controlled Small amount of fertilizer per land unit

6 Fire Retardant Specific purpose - applied aerially or by tanker during fire suppression (loose control. variable area) or around perimeters of controlled burns prior to ignition (high control, small area).

7 Recreation and Aesthetics Specific purpose - to ameliorate heavy use areas, encourage windbreaks and camping unit barriers, etc. Highly controlled Generally small area

8 Wildlife Specific purpose - to encourage palatable and nutritious browse for game species Control variable Area variable. Policy decision by wildlife managers

9 Special Forest Understory Products Special product - to increase quality of floral brush and greens. Generally a secondary benefit of operational forest fertilization, otherwise high control and small area

10. Special Forest Products Special product - to increase quality and/or quantity of high value commodities, such as naval stores, mast, poles and piling, valuable hardwoods, etc Generally highly controlled. Area variable

11. Control of Water Yield Specific purpose - to regulate water yield on all or portions of a watershed through control of vegetative growth and subsequent evapotranspiration. Mainly theoretical and experimental at this time

12. Range Management Specific purpose - to ameliorate rangeland and/or increase quality and quantity of forage Different conditions from the more closed system of a forest stand Control and area variable Policy decision by range biologists

13 Cellulose Silage Specific purpose - to harvest coppice (sprout) vegetation from fast growing species such as cottonwood and sycamore for pulp with approximately five year rotations Relatively new technique with promising potential Fertilization and harvest methods similar to agriculture Acreage under intensive cultivation currently small, possible rapid expansion depending upon economic feasibility

14. Spray Irrigation Specific purpose - primary purposes are alleviation of municipal and industrial treated waste disposal problems and reclamation of spoil banks and harsh sites. Growth response is a derived benefit. Highly planned and controlled Amount of acreage and quantity of nutrients variable

SECTION IV

FOREST FERTILIZATION

Numerous examples of dramatic and substantial growth response in forest stands after application of inorganic fertilizers are presented in the literature In other instances, insignificant additional increment has been observed after treatment The differences in magnitude of response reflect the newness of the cultural practice and the subsequent lack of detailed knowledge necessary for predicting and obtaining optimum growth objectives under a wide range of physiographic, edaphic, climatic, and biotic variables

The state of the art of operational forest fertilization at any point in time depends upon developments in and interaction of socioeconomic conditions, fertilizer and application technology, and soil and tree physiology sciences This interrelationship influences acceleration or modification of the practice

Development

Tamm (43) separates the evolution of forest fertilization in Europe into four periods From approximately 1865 to 1900 there was recognition of forest nutrient cycling and of tree nutrient demands, but very few experiments Investigations of a "trial and error" type, rarely based on analytical thinking, occurred from about 1900 to 1925 The next period witnessed the initiation of forest nutritional work on a firm scientific foundation with numerous experiments The first limited practical applications, particularly liming in Germany, were attempted The start of large-scale forest fertilization began in 1960, and use of fertilizers as a silvicultural tool has increased dramatically.

A similar sequence of development has generally occurred in other areas practicing or investigating forest fertilization, although regional conditions have altered the dates, intervals, and research emphasis.

Some of the reasons for the past neglect of interest in soil fertility improvement as a scientific method for increasing wood fiber production have been outlined by Gessel (13) Adapted for worldwide rather than North American conditions these are

1. An adequate supply of accessible wood products to meet past demands

2 A lack of interest in the management of non-agricultural lands for production purposes

3. A lack of interest in the physiology of forest and range plants, particularly with respect to mineral nutrition, and the common belief that all forest soils contained adequate amounts of essential elements

4. A general opinion among forest biologists that the natural state is perfect, and that any nutritional changes imposed on it by man would upset this balance and be harmful Even though differences in land productivity and plant composition were recognized, very little research was initiated

5 The relatively low value of products from non-agricultural land, commonly expressed in the phrase that "it is not economical to put fertilizers on these lands"

6 The relatively restricted supply of fertilizers available and their high cost of application

7 The general lack of information on the soils of non-agricultural lands

8 The impression that added fertilizers would rapidly be leached and lost from the site

9. The common concept that the crops in question are strictly soil builders, and therefore production does not constitute a drain on the soil

10. Poor design and analysis of some of the forest fertilizer work

Changes in concepts, knowledge, and conditions within the past quarter century have reversed the insignificant attention previously paid to forest soil fertility. The interaction of various factors has contributed to the major role in increased forest productivity that amendments are assuming

The dynamic advancement of forest fertilization to its present status within the past 20 years and possible trends in the future are inseparable components In order to avoid repetition and overlapping emphasis the contributing factors will be summarized briefly in this section for a simplified introduction to Current Status, and discussed in detail under Influences and Possible Trends

Insufficient timber supplies to meet worldwide total wood requirements within several decades have been predicted This problem has focused attention on the necessity of employing intensive management practices to exploit optimum growth and utilization

The situation is further compounded in certain regions by withdrawal of anticipated timber reserves for recreational values, loss of higher site commercial forest land to expanding population pressures, and inaccessibility or low quality of existing timber supplies These conditions have forced forest land managers to attempt to increase wood fiber production on existing commercial forest lands and on converted or reclaimed low quality sites

The value of forest products has risen, and advances in fertilizer technology, production methods, manufacturing capacities (particularly nitrogen fertilizers), and improved application techniques have lowered total treatment costs per acre Investments in operational forest fertilization not previously acceptable from an economic standpoint when compounded over the periods of time involved are now justifiable due to the value of the additional increment realized through fertilization.

Intensified basic and applied research in forest soil and tree physiology sciences has advanced knowledge in the fields of nutrient cycling and deficiencies. Appropriate corrective measures necessary to achieve increased growth objectives have been more adequately determined Three general but major findings of forest soils studies are that (13)

1 The historical concept that forest vegetation is strictly soil conserving is being placed in proper perspective Under intensive management and harvest, non-agricultural soils can be drained of essential plant nutrients just as easily as soils under agricultural production The losses may be more critical than in agriculture because forest soils are frequently of a very low nutrient status

2. Studies of the total nutrient cycle have demonstrated a conservation of applied elements

3 Significant increases frequently occur in overall wood production on forest lands when limiting nutrients are applied Concepts regarding what is productive also are changing as those designated as the best sites actually show more response than poorer sites

Generally, nitrogen has been found to be universally deficient in forest soils, and nitrogenous fertilizers currently comprise the bulk of inorganic chemical amendments used in forest fertilization Phosphorus is required for and is used extensively on certain lands

Current Status

The following compilation of operational forest fertilization practices in various countries and regions is inconsistent in completeness and currentness due to the sources of information available. Other nations not included may be practicing forest fertilization on a small scale, although information on their methods and rates was not available for this review

Sweden (15) (16) (17) (18) (19) (43)

Operational forest fertilization began in 1962 Mineral soils, where mostly nitrogen (N) is applied, receive the main attention of fertilization efforts, while peatlands, which require N, phosphorus (P), and potassium (K) are presently relegated to a minor role in the Swedish fertilization program (Table 1)

Table 1

AREA FERTILIZED ANNUALLY IN SWEDEN

	Mineral Soil		Peatland	
Year	Hectares	Acres	Hectares	Acres
1962	4017	9926	749	1851
1963	5996	14816	1102	2723
1964	11500	28417	1021	2522
1965	40208	99353	765	1890
1966	106131	262249	906	2238
1967	100285	247804	665	1643
1968	81026	200660	978	2417
1969	77710	192021	2049	5063
1970	84187	208026	372	919
1971 1/	115000	284165	?	?
Total	626060	1547437	8607	21266

1/ Estimated

The reduction in area fertilized beginning in 1967 was due to a temporary economic crisis, but the 1971 data indicate resumption of the prior trend.

The majority of fertilizer is aerially applied, mainly by fixed-wing aircraft. Fertilization has been most common in stands 10 years prior to harvest

Until 1968, urea comprised 95-100 percent of the nitrogen fertilizer applied, but from 1968 to 1970 the share of urea decreased to 64 percent, while the use of various types of ammonium nitrate increased in the same proportion The reason for this shift in the type of N applied may be based on a combination of economic and biologic considerations

The amount of N applied on a unit basis has steadily increased from 61 kg/ha (54 lb/acre) in 1962 to 132 kg/ha (118 lb/acre) in 1970 The application rate of N appears to be leveling at the latter figure

The total productive forest land in Sweden is estimated to be 21,500,000 hectares (53,126,000 acres) About 50 percent of the forest ownership, and principally the best forest acreage, belongs to small landowners and is difficult to organize for forest fertilization operations Approximately three percent of the total forest acreage has been fertilized through 1971

On the basis of experimental data, it is estimated that the potential area of forests on mineral soils to be fertilized amounts to 4,000,000 hectares (9,884,000 acres) The corresponding peatland area contains 2,500,000 hectares (6,177,500 acres) Thus, 15 65 percent of the mineral soils and 0 34 percent of the peatlands amenable to fertilization have been treated to date

The Swedisn Cellulose Company (SCA) has been the leader in forest fertilization in Sweden. Their program calls for 15,000 metric tons of N to be applied annually to approximately 60,000 hectares (148,260 acres) The same area is to be treated every five years, meaning that roughly 300,000 hectar s (741,300 acres) of forest land held by SCA will be continually provided with extra N

Other companies are expected to increase their level of participation in the practice

Finland (34) (35) (43)

Finland has the most ambitious and comprehensive forest fertilization program of all countries surveyed Coordinated high level, long range planning, involving both government and forest industries, anticipates increased forest growth of 12,300,000 m^3 (434,313,000 ft^3) per year

More than 71 percent (21,740 hectares - 53,719,540 acres) of the total land area is forested, 9,700,000 hectares (23,968,700 acres) of the forested area are peatlands

Forest fertilization on a practical scale started in the early 1960s, and the area treated annually has approximately doubled each year during the first years for which data were available (Table 2) Contrary to Sweden and Norway, the emphasis of the fertilization program has been on organic peatlands since the beginning

Table 2

AREA FERTILIZED ANNUALLY IN FINLAND

Year	Hectares	Acres
1961	2000	4942
1962	4000	9884
1963	7000	17297
1964	12000	29652
1965	27000	66717
1966	50000	123550
Total to 1966	102000	252042

Fertilization was scheduled for 80,000 to 100,000 hectares (197,680 to 247,100 acres) in 1967.

Revised plans in 1967 anticipated 330,000 hectares (815,430 acres) would be fertilized in 1970 increasing to 633,000 hectares (1,564,143 acres) in 1975, at which time the annual fertilized area was expected to stabilize at that figure.

A summary of the results of fertilization experiments in Finland indicates that in mineral forest soils lack of N seems to most commonly limit growth. Peatlands usually lack P and K, but are also often deficient in N.

Through 1966, 0.46 percent of the total forest area had been fertilized. In 1966, 33,000 hectares (81,543 acres) of the fertilized area were peatlands and 17,000 hectares (42,007 acres) were mineral soils Elemental N applied in urea and NPK fertilizers accounted for only 7.78 percent of the total fertilizers applied in 1966, the remainder was in P, K, and PK fertilizers.

Norway (23) (43)

Based on the results of field trials, the fertilization program in Norway is concentrated in older stands, where N has been found to be the essential element contributing first and foremost to improved growth Applications are repeated every six to eight years In spruce forests the best results are obtained with P in addition to N

Fertilization of younger forests is being investigated, but is still in the research stage.

The first significant operational forest fertilization was conducted in 1963, when about 550 tons of fertilizers were applied Rapid expansion of the practice followed, and 2400 tons of fertilizers, of which 2000 tons were urea, were placed on 7000 7500 hectares (17,297-18,532 acres) in 1966. Ninety-five percent of the fertilized area received N only.

The total forest area of Norway is 7,500,000 hectares (18,532,500 acres). Therefore, approximately 0.10 percent of the forest land was fertilized in 1966 Authorities predict that the area fertilized annually will be 10 to 20 times higher in a few years

Seventy percent of the application is by fixed-wing aircraft, helicopters are rarely used Small ownership units, averaging 20 to 30 hectares (49 to 74 acres) necessitate tractor and manual spreading on much of the land

Twenty-seven percent of the productive forest lands are peat bogs. Utilization of these lands is essential for increased wood fiber production. Every year 10,000 hectares (24,710 acres) of peat bogs are drained, and roughly 50 percent of these organic soils are in need of fertilization In 1966, 1800-2000 hectares (4448-4942 acres) of peat bog were fertilized with PK or NPK fertilizers The goal for the future is significant increases in the fertilization of amenable peat bog areas

Denmark (20)

Forest fertilization is still in the experimental stage in Denmark, and an extremely cautious attitude prevails toward the practice Holstener Jorgensen (20) states that "some years will pass before the first results of the experiments are available, and until then we cannot start any actual consultative work in this field "

Experimental results indicate an overall N deficiency in the forest soils Preliminary results reveal that P is deficient under certain conditions The relationship between additional K and increased growth is weak

France (25)

Because of severe fires which destroyed large areas of forest lands in the past, France has been primarily concerned with reforestation fertilization problems Work is just starting on established stand fertilization

Interest in forest fertilization of older stands is apparently increasing, but information on the scope and methods of field operations is not presently available

West Germany (14) (26) (43)

After a period of minimum attention to forest fertilization, interest in the practice has been revived in West Germany The intensive silvicultural practices employed for different objectives under varying conditions precludes a statistical breakdown of fertilizers and practices employed

Generally, N has received much more attention than previously - even anhydrous ammonia has been used successfully on certain terrain with special equipment. Consequently, centers of nitrogen research in forestry are developing

Available 1966 statistics for West Germany show 50,000 hectares (123,550 acres) of the total productive forest land of 7,200,000 hectares (17,791,200 acres), or 0 69 percent, receiving fertilizer treatment during that year One thousand metric tons of N were consumed in 1966 by forest management practices, and the forecast for future annual consumption (date unspecified) was 5000 metric tons

Great Britain (2)

Until recently, only phosphate fertilizers were normally used in British forestry on a large scale. Their application was confined to older stands on mineral soils where P is usually the most, if not the only, limiting nutrient Younger stands planted on poorer soils, notably acid peat, require only P to produce reasonable early growth, but sooner or later K is generally required to keep the trees vigorous

Nitrogenous fertilizers are beginning to receive more consideration in British forestry - their short-lived effect previously made their use on a field scale economically unattractive In future years, N and K as well as P fertilizers may well be required on a large percentage of the forest land in Scotland, and much of the forest land in Wales and northern England may benefit significantly from P as well as K

Advances in fertilizer technology and application methods are stimulating the interest in and use of fertilizers for increased growth potential in established forest stands Aerial application is becoming more commonplace

Other European Countries (43)

The Netherlands probably have the most intensive use of fertilizers, but their forest area is relatively small

East Germany and Czechoslovakia have some activity in forest fertilization The practice in these two countries is evidently more intensive and advanced than in the rest of eastern Europe, but information on the methods and magnitude of operational fertilization in this area is not available

Ireland (29) has a cautious attitude toward extensive forest fertilization. Current efforts are directed toward providing amendments for plantation establishment on poorer sites P and K, in the form of natural mineral fertilizers, are used

New Zealand (46).

In the mid-1950s, New Zealand started an active and continuing program of applying approximately five-hundredweight (=254 kg = 560 lb) of superphosphate per acre to between 30,000 and 40,000 acres (12,138 and 16,184 hectares) annually Application is primarily by aerial methods (any stand more than five years old is fertilized by air), and 95 percent of the treatment is applied to plantations

Nitrogen has not been used in operational forest fertilization, although research plots have been established However, grasses seeded on forest lands for soil stability have had aerial applications of N.

Australia (12) (46)

Application of phosphates to plantations in Australia has been practiced for some time with rates similar to those in New Zealand The terrain permits ground application, although a small amount of aerial application is practiced in West Australia Trace elements, particularly zinc, sulfur, and boron are applied when specific deficiencies require corrective measures

Research on N requirements is in progress, but to date only handspreading of N fertilizers (mainly urea) around native Eucalypts has been practiced

Japan (24) (36)

In Japanese forestry practices, forest fertilization is an economic necessity. Species composition, quality, and ownership distribution require combinations of intensive cultural methods for effective and efficient management in order to relieve a serious shortage of domestic wood production

Research and technological developments are advanced Japan is one of the world's largest producers of ammonium sulfate and urea New forest fertilizers containing mixtures of N, P, and K have been developed for specific purposes.

Young plantations received prime consideration at the initiation of large scale forest fertilization in Japan. Approximately 40,000 acres (16,184 hectares) of forests were fertilized in 1960 By 1965 the area fertilized annually had increased to 42,000 acres (16,993 hectares) in national forests and 101,000 acres (40,685 hectares) in private forests, for a total of 143,000 acres (57,858 hectares), a 3 6-fold increase in five years Most of the earlier fertilization was confined to young plantations before crown closure, the fertilization of established forests was begun on a large scale only several years ago

Both aerial and ground dissemination methods are utilized in Japanese forestry The means of application selected depends upon both the the type of fertilizer used and the silvicultural practices employed Many of these cultural systems are costly and would not have been feasible in other countries Within recent years, industrial progress in Japan and accompanying wage increases for laborers have focused attention on the need to develop new and less costly techniques for forest fertilization.

The Forest Fertilization Society of Japan, supported by the national and prefectural governments, is the primary coordinating agency for forest fertilization research

Canada (10) (11) (38) (41) (42)

Operational forest fertilization in Canada is not widely practiced, although extensive and coordinated fertilizer trials are being conducted on essential element deficiencies

In 1968, the Inter-Provincial Forest Fertilization Field Trials were established in eastern Canada The Federal Government, five provinces, three universities, and the Pulp and Paper Research Institute of Canada are cooperating in standardized tests, this pooling of talents and results is expected to yield more information more quickly than by independent action Although timber resources in this region are adequate for immediate needs, it is anticipated that the necessary diagnostic, prescriptive, and applicative skills will be sufficiently developed to permit the scientific use of fertilizers in forestry when increased wood fiber production becomes a necessity.

Information from a recent survey on the state of the art of operational forest fertilization in eastern Canada showed two private companies and one province engaged in the practice A total of 4,776 acres (1932 hectares) had been treated through 1970 Aerial application is utilized, and urea comprises the bulk of fertilizers applied The province accounted for nearly 85 percent of the acreage fertilized (1966 through 1970), and was the only participant with a consistent annual program

Operational forest fertilization was initiated in western British Columbia in 1963. From available data, the total acreage operationally fertilized through 1969 was 16,383 acres (6,630 hectares) Fixed-wing aerial application using urea is preferred

Research activities in western Canada are coordinated by the British Columbia Forest Fertilization Board, with supporting members from private forest industry, the Canadian Department of Forestry, and the British Columbia Forest Service As of July, 1969, 118 field trials involving 1,705 plots had been established

United States (1) (4) (5) (6) (9) (14) (21) (22) (27) (32) (38) (39)

Nearly all operational forest fertilization presently practiced in the United States is confined to two distinct areas - the Pacific Northwest (Douglas-fir Subregion) and the pine regions of the southern and southeastern states (Figures 1 and 2) Although other forested sections of the nation may possibly utilize operational forest fertilization to some degree in the future (45), these two areas are widely recognized as the potential primary wood fiber producing regions on a perpetual basis due to past growth performances of indigenous species and other conditions

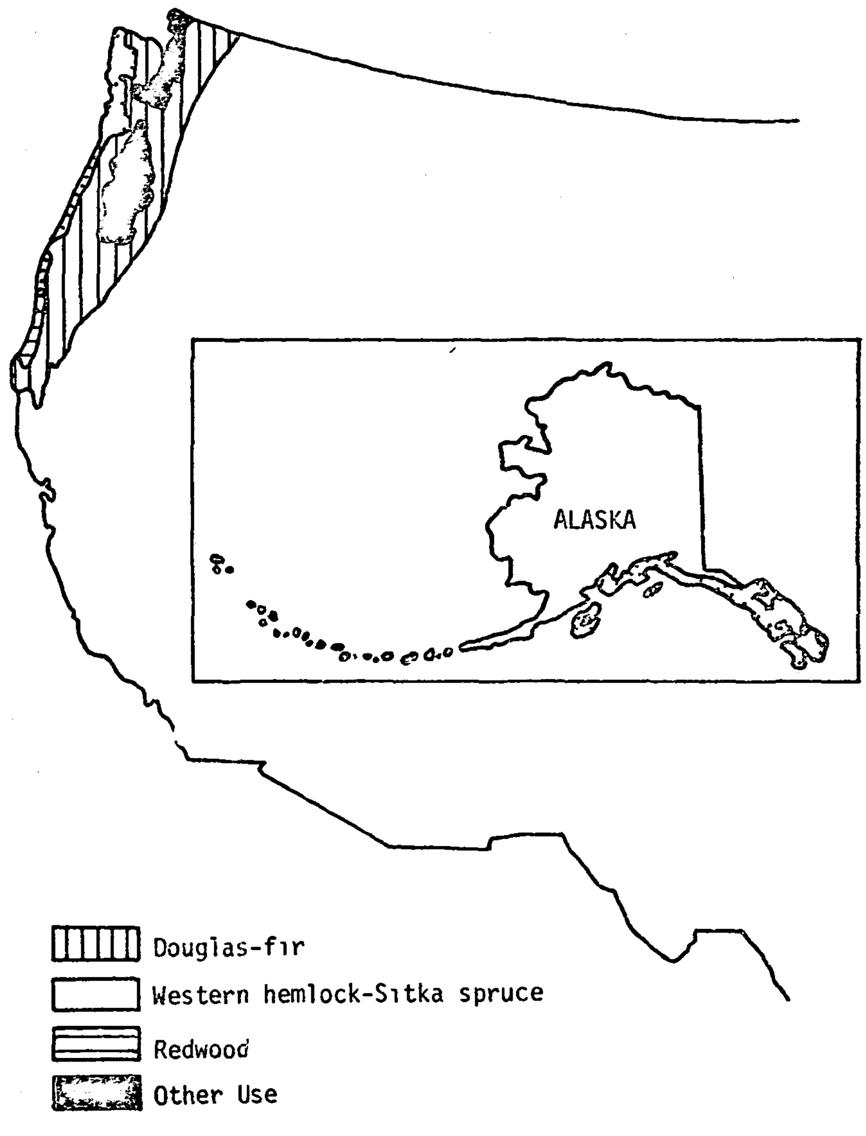

Figure 1 MAJOR WESTERN UNITED STATES FOREST TYPES (Adapted from American Forests 1971 Vol 77(10) Cover).

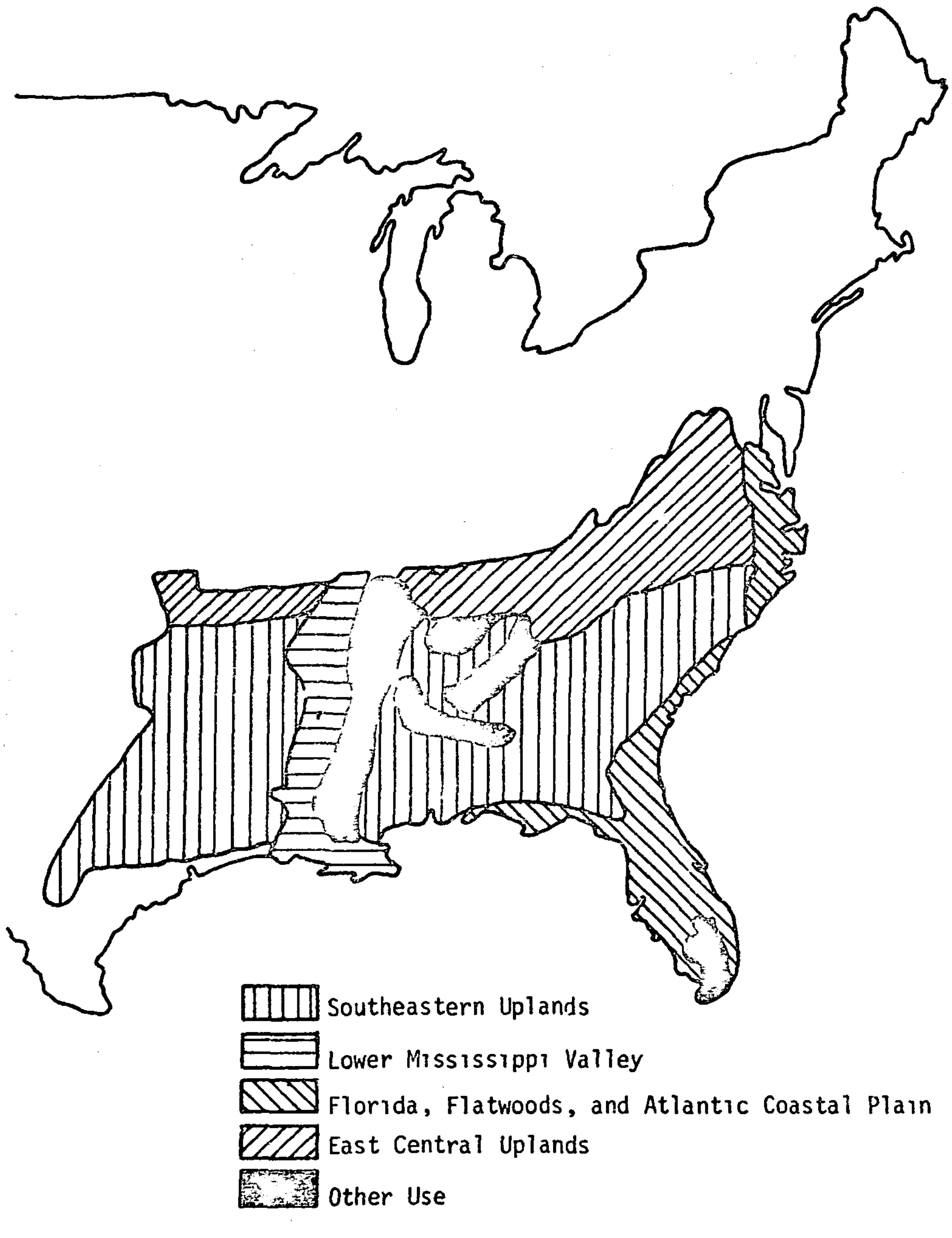

Figure 2. BROAD PHYSIOGRAPHIC-EDAPHIC REGIONS OF THE SOUTHERN UNITED STATES (Boundaries adapted from Stefferud (37) as described by Bengtson (5)

Recommendation 28 of the Public Land Law Review Commission, Dominant Use Timber Production Units (33), proposes the following public land management policies.

> There should be a statutory requirement that those public lands that are highly productive for timber be classified for commercial timber production as the dominant use, consistent with the Commission's concept of how multiple use should be applied in practice
>
> The fact is that the purpose of the 1897 Organic Act of the Forest Service, whose major aim was to assure future timber supplies, has been obscured by changing conditions and needs Yet the United States continues to require timber and wood products in increasing quantities The Commission believes that these and other requirements can best be met by the identification of highly productive areas of public forest lands administered by the Forest Service and the Bureau of Land Management, their classification for commercial timber production as the dominant use, and their inclusion in separate timber management systems.
>
> Lands classified for inclusion in this system would be those that are capable of efficient, high quality timber production, and are not uniquely valuable for other uses
>
> Most of the forest lands to be included in such units are in Alaska, California, Idaho, western Montana, Oregon, Washington, and the southern states
>
> Lands having a unique potential for other uses should not be included Critical watersheds, for example, where cutting may be prohibited or sharply limited. Similarly, important or potentially important intensive recreation use sites close to urban areas should not be included On the other hand, watershed, recreation, or other uses would not be precluded on lands in the system
>
> The best sites for timber growing are mostly at lower or middle elevations in the West and in the southern states In the West, outdoor recreation use tends to occur at the higher elevations where the scenery is more spectacular, where there is snow for winter sports, and where the ground cover is more open and suitable for hiking and other summer sports The conflicts resulting from outdoor recreation on the better national forest timber production areas in the South occur less frequently than in other regions.

> The total area included in timber production units would probably be less than one-half of the total forest land now in Federal ownership, and less than one-fourth of the total area of the national forests.
>
> This is the land that will react most readily to investments in timber management and will be the key source of public timber for industrial uses in the future

The recommendation applies to public forest lands, however, its adoption would have significant impact on private ownership in these regions due to location of processing facilities and research emphasis

Regional information and analyses of timber production potential in the United States are provided by Barrett (3) and Clawson, Held, and Stoddard (7)

Pacific Northwest.

> The Douglas-fir Region of western Washington, western Oregon, and northwestern California is one of the most important forest regions in the nation Almost three-fourths (27 6 million acres) of the total area in the region is commercial forest land Public agencies administer about one-half (13 8 million acres) of the commercial forest land, and the remainder is administered by Forest Industry and other private ownerships For all ownerships, over one-half the net sawtimber volume in western Washington and Oregon is Douglas-fir Throughout the region only 60 percent of all stands are well stocked, 26 percent are medium stocked, 9 percent are poorly stocked, and 5 percent of the area is nonstocked Information presented in the "Douglas-fir Supply Study" published last year by the Forest Service points out that over half of the forested area is potentially more productive than indicated by present net growth rates if subjected to intensified management It is estimated further that 10-1/2 million acres now support stands under 60 years of age At present it is not possible to estimate what part of the total area may be expected to yield an economic response, but the use of fertilizer nitrogen to accelerate growth rates of both old and young stands to full production represents a potential application of thousands of tons of nitrogen fertilizer per year to forested land in the Pacific Northwest (27)

In addition to the Douglas-fir type, the commercial young redwood stands of northern California and the western hemlock-Sitka spruce type along the coasts of Oregon, Washington, and southern Alaska must be considered as potentially amenable to fertilization (Figure 1).

Deficiency symptoms were observed and forest nutrition research was initiated in the Douglas-fir Subregion in 1949 Laboratory studies and field trials indicated and confirmed that nitrogen deficiency is the most common limiting essential element to growth in this area.

Operational fertilization of forest stands was first practiced in 1965 when 1500 acres (607 hectares) were fertilized by Crown Zellerbach Corporation in western Oregon Bulk urea was applied at a rate of 440 lbs/acre (493 kg/hectare) by fixed-wing aircraft on an operational trial basis.

Acreage and tonnage figures from 1966 through 1971, and especially for the years 1970 and 1971, are not exact due to incomplete and extrapolated fertilization data However, using a widely quoted base figure of 200,000 acres (80,920 hectares) fertilized through 1970, the total fertilized acreage through 1971 is probably between 300,000 and 350,000 acres (121,380 and 141,610 hectares) If projections were reasonably accurate, the latter figure should be more correct.

Figure 3 illustrates the rate of growth of operational forest fertilization in the Pacific Northwest from 1965 through 1971

Only a small number (approximately six) of the public and private organizations that could advantageously employ operational forest fertilization on their lands have been actively engaged in the practice since 1965. Three forest land management operations (Crown Zellerbach Corporation, Weyerhaeuser Company, and the State of Washington Department of Natural Resources) have accounted for more than 99 percent of the total forest acreage fertilized in the Douglas-fir Subregion thus far, according to available data.

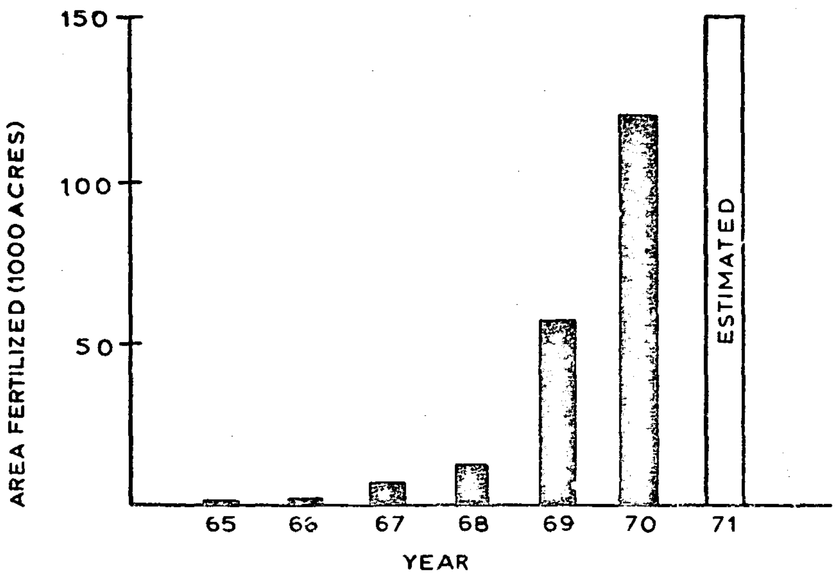

Figure 3 ANNUAL ACREAGE FERTILIZED, PACIFIC NORTHWEST

Authorities anticipated annual fertilization of approximately 100,000 acres (40,460 hectares) in the first five years of the 1970 decade, this figure has already been exceeded Annual fertilization is foreseen on 250,000 acres (101,150 hectares) during the last half of the decade

The original operational applications were performed by fixed-wing aircraft Helicopters were first used in 1967, and since that time all recorded fertilization projects in the Douglas-fir Subregion have utilized this dissemination method

Trials have been conducted with mechanical ground equipment, but terrain and logistics have indicated little practical value for this method, especially on larger acreages

Inasmuch as the soils of this region are commonly deficient in nitrogen, urea pellets and prills have been used exclusively Application rates are in the range of 330 lb urea/acre (370 kg urea/hectare) (150 lb N/acre) to 440 lb urea/acre (493 kg urea/hectare (200 lb N/acre)

The coordinating organization for fertilization research and information dissemination is the Regional Forest Nutrition Research Project. This body was officially formed in 1969 under the direction of the Institute of Forest Products of the University of Washington, and is concerned with Douglas-fir, western hemlock, and Sitka spruce in Oregon and Washington.

Cooperative sponsorship involves municipal, state and federal agencies, forest industries, aerial application firms, and chemical companies Twenty-nine organizations contribute funding and facilities. The first field trials were established and initial measurements taken on 702 Douglas-fir and western hemlock plots in western Washington and western Oregon during 1969-1971. The Project is now commencing thinning-fertilization interaction trials, corollary examinations on the effects of forest fertilization on various components of the ecosystem are also being conducted

As a result of preliminary findings, the following general statements appear to be applicable to growth response through fertilization in the Douglas-fir Subregion.

1. From all indications, nitrogen is the most effective element for stimulating growth of Douglas-fir and western hemlock Other elements, alone and in combination with N or other elements have not been adequately tested to evaluate their potential importance Other elements are likely to become growth-limiting when inadequate natural supplies of N have been corrected by fertilizer application

2 Western redcedar and Sitka spruce have also shown response to fertilization.

3. Cubic volume responses by Douglas-fir to nitrogen range from 0 to more than 100 percent over the pretreatment growth rate and probably average about 30 percent during a five to seven year response period

4. Growth response has been obtained in Douglas-fir up to 300 years of age Most operational fertilization has taken place on younger stands with closed crowns, the Regional Forest Nutrition Research Project is concentrating its efforts on field trial plots established in 15- to 60-year old stands

5 Response to nitrogen fertilization has been noted over a wide range of stocking densities and site qualities

Southern Pine Region The characteristics of the Southern Pine Region present a more complex situation in respect to forest fertilization than the Douglas-fir Subregion The primary differences are

1 Four distinct physiographic-edaphic subregions with varying potential for increased wood fiber production

2 A more intensive cultural program and shorter rotations

3 Use of P as well as N fertilizers, ground as well as aerial application, and fertilization of both young and old stands

There are approximately 200,000,000 acres (80,920,000 hectares) of commercial forest land in the southern and southeastern states Roughly one-half of this area is presently in hardwoods--the remainder is in pine lands. Inasmuch as operational forest fertilization is not currently practiced on the hardwood lands, discussion of the present status of forest fertilization in the South will be primarily restricted to the intensively managed pine lands.

Bengtson's (5) evaluation places the status and potential of the four subregions (Figure 2) in perspective, and provides an understanding of the current situation and probably development of forest fertilization within each area to the year 2000 His summary is as follows

1 The outlook for profitable use of fertilizers in the East Central Uplands is not promising The forest base upon which fertilizers would be applied does not lend itself to efficient fertilizer use The potential for considerable forest growth increase is present on many acres, but the quality and quantity of trees per unit area are generally deficient for an economic response Landowners in this area will probably choose to invest available capital in regeneration and stand improvement activities for some time to come

2. In the Lower Valley of the Mississippi and its similar bottomlands, environmental conditions and native tree species combine to provide a tremendous potential for response to forest fertilization But the forests in general are not in condition to fully realize this potential. Forest fertilization will not contribute greatly to production in this area until problems of regeneration, stand composition, and early stand management are more completely worked out and the results applied extensively Substantial effects of forest fertilization on hardwood pulp production are a distinct possibility, but important increases in the supply of quality hardwood timber as a result of fertilization cannot be expected in this century

3. In the Southeastern Uplands, the outlook is more promising Stands on many acres, particularly those of pine types, are well-stocked, generally vigorous, and on soils at least marginally deficient in nitrogen Judicious selection of acres to fertilize can lead to increased total production in this area of perhaps 5 percent, while yielding an acceptance profit on the investment As more stands are regenerated and holdings are consolidated, the potential for increased production from both pines and hardwoods through fertilization will increase

4. In Florida and the Flatwoods and the Middle Atlantic Coastal Plan, I am virtually certain that a substantial increase in production--perhaps 10 percent for the region as a whole--will be made through forest fertilization in the next three decades Most of this increase will come from the less well-drained sites in the area where excess moisture and nutrient deficiencies have, in the past, strongly limited stand establishment and tree growth."

Because of these conditions, operational forest fertilization has been mainly confined to the phosphorus deficient, poorly drained soils of the pine Flatwoods of the Gulf and Atlantic Coastal plains

Two general fertilization principles have been prescribed for this subregion. Early fertilization of between 80 and 100 pounds of P_2O_5 per acre (90 and 112 kg/hectare) is recommended on the phosphorus deficient soils of the Flatwoods Delaying the fertilization results in very slow tree growth, and often in poor survival. Since applied phosphate remains available to the stand for long periods of time, application should be at planting time or soon thereafter Small amounts of nitrogen applied in combination with the phosphates usually result in better growth than phosphates alone

Older stands appear to respond favorably to nitrogen fertilizers (or to nitrogen plus phosphate if the stand is in a phosphorus (ficient area) Applications of 80 to 120 pounds of nitrogen per acre (90 to 134 kg/hectare) have been used in established stands after crown closure Urea is the most popular source of nitrogen

Serious research in the field of forest fertilization started about 25 years ago, and the first operational fertilization was conducted in 1963 on 630 acres (255 hectares). Through 1969, a total of 33,000 acres (13,350 hectares) had been fertilized. Most of the fertilization during this period took place in 1968 and 1969

Available data through 1969 indicate that approximately one-half of the fertilization was accomplished with ground equipment, and that 79 percent of the fertilizers were applied to young stands

The proportion of various types of fertilizers applied were 82 percent superphosphate only, 7 percent urea only, and the remainder were N-P combinations

Fifty thousand acres (20,230 hectares) were fertilized in 1971 and, assuming a moderate interim figure for 1970, approximately 110,000 acres (44,500 hectares) have received chemical amendments through 1971.

Thus, the total acreage fertilized through 1971 is roughly one-third of the total area fertilized in the Pacific Northwest, a gross estimate of total fertilized acreage in the United States through 1971 would be 450,000 acres (182,070 hectares).

Two cooperative forest fertilization programs exist for the basic goal of coordinated, efficient research into increased wood production Both programs include participation by commercial forest owners, public agencies, and fertilizer producers.

The Cooperative Research in Forest Fertilization (CRIFF) effort was initiated in 1968 under the supervision of the University of Florida Its responsibility is investigation of fertilization in the pine region in Florida and in the lower Coastal Plain of neighboring states

The other program was officially started in 1970 and is administered by North Carolina State University Its concern is the southern pine range from Virginia south and west into Mississippi exclusive of the area covered by CRIFF

Influences and Possible Trends

The preceding survey indicates the wide range of emphasis placed upon forest fertilization throughout the world due to varying concepts, conditions, and objectives Bengtson's (5) assessment of the "prospects and challenges ahead" for forest fertilization in the South are also applicable in some degree to all fertilization programs His conclusions are that

> " . Beyond the year 2000, it is difficult to conceive of what our forests will be like, what types of land they will occupy, how extensive they will be, and what the demand price situation for forest products will be Nevertheless, there is good reason to believe that if we continue to upgrade the stocking and quality of our existing forest, to employ, where appropriate, land management techniques which complement fertilization, such as wetland drainage, sub-soiling and liming, and more effectively control competing vegetation, wildfire, insects and other pests and pathogens, and press ahead with the selection and propagation of tree genotypes having high fertilizer response potential, we eventually will see fertilizer of some type being used profitably on virtually every acre of commercial forest land in the South. With these complementing factors of production brought into effective coordination, we could easily double our present pine growth rates per acre and perhaps treble current average rates of growth of quality hardwood. Or we could, to put it another

way, maintain present levels of production with half as many acres of commercial forest land The achievement of the effective coordination of tree improvement, stand regeneration, site amelioration, and forest protection required to attain these goals is the challenging task for silviculturists in the years immediately ahead It certainly ranks in importance with the research activities of the specialists in these areas, because the greatest increases in forest production will come, in most cases, not from any one of these silvicultural activities but from their multiplying effects one upon the other "

The newness of the practice and the resulting dynamic changes occurring preclude accurate predictions on the magnitude and trends of operational forest fertilization in the future Rather, the interacting influences of social, economic, technologic, and contemporary scientific knowledge will determine future policies That forest fertilization will increase and become more refined and predictive is evidenced by the progress made in the past few years, the rate and magnitude of acceptance and growth of the practice will depend upon the interaction of the following variables with each other at any point in time.

Social

According to Osara (30), a number of countries have problems of over-population and/or climatic factors that have led to such pressures on good land that little or nothing can be set aside for the production of wood.

Some marginal lands may be available for this purpose, but the question arises whether it will be possible to develop international trade to such an extent as to enable these countries to cover their requirements by imports from wood surplus areas Perhaps one day fertilizers will play a role in expanding indigenous production of wood, despite adverse conditions and high costs, at the present time, however, it would hardly be opportune to speak of a major use of fertilizers for trees in countries where the population suffers from hunger or malnutrition

Therefore, it may reasonably be assumed that forest fertilization in the future will generally be confined to developed nations with a past history of substantial wood fiber production and that are currently practicing intensive and progressive forest management practices. In effect, these conditions restrict operational forest fertilization in the foreseeable future to those countries listed in the preceding survey that are employing or considering fertilization as a silvicultural tool

Other nations and regions not listed, such as the U S S R and sections of the U.S. and Canada could conceivably initiate fertilization practices if economic, technologic, and scientific factors become favorably balanced

Pressures in the developed wood fiber producing countries due to expanding populations very likely will force further withdrawal of some of the higher site lands for population expansion and existing mature timbered areas for recreation and other values, in turn shifting some forest land management operations to previously neglected, poorer site lands

Economics

The basic inducement to fertilize depends upon the realization of a substantial increase in wood fiber increment Objectives vary as a result of the combination of existing forest conditions and economic situations unique to each land manager practicing forest fertilization

The economic reasons for employing operational forest fertilization for increased growth are varied, several economic factors may be considered and applied in order to attain specific goals.

The most basic principle is production of a greater volume of wood fiber from a treated stand than would be realized over the same period of time and on the same area of unfertilized land Thus, if X units of wood fiber per acre would normally be anticipated from an unfertilized stand, and if X + F units were produced through fertilization alone or in combination with other cultural treatments, the added increment provided by F would justify the treatment investment, provided the value of F were equal to or exceeded the fertilizer investment compounded annually at an acceptable rate of return

Perhaps a more realistic way to consider the economics of fertilization caused by a shrinking forest land base is through a shortening of the rotation period. This example of resource substitution would produce the same volume (due to increased increment through fertilization) on the same area but in less time -- equivalent to growing the same volume on less land.

This concept in effect increases the amount of land under management without additional acquisition, and eliminates the purchase price of land and additional fixed costs such as taxes, road construction and maintenance, protection, and cultural practices The price of land and fixed costs per acre have been rising, while the expense of fertilization has dropped within the past decade and remained relatively stable over the past several years

Another option to be considered by forest land managers is the stimulation of growth in immature stands on better sites close to established mills, thereby decreasing transportation costs and, in some instances, increasing wood quality

Correcting existing imbalanced age class distributions for sustained yield is another potential benefit that may be possible through fertilization

Preliminary investigations indicate that under certain conditions the growth effects produced by forest fertilization interactions with other cultural practices are synergistic and not additive Silvicultural methods such as thinning, drainage, irrigation, and tree improvement, employed in conjunction with fertilization, may make the combined practices economically attractive, whereas if conducted singly their contribution to increased increment would be inadequate

In dense young precommercial stands, fertilization has accentuated expression of crown class dominance, thus enhancing its feasibility as a less costly method of precommercial thinning than the currently used mechanical methods A bonus is the addition of necessary soil amendments

Certain countries must maintain a favorable export-import balance through forest products in order to support the development of other industries. An associated aspect in areas with a past history of wood fiber production and declining resources is "national pride "

Technology

Application. On operational forest fertilization projects, hand spreading, ground machine, or aerial application methods are employed.

Hand spreading is feasible only in areas where labor costs are low and accessibility, size, and terrain of the project site are not prohibitive factors This technique offers few advantages except in specific unique situations, and is not nor will it become a dominant factor in operational forest fertilization. Ground machine applications are presently the cheapest methods and are particularly adaptable for treating young plantations on level ground They are only effective when soil conditions, vegetation, tree size and distribution, or topography do not limit operations.

Control of fertilizer distribution by ground equipment is highly regulated. No substantial cost reductions can be anticipated through development of new equipment.

Aerial application is most commonly used because it enables treatment despite highly variable ground conditions

Fixed-wing aircraft are preferred for certain situations, but this method has the liability of requiring a suitable runway close to the fertilization operations Helicopters, on the other hand, have greater maneuverability and less stringent landing site requirements.

Increased load capacity and improvements in design of dissemination systems developed over the past few years have further advanced the helicopter to the forefront of application methods.

Helicopters with pod capacities up to 4000 pounds (1814 kilograms) are currently utilized This size is capable of applying 25 tons of fertilizer per hour. The logistic problems of supplying fertilizer in bags or bulk containers to the landing site in quantities necessary for continuous operation and the larger transport systems and landing, storage, and loading areas required preclude an indefinite increase in helicopter size The amount of acreage involved in the individual fertilization project also favors smaller aircraft in certain situations

Bergland (6) believes that improved equipment designs are possible through several avenues These are reduced costs of coordination, handling, and application, simplified adjustments for rate and swath width, and greater accuracy, uniformity, and versatility throughout the dissemination process Incomplete operational cost data and technical difficulties of equipment evaluation cloud the tangible dollar benefits of new equipment designs Environmental constraints, caused by the need to exclude streams and lakes from treatment areas dictate that equipment development should provide accurate placement of fertilizer more economically rather than provide economy by sacrificing accuracy.

Fertilizers The impetus for development of new fertilizer formulations or changes in the use of existing chemical amendments for specific conditions will depend upon the findings of continuing research efforts of soil and tree physiology sciences

Many of the operational forest fertilization projects undertaken have been conducted without definitive knowledge of the correct timing, rate, and fertilizer formulation required for optimum growth response of the species based on site, age, and stocking. As a consequence, applied nitrogen has been lost through volatilization, leaching, and luxury consumption

The cooperative forest nutrition research programs and other pertinent investigations are designed to provide this essential information Fertilization programs may then be objectively planned for maximum growth benefits with least expenditure and environmental degradation

Commercial fertilizer manufacturers anticipate no major production breakthroughs in the immediate future which will increase the proportion of nutrient(s) per unit of weight or reduce the bulk price of fertilizers significantly below their present costs Formulations, additives, and prill coatings are presently undergoing testing for nitrogenous fertilizers to reduce volatilization loss or to inhibit nitrification and subsequent leaching.

One technique which could possibly become operational is the use of liquid or fluid fertilizers instead of pellets and prills in aerial application. This method would further diminish control during dissemination and subject initial distribution to the atmospheric loss and drift experienced by aerially applied pesticides (28)

Soil and Tree Physiology Sciences

The number of variables to be investigated and the length of time required for conclusive results to be obtained control the rate and magnitude at which forest fertilization will be accepted and practiced, especially where only marginal economic returns are anticipated A number of indicative findings have been accomplished, many more interdisciplinary efforts are being conducted or contemplated

Results of studies in these sciences will ultimately determine the economic feasibility of fertilization, delineate the areas included or excluded from the practice, and specify the fertilizer formulations, rates, and time of application necessary to optimize tree growth and minimize nutrient loss.

SECTION V

EFFECTS ON WATER QUALITY

Concern has been expressed by both participants and observers over possible detrimental effects to the environment caused by the use of inorganic fertilizers on forest lands No deleterious consequences have been discovered so far, but interested organizations, especially in the United States, are accelerating water quality research efforts in order to understand the effects of forest fertilization on the ecosystem, to dispel incorrect assumptions with concrete information, to recognize and correct harmful aspects before they become irreversible and, ultimately, to insure that forest fertilization will not be placed under restrictions that will diminish its value as a silvicultural tool

Former concepts that 1) all forest soils contained adequate amounts of essential elements, 2) any nutritional changes imposed on the natural state by man would upset the balance and be harmful, 3) fertilizers would rapidly be leached and lost from the site, and 4) forest crops are strictly soil builders and production does not constitute a drain on the soil (13) have been revised through findings of research efforts conducted within the past several decades

Forest soils have generally been found to be deficient in certain essential elements, especially nitrogen In some instances, adequate reserves of essential elements are present, but in forms unsuitable or unavailable for plant growth Even the higher sites which were previously considered to be sustaining maximum growth have shown dramatic increases in increment when fertilizers have been applied

In contrast to cultivated lands, the forest soil generally has a highly organic layer over its surface and organic matter content of the top few inches is almost always greater than that in cultivated soils. This substantial amount of organic matter provides a large number of adsorption sites for applied chemicals Further, most well-established forest stands, including understory vegetation,

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have a massive root system that offers great opportunity for interception and rapid uptake of chemical fertilizer nutrients (27).

Undisturbed forest soils, in contrast to agricultural soils, are credited with restricting losses of essential elements through leaching since elements are retained within a cycle between the plant and soil systems, and a general deficiency of anions exists in a forest soil profile of the temperate region (8).

The two primary methods by which applied nutrients may enter stream channels are by direct application to the water surface or through subsurface flow Overland flow of water on well-vegetated land is inconsequential as a means of transporting applied fertilizers into water courses, except for occurrence on roads, trails, and other compacted areas with exposed mineral soil.

A number of lysimeter studies and several watershed monitoring investigations have been conducted on fertilized areas. Most of the research emphasis has been directed toward determination of conversion, cycling, and loss of the mobile forms of nitrogen

The lysimeter work has shown rather conclusively that leaching of nitrates (the toxic form of nitrogen) into the ground water is insignificant Forest soils are excellent filters for most plant nutrients because of their high exchange capacities and the dense root systems which can absorb and recycle nutrients (28).

The few watershed monitoring studies completed to date were accomplished by sampling and analyzing stream flow from fertilized watersheds or portions of drainages. In all investigations, application was by helicopter, except for one trial application of ammonium sulfate, urea was used exclusively A listing of the completed and analyzed studies is presented in the Appendix

Although the degree of sophistication in experimental design, timing and rate of application, and components analyzed differed among studies, similarities in the behavior of critical parameters were observed.

A summary of the major findings indicates the following general characteristics

1. Urea-N and Kjeldahl-N reached short-lived peak concentrations shortly after fertilizer application, and returned to pretreatment levels within several weeks Strong evidence is presented that the initial increase of urea-N concentrations was primarily due to direct application to surface waters, this contention is substantiated by low initial concentrations where surface waters were intentionally avoided during application

2 A small increase in ammonia-N above pretreatment levels was observed shortly after application Concentrations quickly returned to pretreatment levels, the magnitude and duration of ammonia-N loss appeared to be associated with surface water application and with volatilization loss dependent upon climatic conditions immediately after application

3. Loss in the form of nitrite-N was minimal and insignificant, apparently due to rapid conversion of nitrite-N to nitrate-N through nitrification

4 Nitrate-N contributed to the greatest and most persistent loss of nitrogen on all study areas The initial significant loss occurred within a period of several days after application, subsequent substantial losses were associated with the intensity and duration of precipitation Virtually all of the nitrogen losses after the initial peaks associated with application were in the form of nitrate-N

5 Short-lived and inconsequential ammonium-N losses immediately preceded the nitrate-N losses, and coincided with the initial onset of precipitation

6 Data from one study suggest the possibility of significant interactions involving urea fertilization and discharge of cations from the watershed. A definite increase in the concentrations of calcium, magnesium, sodium, and potassium in the stream following fertilization was observed

7. In none of the studies was the Public Health Service maximum permissible level of nitrogen in public water supplies seriously approached as a result of fertilization

8 Losses of applied nitrogen to stream channels ranged from inconsequential to a maximum of three percent Data vary according to stream surface area, rate and consistency of application, and other factors unique to each study, but approximately one-third to one-half of the total nitrogen loss may be associated with direct application to the surface water and immediate riparian zone

A study on the possible transport of urea-N conducted in Sweden showed a slight increase in the nitrogen content (mainly ammonium-N) in stream and lake water. After fertilization in 1969, it was calculated that 30 to 40 kg (66 to 88 lb) of nitrogen out of a total of 11,000 kg (24,250 lb) of nitrogen was deposited in the recipient. In 1970, the corresponding figures were 10 to 20 kg (22 to 44 lb). The maximum percentage lost over the two years would not exceed 0 5 percent of the total nitrogen applied (18)

Early in 1971, a number of areas in Sweden scheduled for fertilization later in the year were selected, and one or more natural springs, including controls, were used for water sampling at definite intervals before and after fertilization Preliminary data show that an appreciable increase in ground water nitrogen resulted only after ammonium nitrate application, this condition occurred in only a few cases However, in one of the springs and on one occasion the nitrogen concentration reached a value of 8-9 ppm of nitrate-N. Urea produced no noticeable increase in the water nitrogen concentration. This study is continuing (18).

The application of phosphorus on organic soils has received the greatest research attention in Sweden Two projects have been initiated, results to date indicate that on one peat type no P fixation occurs when the fertilizer is applied in a water soluble form (superphosphate), while the nonsoluble forms used (basic slag, apatite) do not seem to be leached out (18).

An extensive survey of public and private organizations concerned with the practice of forest fertilization and its effects on water quality revealed a large number of well-planned lysimetry and barometer watershed studies in various stages of preparation and sampling Government agencies, universities, and private industry are involved individually or cooperatively The studies are not wholly confined to the regions presently practicing operational forest fertilization, and the behavior of other essential elements in addition to nitrogen are being investigated The numbers, types, and sophistication of current research efforts, in addition to the restrictions imposed by the lack of a coordinating agency, precludes a listing and summary of these research projects and objectives

The scope and intensity of these studies will eventually form the basis for more predictive parameters than the few previously conducted The projects range from simple monitoring of fertilized watersheds to assessment of the impacts of introduced nutrients on the whole forest ecosystem The water quality studies must naturally be evaluated in their relationship to the findings of tree growth, economics, environmental impacts, and other criteria

As well as specifying the type, quantity, and pathways of applied nutrient loss under a wide range of conditions, the conclusions will aid in minimizing and controlling losses through delineation of the

1 Most suitable rate of application

2 Most satisfactory type of fertilizer formulation

3. Proper seasonal and chronological timing of application and reapplication.

4. Areas with potential for substantial nutrient accumulation in impoundments

The National Environmental Protection Board of Sweden and the Royal College of Forestry have a small budget allocated for water quality studies. In addition to those previously mentioned, the largest project encompassing investigation of all components of a fertilized forest ecosystem is underway. It is not anticipated that many more water quality studies will be initiated in Sweden until a substantial increase in forest fertilization can be foreseen (18).

Investigations are being carried out in Finland on the washing away of nutrients on peatlands as well as the total nutrient balance. No results have been published to date (31).

In New Zealand, catchments have been established for research on phosphate levels, but otherwise there has been very little investigation in this area (46).

SECTION VI

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SECTION VII

APPENDIX WATERSHED STUDIES

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16 Abstract

Information pertaining to the concepts, scope, and methods of forest fertilization in various nations and regions of the world has been compiled from available sources Factors influencing development to present status, possible trends, and impacts on water quality are discussed.

Results of completed forest fertilization-water quality studies have been summarized and evaluated, and the status of current water quality studies is described. Recommendations for state-of-the-art reviews and essential research efforts are presented (Groman--EPA)

17a Descriptors

*Forest management, *Fertilization, *Environmental effects, Silviculture Forest soils, Soil treatment

17b Identifiers

*Forest fertilization, *Water quality studies

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