A REVIEW OF RESEARCH LITERATURE ON FOREST FERTILIZATION

by
Yam (Jim) Lee

FOREST RESEARCH LABORATORY
VICTORIA, BRITISH COLUMBIA
INFORMATION REPORT BC-X-18

CANADA
DEPARTMENT OF FORESTRY
AND RURAL DEVELOPMENT

FORESTRY BRANCH
MARCH, 1968

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Yam (Jim) Lee[1/]

The British Columbia Forest Fertilization Board, a co-operative effort of the forest industries and government agencies, is making plans to implement a comprehensive program to investigate the effect of fertilization on growth and stand development, with particular reference to Douglas fir (Pseudotsuga menziesii) and western hemlock (Tsuga heterophylla).

It is essential that pertinent research findings be brought out to provide background information and basis for planning.

A review of literature is now completed and presented here for the British Columbia Forest Fertilization Board.

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INTRODUCTION

There are at present very limited publications on forest fertilization projects in British Columbia and elsewhere in Canada. A recent survey by Armson (1967) showed 90 forest fertilization research projects underway in Canada, 25 of which are in British Columbia. Of the 25 British Columbia projects cited by Armson (second in number to Ontario), only 4 are concerned with the growth response in established stands. It is apparent that information on established stands based on British Columbia data will be restricted for some time to come.

In Table I, these projects across Canada are compiled by provinces and type of stand, and in Table II, the British Columbia projects by agencies and type of stand. It is noted that all British Columbia projects are concerned with Douglas fir except one, which is on lodgepole pine (<u>Pinus contorta</u>).

Table I. Number of forest fertilization projects in Canada, classified by provinces, and type of stand.

Province	Type of stand				
	Seed and cone production	Nursery seedbeds	Plantations at time of establishment	Established stand	Total
British Columbia	10	6	5	4	25
Alberta			1	3	4
Saskatchewan		1			1
Manitoba	1				1
Ontario	3	7	9	15	34
Quebec		1	7	16	24
New Brunswick			1		1
Total	14	15	23	38	90

Table II. Number of forest fertilization projects in British Columbia, classified by agencies, and type of stand.

Agency	Type of stand: Seed and cone production	Nursery seedbeds	Plantations at time of establishment	Established stand	Total
Tahsis	1		1		2
Univ. of B.C.	2	2	1		5
B.C. For. Prod. Ltd.	1		2	1	4
Dept. of Forestry	5				5
M. & B. Ltd.	1				1
B.C. For. Serv.		4		1	5
P.P.R.I.C.			1		1
Pacific Logging Co.				1	1
S.M. Simpson Ltd.				1	1
Total	10	6	5	4	25

The review of literature on fertilization, from Canadian and other sources, is reported in this paper under the following headings:

Nutrient Requirements of Forest Trees

Nitrogen Cycle in Forest Stands

Soil Elements

Foliar Analysis

Growth and Survival of Planting Stock

Combined Effect of Thinning and Fertilizing

Rate of Fertilizer Application

Duration of Response

Time of Application

Methods of Application

Insect and Disease

Wood Quality

Economic Considerations

Discussion and Conclusions

NUTRIENT REQUIREMENTS OF FOREST TREES

Six macro-nutrients (nitrogen, phosphorus, potassium, magnesium, calcium and sulphur), and seven micro-nutrients (boron, coppor, zinc, iron, manganese, molybdenum and chlorine) are required for healthy and vigorous growth of forest trees (Arneman, 1960; Gessel *et al.*, 1960; Swan, 1965). Very often, a few of these elements are so deficient in forest soils that fertilizer chemicals must be added to obtain optimum productivity from the forest land. The elements nitrogen, phosphorus, potassium and calcium are the most commonly used chemicals for forest stands. Other elements are less commonly used.

Nitrogen

Nitrogen is a necessary part of all amino acids, proteins, and many other compounds in forest trees, and is therefore an essential nutrient for tree growth. Nitrogen deficiency can cause considerable decreases in growth, while excesses result in profuse shoot growth and light wood. Toxic amounts of nitrogen can retard growth for a number of years (Mustanoja and Leaf, 1965).

Phosphorus

Phosphorus is important to trees mainly for cell division and flowering. It is absorbed by plants in ionic form and for a limited amount in organic form. An adequate supply of phosphorus is essential in the formation of the reproductive organism. Deficiency in phosphorus has been found in large areas of pine (*Pinus radiata*) forest soil in New Zealand (Conway, 1962).

Potassium

According to Arneman (1960) potassium is associated with metabolism in plants, and is essential for chlorophyll synthesis, the manufacture of carbohydrates, and in regulating the use of nitrogen and phosphorus. Mustanoja and Leaf (1965) state that the exact role of potassium deficiency is not too well known and that there are few known cases of potassium deficiency in the world. Ugolini (1968) reported that potassium exists in plants in ionized form and therefore is relatively mobile. It is often transported from older leaves to the younger part of the plant.

Calcium

Calcium is required for the building of cell walls and the development of root systems. It also acts as an adhesive between the cell walls (Arneman, 1960). Although calcium is needed in large amounts for tree growth, forest soil is often capable of supplying this need (Mustanoja and Leaf, 1965).

Magnesium

Magnesium is an essential part of the chlorophyll molecule and credited with the ability to combine with phosphate so as to move the latter to its proper place in the plant (Arneman, 1960).

Other elements

The remaining elements are also required for healthy tree growth, but very little research has been carried out to investigate their role in the growth of forest trees. Generally they are not deficient in the soil (Arneman, 1960).

Comment

It is noted that there is no complete information on nutrient requirements of important tree species in British Columbia.

NITROGEN CYCLE IN FOREST STANDS

Nitrogen is the greatest uptake among the nutrients stored in forest trees. It is also the most essential element in stimulating growth (Ebell, 1962; Van den Driessche, 1963; Crossin *et al*., 1966; Hagner *et al*., 1966; and Hagner, 1967). Table III shows the values represented in the uptake of nitrogen, phosphorus and potassium, with data extracted from Maki (1966).

Table III. Values represented in the uptake of N, P, and K.

Species or Site	Age years	Nutrient uptake in bole and bark, lb./acre			Source
		N	P	K	
Picea abies	120	45	6	24	Kvist (1964)
Pinus sylvestris	55	101	9	58	Ovington (1957, 1959)
Pinus radiata	35	200	30	230	Will (1964)
Pinus resinosa					
Good site	31	87	9	35	Madgwick (1962)
Poor site	31	38	5	9	Madgwick (1962)
Pinus resinosa	20	52	6	18	Heiberg *et al*. (1959)
Pseudotsuga menziesii	35	112	17	86	Cole (1968)

In nature, the uptake of nitrogen from soil is stored by plants. Part of this uptake returns to the soil from trees and ground vegetation in the form of litter fall, root excretions and dead roots. According to Cole (1968), the amount of nitrogen contained in soil in the forest ecosystem is very large:—soil 85%, forest floor 5%, subordinate vegetation 1% and forest tree 9%. Weetman (1961), however, indicates that much of this nitrogen may not be readily available for tree growth.

Weetman (1961) reported that loss of nitrogen in the forest ecosystem often occurs through volatilization as (1) Ammonia volatilization, (2) nitrous oxide, or (3) nitrogen gases (chemical reactions or bacterial denitrification). Ammonia volatilization occurs generally at a pH value of more than 7, and volatilization increases with increased temperature in soils of low exchange capacity. Following cutting, the exposure of alkaline organic layers in the forest can also result in significant losses of nitrogen. Increased soil acidity hastens the decomposition of nitrites into nitrous oxide. In addition, nitrous acid may react with soil, produce nitrous gas, and lose nitrogen in the process. Loss of nitrogen in the forest ecosystem through harvesting, burning and litter-collection is well-known.

Figure 1. gives the approximate nitrogen cycle in the forest ecosystem as reported by Weetman (1961).

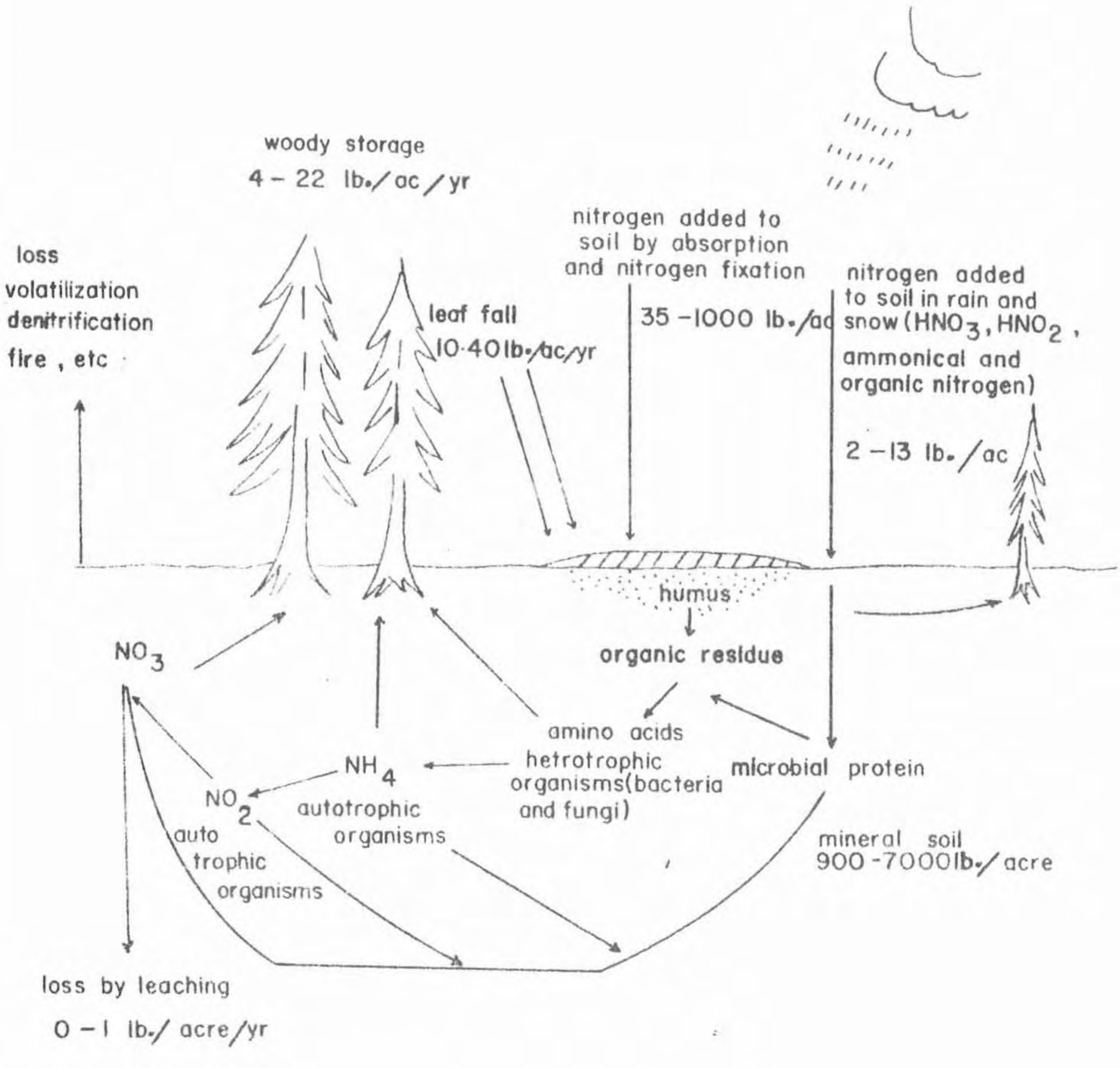

FIGURE I· NITROGEN CYCLE IN A FOREST ECOSYSTEM
(after Weetman, 1961)

SOIL ELEMENTS

Factors influencing the level of nutrients in the soil are aeration, temperature, moisture, and biological activity. Accurate diagnosis of soil nutrient deficiency may help to determine the most suitable kind of fertilizer for a certain area, but Youngberg (1968) pointed out that the numerous complex inter-relationships between various components in a forest community are additional factors to be considered. Soils may respond differently to different fertilizers, and tree species may have different nutrient requirements. The relationship between the nutrient content of the soil and forest tree growth, as pointed out by Gessel *et al.* (1960), has not been established. Youngberg (1968) also noted that a soil may have an abundance of available nutrient (as determined by soil analysis), but if soil physical conditions are not favourable for root development and biological acitivity in the soil, the tree may still experience nutrient stress.

According to Ugolini (1968), chemical analysis of forest soil can be performed more rapidly than chemical analysis of biological matters. To obtain meaningful results, care must be taken in soil sampling procedure. Ugolini (1968) suggested that 10 to 15 samples per acre are sufficient. These samples are then thoroughly mixed and a composite sample is obtained for the area. Areas which differ in slope, drainage, soil type and species composition should be sampled separately.

FOLIAR ANALYSIS

Foliar analysis is frequently used to study the nutritional status of a tree or forest stand. Mitchell (1936) analyzed samples dried to a constant weight, and published extensive information on mineral nutrient of North American forest trees. In studying the mineral nutrient relationships of forest trees, Leyton (1948) indicated that mineral composition of foliage varies greatly according to (1) the type of leaf and its location on the tree, (2) season, (3) time of the day sampled, (4) age of the foliage, and (5) age of the tree. In a study of forest nutrition by means of foliar analysis, Tamm (1960) reported that there is considerable variation in nutrient content in the same tree from year to year, which is a serious obstacle to making an accurate estimate of the nutritional status of the forest. Lavender and Carmichael (1966) found that the mineral concentration of Douglas fir needles varies significantly with foliar age, crown position and season of the year. Smith *et al*. (1967) investigated the influences on cone production and growth of young Douglas fir, western hemlock and western red cedar (*Thuja plicata*) on the U.B.C. Research Forest. They found that neither soil analyses nor foliar nutrient analyses provide adequate evidence of fertilization effects or serve as useful indicators of probable responses to fertilization. In spite of these negative results, many research workers are continuing their investigations. Dr. R. E. Miller of the U. S. Forest Service, Olympia Research Center has established field fertilizer plots in the Roseburg area of western Oregon to study mineral nutrition for Douglas fir (Gessel, 1968).

In view of the foregoing, Lavender (1968) considered several factors important in collecting samples for foliar analysis. These are (1) current foliage, (2) upper three whorls in the crown position, (3) sampling in September through December, and (4) samples limited to dominant and codominant trees. With regard to the number of sample trees required, Lavender (1968) stated that Wehrmann of Germany, working with Scots pine (*Pinus sylvestris*) stands in 1959, recommended that 10 trees be sampled to estimate the nitrogen and phosphorus status, 30 trees for potassium and magnesium and 100 trees for calcium.

Comment

To properly relate the foliar nitrogen concentrations to tree growth, complete information on the physical and chemical characteristics of the soil, together with thorough understanding of the ecology and environment of each site, is required.

GROWTH AND SURVIVAL OF PLANTING STOCK

In an evaluation of the benefit of nursery fertilization, the results of nursery fertilizer experiments with Douglas fir were reported by Van den Driessche (1963). Favourable response was obtained with nitrogen fertilizer used at a rate of 40 pounds per acre. Field growth and survival of these fertilized seedlings was not reported.

Evidence appears to be predominantly against fertilizing as an integral part of the planting operation (Lunt, 1945; Wakeley, 1954; Zehetmayer, 1960; Wells, 1964; Tamm, 1965; Maki, 1966). As the seedling struggles to recover from shock due to transplanting, the critical need seems to be for moisture, not fertilizer. The weight of opinion (Maki, 1966) is that at the time of planting, fertilizing may stimulate vigorous growth of adjacent ground vegetation, which in turn consumes the available moisture supply, leaving very little for the seedling.

Lunt (1945) investigated white spruce (*Picea glauca*) and Norway spruce (*Picea abies*) 2-1 nursery stock which were planted in the field and measured at intervals. The experiment was to determine (1) the effect of fertilizer treatment in the nursery, and (2) the effect of fertilizer treatment at the time of planting upon subsequent growth and survival. The variations in survival and growth of controlled and treated plots were great, and no significant correlation was found between treatment and growth or survival.

Austin and Strand (1960), applying slow soluble fertilizers in forest planting in Pacific Northwest in a scarification trial area, found that Sitka spruce (*Picea sitchensis*) and Douglas fir seedlings increased their height growth by 26% and 20% above control, respectively, after the first growing season. Height growth of grand fir (*Abies grandis*) seedlings was not affected by fertilizer treatment.

Walters *et al*. (1961) reported on fertilization of planted 2-0 Douglas fir seedlings. Fertilizer pellets were deposited in the planting hole immediately prior to planting, and the result was either neutral or harmful (Walters *et al*., 1966).

With loblolly pine (*Pinus taeda*) seedlings, Wells (1964) found that fertilizing to stimulate early growth often caused injury to seedlings or stimulated weed growth instead.

The outcome of fertilization experiments are varied and depend upon the form and amount of fertilizers as well as soil conditions. In fact the toxicity of large amounts of fertilizer has increased mortality in some cases (Richards, 1961; Pharis *et al*., 1962). Lush growth of weeds resulting from fertilization at planting has also caused heavy losses in plantation (Derr, 1957; Boggess and Gilmore, 1960).

COMBINED EFFECT OF THINNING AND FERTILIZING

Thinning prior to fertilizing may concentrate fertilizer effect on selected trees. Heacox (1968) "conjectured" that fertilizer treatment on thinned stands may produce a specific tree size in a shorter period of time than in the case of untreated stands, and may provide great flexibility with respect to the selection of harvest age. Findings, however, are not yet conclusive.

The major purpose of thinning is to regulate the areal distribution of trees to a desired spacing by eliminating the small, unhealthy, poorly shaped or excessively crowded trees for the benefit of the remaining crop. The influence of fertilizer on plantations at various spacings is reported by Heiberg et al. (1959) and Marlow (1966).

The pronounced effect of potassium fertilizer on a potassium-deficient red pine (*Pinus resinosa*) plantation in Adirondack becomes evident 10 years after its application, according to Heiberg et al. (1959). Wide spacing produces larger diameter and greater height in the dominant trees, but basal area remains constant on a per acre basis. Stands of wide spacing, due to their low density, have a lower nutrient uptake per unit area, compared with that of closer spacing.

Marlow (1966) reported on radial growth of Douglas fir, western hemlock and western red cedar four years after thinning and fertilizing, in two 1-acre plots at the U.B.C. Research Forest. These plots were thinned to favour Douglas fir wherever possible, and also trees having full and healthy crowns. Ammonium nitrate in the form of nitro-cubes was applied in the first and the second year at the rate of 625 pounds per acre, and repeated on one-half of each plot in the third year. One year after fertilization, no response was found in percentage height increment by crown classes. This was attributed to a probable temporary depressing effect of thinning (Walters, 1961). The effect of treatments was found significant on radial growth at the end of the fourth year (Marlow, 1966).

Comment

Findings are not conclusive. More research is required.

RATE OF FERTILIZER APPLICATION

The results of twelve research studies on the relationship between rate of fertilizer application and growth response are compiled and presented below:

Species and location	Fertilized age yr.	Kind of fertilizer	Rate lb./ac.	No. of years post-fertilization	Response	Source
(1) Douglas fir, Washington State, U.S.A.	30	Ammonium nitrate (1st yr.)	100	4	Range in growth rate	Erickson and Lambert (1958)
		Urea (2nd yr.)	100			
		Urea (3rd yr.)	50			
		Urea (4th yr.)	50			
	30	"	"	4	Greatest-thinning + fertilizing	
	30	"	"	4	2nd-fertilizing only	
	30	"	Nil	4	3rd-thinning only	
	30	"	Nil	4	least-control	
(2) Douglas fir,	Fertilized age yr.	Kind of fertilizer	Rate lb./ac. (N)	No. of years post-fertilization	Total uptake of NPK (lb./ac)*	Heilman and Gessel (1963)
Washington State, U.S.A.	22	Urea	400	8	1.6 times of control	
	25	Ammonium sulfate	400	7	1.5 times of control	
	29	Ammonium nitrate	700	9	1.5 times of control	
	37	Ammonium nitrate	100	1	less than control	
	50	Ammonium sulfate	100	2	1.3 times of control	

* paired in control vs treatment

(3) Douglas fir,	Fertilized age yr.	Ammonium nitrate + Super-phosphate	Rate lb./ac. (N)+(P_2O_5)	No. of years post-fertilization	Range in dbh increment	Steinbrenner *et al.* (1960)
Washington State, U.S.A.	20	"	400 + 200	1	Greatest	
	20	"	400 + 400	1	2nd	
	20	"	200 + 400	1	3rd	
	20	"	200 + 200	1	3rd	
	20	"	Nil	1	Least	
	20	"	400 + 400	2	Greatest	
	20	"	400 + 200	2	2nd	
	20	"	200 + 200	2	3rd	
	20	"	200 + 400	2	4th	
	20	"	Nil	2	Least	

(4) Douglas fir,	Fertilized age yr.	Kind of fertilizer	Total N in 3 years	No. of years post-fertilization	Range in mean dbh	Ebell (1962)
South Central Vancouver Island, B.C., Canada	13	NPK(NH_4-N)	400 - 4000	3	Greatest	
	13	$(NH_4)NO_3$	400 - 4000	3	2nd	
	13	$(NH_4)_2SO_4$	400 - 4000	3	3rd	
	13	NP(NH_4-N)	400 - 4000	3	4th	
	13	$Ca(NO_3)_2$	400 - 4000	3	5th	
	13	$Co(NH_2)_2$	400 - 4000	3	Least	
	13	$CaCN_2$	400 - 4000	3	Not Significant	
	13	P	400 - 4000	3	Not Significant	
	13	K	400 - 4000	3	Not Significant	
	13	Cu	400 - 4000	3	Not Significant	
	13	Control	Nil	3	—	

(5) Douglas fir,	Fertilized age yr.	Kind of fertilizer	Rate lb./ac. (N)	No. of years post-fertilization	Ht.increment in % of ht.pre-fertilization	Crossin et al. (1966)
Southern Vancouver Island, B.C., Canada	10 - 15	Ammonium nitrate 33.5/0/0	66	2	157	
	10 - 15	"	133	2	267	
	10 - 15	Ammonium phosphate-sulfate 16/20/0	256	2	500	
	10 - 15	Nil	Nil	2	140	

(6) Douglas fir,	Fertilized age yr.	Kind of fertilizer	Rate lb./ac. (N)	No. of years post-fertilization	Basal area response	Strand (1968)
Oregon, U.S.A.	15 - 90	Urea	100	-	100% *	
	15 - 90	Urea	200	-	54% *	
	15 - 90	Urea	200	-	34% **	
	15 - 90	Urea	400	-	41% **	

* Based on 21 sets of paired trees.

** Based on 8 sets of paired trees.

(7) Western hemlock,	Fertilized age yr.	Kind of fertilizer	Rate lb./ac. (N)	No. of years post-fertilization	Basal area response	Strand (1968)
Oregon, U.S.A.	15 - 90	Urea	100	-	-5% *	
	15 - 90	Urea	200	-	5% *	
	15 - 90	Urea	200	-	37% **	
	15 - 90	Urea	400	-	35% **	

* Based on 21 sets of paired trees.

** Based on 8 sets of paired trees.

(8) Red pine,	Fertilized age yr.	Potassium chloride (0-0-60)	Rate lb./ac. (K)	No. of years post-fertilization	Average ht. of the 10 tallest trees in feet	Heiberg *et al.* (1959)
New York State, U.S.A.	18	"	Nil	9	7	
	18	"	25	9	11	
	18	"	50	9	14	
	18	"	100	9	12	
	18	"	150	9	13	

(9) Pinus radiata,	Fertilized age yr.	Super-phosphate	Rate lb./ac.	No. of years post-fertilization	Average basal area growth	Conway (1962)
New Zealand	20 - 29	"	Nil	5	110 sq.ft./acre	
	20 - 29	"	500	5	1.1 times of control	
	20 - 29	"	1000	5	1.2 times of control	
	20 - 29	"	2000	5	1.3 times of control	
	20 - 29	"	5400	5	1.4 times of control	

(10) Pine,	Fertilized age yr.	Kind of fertilizer	Rate lb./ac. (N)	No. of years post-fertilization	Relative response in basal area increment %	Hagner (1967)
Sweden	40 - 70	Urea	50	7	20	
	40 - 70	Urea	100	7	38	

(11) Spruce,	Fertilized age yr.	Kind of fertilizer	Rate lb./ac. (N)	No. of years post-fertilization	Relative response in basal area increment %	Hagner (1967)
Sweden	40 - 70	Urea	50	7	14	
	40 - 70	Urea	100	7	36	

(12) White spruce and Norway spruce,	Fertilized age yr.	Kind of fertilizer	tons/acre	No. of years post fertilization	Total yield in cubic volume	MacArthur (1957)
Quebec, Canada	2	Manure	15	38	3.4 times of control	
	2	Manure	30	38	3.1 times of control	
	2	Manure	15	38	6.1 times of control	
	2	Manure	30	38	6.0 times of control	
	2	Manure	Nil	38	956 cubic feet/acre	

Comment

The foregoing indicates that species have different nutrient requirements, and react differently to a given environmental condition. Research findings in one area for a particular species may not be applicable to another area, even for the same species. In British Columbia, no conclusive recommendation can be made yet on the exact rate of fertilizer application.

DURATION OF RESPONSE

Heiberg et al. (1964) used potassium chloride (0-0-60) with up to 150 pounds of potassium per acre in a red pine plantation, and found that maximum height growth was obtained in the fifth or sixth year, followed by a slight decrease in response, but height growth attained was still 45% above the unfertilized trees 20 years after fertilization.

Hagner et al. (1966) applied 90 pounds of nitrogen per acre in the form of calcium ammonium nitrate to Norway spruce (Picea excelsa) stands in Sweden, and the response in height increment was far greater than in basal area increment. At the end of the eighth year after fertilization, response in basal area was found to be at zero but response in height was well over 50% above control. The following is a comparison of the annual responses in the eight years following application:

Duration, yr.	1st	2nd	3rd	4th	5th	6th	7th	8th
	Increment in per cent							
Height	26	44	54	104	71	71	71	69
Basal area	14	46	57	50	60	35	32	0

Crossin et al. (1966) reported on a Douglas fir nutrition study on Vancouver Island and stated that eight years after fertilization, duration of response still continued.

Comment

In spite of numerous research undertakings, the longest duration of response is not yet known. Until the duration is known, a second application of fertilizer in a stand is questionable in practice.

TIME OF APPLICATION

Important factors to be considered in studying the time of fertilizer application are (1) growth response to availability of fertilizer, (2) loss of fertilizer through leaching, volatilization and denitrification, and (3) the economics of the operation. Scientific evidence on these three factors is not yet available. Strand (1968) recommends November through March as the most favourable time for application of urea in the Washington and Oregon areas, followed by October and April. For other chemicals, the months of May and September are also suitable. He stated that available information is not sufficient to recommend specifically the best time for fertilizer application. It is evident that further research is required.

METHODS OF APPLICATION

Efficiency and economics of forest fertilization depend largely on transport and dissemination costs. Aerial application is practicable when extensive areas are involved. Ground application is feasible only for small areas, and generally for research purposes only.

Since 1962, fixed-wing aircraft have been used by Swedish Cellulose Company in fertilizing thousands of acres (Hagner, 1967). Before 1966, Piper Pawnee type (fixed-wing) aircraft with a capacity of 1,000 pounds of urea were employed. Since 1966, large Aero Commander Snow and Ag Cat types (fixed-wing) with a capacity of 1,800 pounds have been used by the same company. These aircraft are operated from an airstrip 1,500 feet in length and 10 to 35 feet in width. A fertilizer distribution with 10% of total area too heavy and 10% too light is considered a satisfactory distribution. Aerial application by helicopter is estimated to be too expensive and has not been tried to date by the Swedish Cellulose Company.

In New Zealand, 14,400 acres of *Pinus radiata* have been fertilized by a Fletcher FU 24 (fixed-wing) with a capacity of 1,500 pounds, operating from an airstrip 450 to 1,320 feet in length (Conway, 1962).

Applying urea fertilizer by helicopter, Steinbrenner (1968) found that a larger size granulated urea gave a wider swath (80-85 feet) and a more even distribution than the smaller size (swath width 55-60 feet). The cost was estimated at $30 per acre (at a rate of 150 pounds of nitrogen per acre).

Crown Zellerbach Corporation in Oregon has been fertilizing 1,500 to 2,600 acres annually since 1965 (Clark, 1968). Fixed-wing aircraft are employed and have proved to be quite effective. Table IV shows the detailed statistics in the operation.

The Pacific Logging Company of Victoria, British Columbia, has also used fixed-wing aircraft in its fertilizing operation on Vancouver Island (MacRae, 1968). Table V provides the detailed statistics in the operation.

Comment

From the preceding information, it seems that fixed-wing aircraft are the most economical and efficient means of forest fertilization on a large tract of land. This method of application can be further improved with experience. If local co-operative efforts can be made for the purpose of forest fertilization (similar to the arrangement among British Columbia forest industries for air tankers in combating forest fires), aerial application with fixed-wing aircraft in British Columbia on an operational basis will be both effective and economical.

Table IV. Statistics on forest fertilization (Crown Zellerbach Corporation).

Year of Application	Type of aircraft	Aircraft capacity lb.	Swath width ft.	Flying height ft.	Runway length	Distance between air-strip and project area miles	Age of stand yr.	Acres ferti-lized acres	Maximum daily production lb.	Maximum daily production acre/day	Average total cost/ acre
1965	Consol-idated PBY-6A	9,000	50	50-200	3/4 - 1 mi.	19	40-100	1486	125,000	284	$28
1966	Call Air A-9	1,000	30	-	2000 ft.	2-4	40-140	1500	94,000	214	$29*
1967	Call Air B-1	1,900	40	-	2000 ft.	2-4	20-120	2640	216,000	492	$24**
1968	Call Air B-1	1,900	40	-	2000 ft.	2-4	-	2400	216,000	492	$23***

* cost includes construction of a 2000-foot airstrip.

** cost does not include construction of a 2000-foot airstrip.

*** expected cost.

Rate of application is 440 lb. of urea/acre = 200 lb. of N/acre.

Table V. Statistics on forest fertilization in Robertson River area, Vancouver Island (Pacific Logging Company)

Year of Application	Type of aircraft	Aircraft capacity lb.	Swath width ft.	Flying height ft.	Runway length ft.	Rail to airstrip miles	Distance between air-strip and project area miles	Age of stand yr.	Site index of stand ft.	Acres of fertilized area acres	Average total cost/ acre
1967	Stearman	1,400	70	50-100	1,300	14	2-8	20-40	110-150	3,176	$13.50

Rate of application is approximately 100 lb. of N/acre.

Fertilizer is urea (45% of N).

INSECT AND DISEASE

The most effective way to combat insect and disease attack is to maintain healthy, vigorous stand growth. According to Armson (1966), fertilization in increasing growth rate may reduce the rotation age, thereby minimizing the spread of insect and disease attack. However, according to Mustanoja and Leaf (1965), abundance of a certain nutrient may cause a particular tree species to become susceptible to a particular insect or disease. For instance, Aphis populations on conifers generally increase with application of mineral fertilizers and lime to the stand. The following is a compilation of findings from 13 research studies on the inter-relationship between fertilization and insect attack as well as disease.

(1) Insect

(a) Resistance to insect attack

Species	Description	Source
Scots pine	Pristiphora abietina Christ. larvae population depend on the sugar-protein ratio of the needles for their nutrition. Anything that decreases this ratio -- water or mineral fertilizers, especially N, Ca, and P increases larval mortality.	Buss, 1960 (from Mustanoja and Leaf, 1965)
Pinus elliottii	It was found that 46 to 56% less infestation by European pine shoot moth (Rhyacionia buoliana) in plots which have been fertilized (3 years before) with the combination of N, P, K, Mg, B and S as compared to control plots.	Schindler and Baule, (1964)
Abies amabilis	In the greenhouse, foliar sprays of 1% ammonium nitrate solution resulted in a 23% decrease in balsam woolly aphid (Adelges piceae) population in 10 weeks, as contrasted with a 31% increase in control population. In the field, larval establishment was 31 to 37% lower on the treated trees than on the control trees.	Carrow (1968)

(1) Insect (Cont'd)

(b) Susceptible to insect attack

Species	Description	Source
Slash pine (*Pinus elliottii*)	*Diorychria amatella* attacks especially the largest and fastest growing young slash pine and the fertilized (Phosphorus and other mineral fertilizers) trees are therefore especially susceptible.	Hughes and Jackson (1962)

(2) Disease

(a) Resistant to disease

Species	Description	Source
Shortleaf and loblolly pine	The littleleaf disease of *Pinus taeda* L. and *Pinus echinata* Mill has been successfully controlled at its early stages by N fertilization.	Campbell and Copeland, 1954 (from Mustanoja and Leaf 1965)
Slash pine (*Pinus caribaea*)	Increases tree growth without increasing incidence of disease by adding fertilizers to a stand where *Gossypium sp*. is grown between the rows of trees.	Gilmore and Livingstone, 1958
Sitka spruce	Fungi attacked tips of needles in *Picea sitchensis* "burned" as a result of Cu deficiency; the tip-burn is prevented by addition of Cu in various forms.	Benzian and Warren, 1956 (from Mustanoja and Leaf 1965)

(b) Susceptible to disease

Species	Description	Source
Southern pine	*Fusarium* spp. can become primary parasites at high levels of available soil nitrogen, while they usually are secondary and follow attacks of *Pythium* and *Rhizoctonia* spp.	Foster 1959 (from Mustanoja and Leaf 1965)
Pine	Greatly increased incidence of fusiform rust infestation as a result of fertilization.	Maki (1966)

(2) Disease (Cont'd)

(b) Susceptible to disease

Species	Description	Source
Pine and spruce	Excessive liming has occasionally caused soil pH value to rise to the range where damping-off causes large seedling mortality.	Voigt *et al.*, 1958 (from Mustanoja and Leaf, 1965)
Scots pine and Norway spruce	Sometimes NH_3 gas causes soil pH value to rise to the range where damping-off causes large seedling mortality immediately after application.	Duchaufour and Turpin, 1960 (from Mustanoja and Leaf, 1965)
Norway spruce	Checked trials on *Fomes annosus* established in a Norway spruce plantation show that cultivation, liming, and addition of mineral fertilizers increases the number of trees attacked.	Paludan and Rafn 1958 (from Mustanoja and Leaf, 1965)
Norway spruce	Susceptibility of Norway spruce is greater on good than on poor soils, hence increasing this susceptibility on poor soils by fertilizing may result in an attack by fungus.	Holsterner-Jongensen 1958 (from Mustanoja and Leaf, 1965)

WOOD QUALITY

It is generally thought that increased wood growth following fertilization results in a change of wood property. Several research workers (Erickson and Lambert, 1958; Williams and Hamilton, 1961; Zobel *et al.*, 1961) arrived at the same conclusion that specific gravity and wood density decrease as a result of fertilization treatment. However, Rendle and Phillips (1958) indicated that this decrease may hold true only at the early stages of tree development.

Due to different rates of growth, wood produced on good sites differs in specific gravity and wood density from those produced on poor sites. Wilde *et al.* (1951) found that the weight of a cord of jack pine (*Pinus banksiana*) wood produced in fertile soil was higher than that produced on poor sites, in spite of the general tendency of lower specific gravity for fast-grown trees. The difference at times amounted to about 3%. They also reported that the relationship between wood quality and site became even more obvious when the content of alpha-cellulose was taken into account. In some cases, the yield of alpha-cellulose per cord in wood from good sites was 8% greater than that from poor sites.

Erickson and Lambert (1958) studied the effect of fertilization and thinning on wood produced over a 4-year growth period, on a 30-year-old Douglas fir stand growing on a good site. They found that the percentage of summer wood decreased significantly after thinning and fertilizing. Decreases in specific gravity as a result of fertilization treatment were especially obvious in the case of thinning and fertilizing.

In an investigation into the effects of nitrogen fertilization upon wood properties of loblolly pine in North Carolina, Posey (1964) found that nitrogen fertilizer stimulated volume growth, but the wood produced after fertilization was lower in specific gravity, with thinner cell walls and shorter tracheids.

Large areas have been fertilized in Sweden, and intensive investigations into the properties of post-fertilization wood have been conducted. (One company, Swedish Cellulose alone, has fertilized since 1960, over 375,000 acres, using 37,000 metric tons of fertilizer.) Hagner (1967) reported these investigations (also added findings from sources outside Sweden). His report is summarized below:

(1) Annual ring width: correlated with wood density, a factor strongly influencing pulp yield.

(2) Paper produced:
- (a) a higher tensile strength
- (b) a higher burst factor
- (c) a lower tear factor
- (d) a denser and less bulky paper

(3) Density of earlywood:
- (a) for Scots pine, decrease in density varies between 4% to 6%
- (b) for Norway spruce, decrease in density is approximately 6%
- (c) for loblolly pine and slash pine, decrease in density varies from 5% to 10%
- (d) for Douglas fir, density decrease is about 8%

(4) Relative dry matter: When dry matter value in percentage is plotted against growth response in percentage by change in basic density of wood in percentage, the relative dry matter value of the additional growth volume amounts to 90% (assuming growth response of 100% and change in basic wood density of -5%). This means that in the additional volume for the production of fiber, only 10% of it is wasted in the pulp mill.

Comment

It is obvious that there is loss in specific gravity, loss in wood density and shorter tracheids as a result of fertilization, but it appears that these can be compensated by gain in additional growth.

ECONOMIC CONSIDERATIONS

Comprehensive research in the economics of fertilization has not been reported. The cost involved in the treatment, including material and operation cost, was reported by Green and Bentley (1954), Conway (1962), Swan (1965), Maki (1966), Hagner et al. (1966) and Hagner (1967). However, the cost values cited by them do not apply to British Columbia conditions, due to differences in cost of material, labour and other factors. Clark (1968) reported a cost per acre (at a rate of 200 pounds of nitrogen per acre for 1500 to 2600 acres) ranging from $23 to $30 for the Pacific Northwest, United States. MacRae (1968) estimated an average cost of $13.50 per acre (at a rate of 100 pounds of nitrogen per acre for 3000 acres) for his forest fertilization on Vancouver Island. With improvement in application procedures gained from experience, and reduction in manufacturing costs of fertilizers, expenses of forest fertilization will probably decrease.

Comment

In an analysis of the value of increased volume growth due to fertilization for British Columbia, a comprehensive wood and product value yield table resulting from fertilization can serve as the basis for the evaluation of overall operation. Such an analysis should also take into account the number of years gained by shortening the rotation age, as well as the reduced harvesting cost due to the uniformity of tree size in the stand (assuming tree harvester is used).

DISCUSSION AND CONCLUSIONS

An analysis of the research findings shows that the following should be considered:

(1) A forest soil inventory similar to that by Day et al. (1959) is urgently required for British Columbia forest fertilization program.

(2) Diagnostic problem for commercial fertilization should be based on management and mensurational information (Hagner's article on fertilization model, 1967, page 18-21) instead of on soil or foliar analysis. (In foliar analysis, the problems of variation in nutrient content within the crown and from season to season have not yet been solved. Soil analysis from small samples yields similar variations.)

(3) Evidence is predominatly against fertilizing immediately after planting. Benefit may be gained from fertilization after the seedling is established.

(4) Thinning prior to fertilization appears to concentrate fertilizer effect on selected trees, enabling them to reach a desired size in a shorter rotation. More research is required in this area.

(5) The dominant effect of nitrogen in tree growth appears to be outstanding in most cases.

(6) A rate between 200 to 300 pounds of nitrogen per acre appears to be the best, both from biological and economic stand-point. Further research is required.

(7) Duration of response is not clearly known. It appears to be related to tree species, to the initial forest land conditions and to the amount of fertilizers used. The maximum response is generally at the fifth year after application.

(8) Flowering, cone and seed production are affected by fertilization, hence these aspects should be taken into consideration in evaluating growth response.

(9) The different effect between a fall and spring fertilizer application is not clearly known. Research is required. The micro-climatic information should also be taken into account.

(10) Studied areas are to be inspected periodically by a pathologist and entomologist so as to minimize insect and disease attacks on tree growth.

(11) The effect of fertilization on wood quality should be thoroughly analyzed to provide basic information for economic analysis.

(12) Research programs should be planned to provide adequate information for the construction of a wood and product value yield table for industrial management purposes.

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