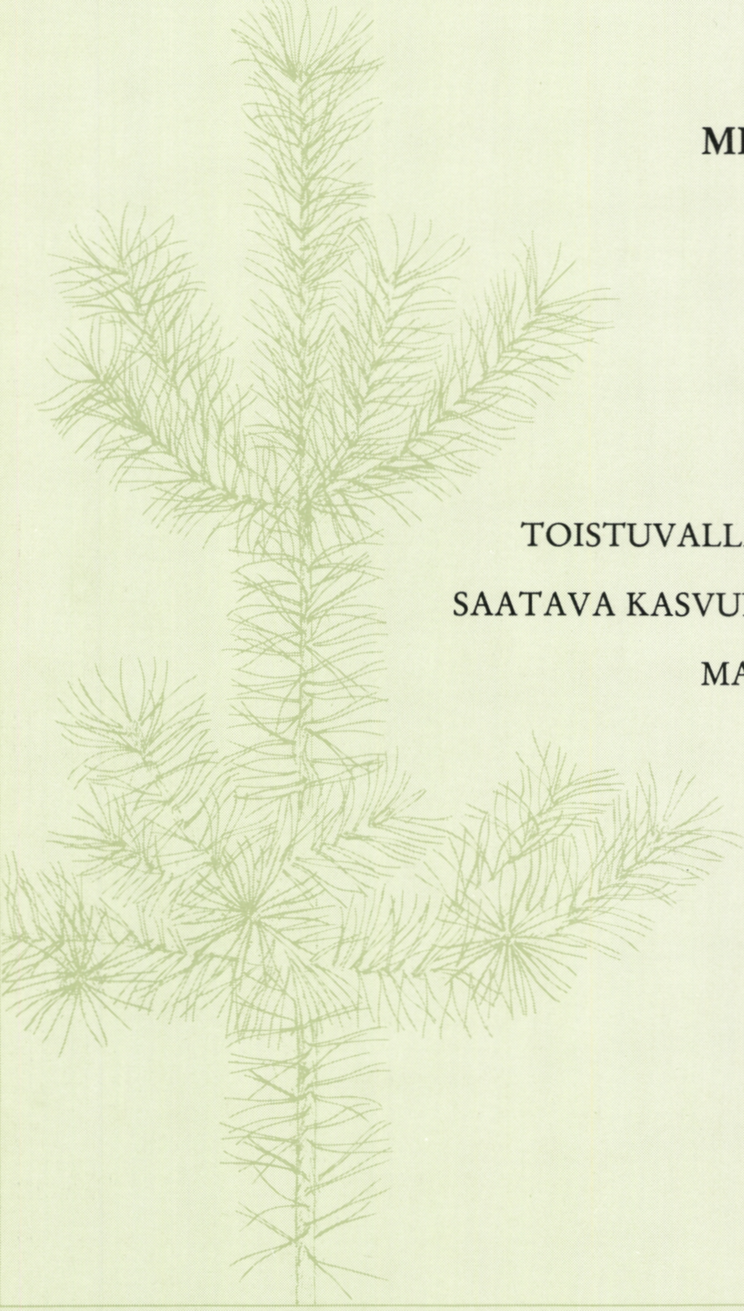
COMMUNICATIONES INSTITUTI FORESTALIS FENNIAE 114

GROWTH RESPONSE IN REPEATEDLY FERTILIZED PINE AND SPRUCE STANDS ON MINERAL SOILS

MIKKO KUKKOLA &
JUSSI SARAMÄKI



SELOSTE

TOISTUVALLA LANNOITUKSELLA SAATAVA KASVUNLISÄYS KIVENNÄISMAIDEN MÄNNIKÖISSÄ JA KUUSIKOISSA

HELSINKI 1983

COMMUNICATIONES INSTITUTI FORESTALIS FENNIAE

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Cover (front & back): Scots pine *(Pinus sylvestris* L.) is the most important tree species in Finland. Pine dominated forest covers about 60 per cent of forest land and its total volume is nearly 700 mill. cu.m. The front cover shows a young Scots pine and the back cover a 30-metre-high, 140-year-old tree.

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The material for southern Finland comprised 145 plots fertilized with nitrogen and 141 control plots in pine stands, and 44 plots fertilized with nitrogen and 46 control plots in spruce stands. The corresponding figures in northern Finland were 32 and 36 for pine stands and 17 and 17 for spruce stands. The development of the experiments was followed over a period ranging from 9 to 19 years. The interval between nitrogen fertilizations varied from 1 to 10 years and the average number of applications was three. Ammonium sulphate, urea and ammonium nitrate with lime were used as the nitrogen fertilizers.

A model describing the annual response was devised separately for the pine and spruce stands comprising the southern material. The independent variables were the time elapsed since fertilization, fertilizer dose and type as well as various stand variables. A predicted value for the response in repeatedly fertilized stands is obtained in such a way that the response caused by each successive fertilization is predicted for the growing season in question. The predictions are then summed. The response brought on by each individual fertilization is also affected by previous fertilizations, which are taken into account by means of the time elapsed since the fertilizations and the amounts of nitrogen applied.

The response to urea was found to be weaker than that to the other types of nitrogen fertilizer. This was partly due to the fact that spring is an unfavourable time to spread urea. Phosphorus fertilization did not improve the growth of the pine stands, but in the spruce stands it clearly increased growth when applied together with nitrogen. In southern Finland the average response given by N fertilization was 1,4 m^3/ha/a in the pine stands, 1,3 m^3/ha/a in the spruce stands, and that given by NP fertilization 1,7 m^3/ha/a in the spruce stands. In northern Finland the average response in the pine stands was 63 % and in the spruce stands 69 % of the values predicted by the model devised for southern Finland.

The best result was obtained on sites which, as regards the site requirements of the tree species, were average in the case of pine and rather infertile in the case of spruce. The greatest response was obtained in young stands, the response slowly declining as the stand aged.

Taking the different factors into account, the recommended interval between fertilizations is 4—8 years and the size of a single fertilizer dose 100—150 kg N/ha in southern Finland. If the aim is to obtain the greatest response within these limits, then the shortest interval and the highest single fertilizer dose should be used. If the aim is to obtain the greatest response per kilogram of nitrogen, then the interval should be as long as possible and the size of the individual application small.

The response model programme (FORTRAN) is available from the authors.

Tutkimusaineistona oli Etelä-Suomen männiköissä 145 typpilannoitettua ja 141 vertailukoealaa sekä kuusikoissa 44 typpilannoitettua ja 46 vertailukoealaa. Pohjois-Suomessa vastaavat luvut olivat männiköissä 32 ja 36 sekä kuusikoissa 17 ja 17. Kokeiden kehitystä seurattiin 9—19 vuotta. Typpilannoitusväli vaihteli 1—10 vuotta ja lannoituskertoja oli keskimäärin kolme. Typpilannoitelajeina oli käytetty ammoniumsulfaattia, ureaa ja oulunsalpietaria.

Etelä-Suomen koeaineistolla laadittiin vuosittaista kasvunlisäystä kuvaava malli erikseen männikölle ja kuusikolle. Selittävinä muuttujina olivat lannoituksesta kulunut aika, lannoitemäärä ja -laji sekä puustomuuttujia. Mallilla saadaan kasvunlisäysennuste toistuvasti lannoitetussa metsikössä siten, että ennustetaan kunkin lannoituksen aiheuttama kasvureaktio kyseisenä kasvukautena ja summataan ennusteet. Kunkin lannoituksen aiheuttamaan reaktioon vaikuttavat myös edelliset lannoitukset, jotka otetaan menetelmässä huomioon niistä kuluneen ajan ja niiden typpimäärän avulla.

Urealla saatiin heikompi kasvunlisäys kuin muilla typpilannoitelajeilla, mikä aiheutui osaltaan urealle epäedullisesta kevätlevityksestä. Fosforilannoitus ei parantanut männiköiden kasvua, mutta kuusikoissa yhdessä typen kanssa annettuna se lisäsi selvästi kasvua. Aineiston keskimääräinen kasvunlisäys N-lannoituksella oli Etelä-Suomen männiköissä 1,4 m^3/ha/a ja kuusikoissa 1,3 m^3/ha/a sekä NP-lannoituksella kuusikoissa 1,7 m^3/ha/a. Pohjois-Suomen männiköissä kasvunlisäys oli 63 % ja kuusikoissa 69 % ennusteesta, joka niille oli laskettu Etelä-Suomelle laaditulla kasvunlisäysmallilla.

Paras tulos saatiin kasvupaikoilla, jotka puulajien kasvupaikkavaatimukset huomioon ottaen ovat männylle keskinkertaisia ja kuuselle karuhkoja. Kasvunlisäys oli suurimmillaan nuorissa metsiköissä ja heikkeni hitaasti metsikön ikääntyessä.

Eri tekijät huomioon ottaen lannoitusväliksi suositellaan 4—8 vuotta ja kerta-annokseksi 100—150 kg N/ha Etelä-Suomessa. Kun näissä rajoissa halutaan suurin määrällinen kasvunlisäys, käytetään tiheintä toistamisväliä ja suurinta kerta-annosta. Jos tavoitteena on suurin kasvunlisäys typpikiloa kohti, on toistamisväli mahdollisimman pitkä ja annos pieni.

Kasvunlisäysmalli on ohjelmoitu (FORTRAN) ja ohjelma on saatavissa tekijöiltä.

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CONTENTS

SYMBOLS — *MERKINNÄT*

T age, years (a)
ikä, vuotta (a)

D_w mean diameter at breast height incl. bark, weighted with basal area, cm
pohjapinta-alalla painotettu keskiläpimitta rinnan tasalla kuorineen, cm

H_{dom} dominant height, average height of 100 thickest trees per hectare, m
valtapituus, hehtaaria kohti 100 paksuimman puun keskipituus, m

H_{100} site index, dominant height at an age of 100 years, m
pituusboniteetti, valtapituus 100 vuoden iällä, m

V stem volume incl. bark, m^3/ha
kuorellinen tilavuus, m^3/ha

I_v annual volume increment incl. bark, $m^3/ha/a$
vuotuinen kuorellinen tilavuuskasvu, $m^3/ha/a$

ΔI_v annual growth response to fertilization, $m^3/ha/a$
lannoituksen aiheuttama vuotuinen kasvureaktio, $m^3/ha/a$

IND radial growth index, the normal level = 100
lustoindeksi, normaalivuoden sädekasvun taso = *100*

Fertilizers — *Lannoitelajit*

As ammonium sulphate (20,5 % N)
ammoniumsulfaatti

U urea (46 % N)

Os ammonium nitrate with lime (25—27,5 % N)
oulunsalpietari

NPK N, P and K combined
Y-lannoite

PREFACE

The fertilization of mineral soil stands has been an object of systematic research at the Finnish Forest Research Institute for over 20 years. During this period, special emphasis has been put on elucidating the biological principles involved in forest fertilization. In 1977, following the expansion of the field experiments and the gradual accumulation of research material, the time was considered ripe to instigate a research project with the aim of carrying out a production study on the growth response obtained through successive fertilizer applications and a separate study on the profitability of repeated fertilization from the point of view of wood production.

The research workers responsible for the production part of the project are Mr. Mikko Kukkola and Mr. Jussi Saramäki. Profs. Jouko Hämäläinen, Eino Mälkönen and Yrjö Vuokila have been members of the coordination group of the project.

Starting from the design of the fertilization experiments devised by Prof. P. J. Viro, and the monitoring of the field experiments carried out under his leadership, a large number of persons have assisted in the collection and handling of the material used in this study. The persons primarily involved during the field work stage have been Mr. Väinö Harjuaho, Mr. Reijo Jokinen, Mr. Teuvo Levula and Mr. Arto Ursin. Mrs. Marja Huotari has been in charge of the material. Mr. Erkki Lipas, Mr. Pertti Hari and Mr. Jaakko Heinonen have given valuable advice during the data handling stage and the examination of the results and have also read the manuscript, as have Mr. John Derome and Mr. Timo Pekkonen. The Finnish manuscript has been translated into English by Mrs. Leena Kaunisto. The figures were drawn and the manuscript typed by Miss Irene Isokangas, Mrs. Marja-Liisa Herno and Mrs. Anja Sanaslahti.

Most of the work carried out by the researchers during the material handling stage has gone into the development of new methods, as the earlier applied models were not suitable for this study. Now that the research report is ready, there is reason to thank the researchers for the excellent work which they have done. Mikko Kukkola has been responsible for writing Chapters 3—5 of the manuscript and Jussi Saramäki for the rest.

Our sincere thanks to all those who have assisted in getting this study ready.

Helsinki, November 1982

Eino Mälkönen *Yrjö Vuokila*

1. INTRODUCTION

The growth response brought on by fertilization is affected by the site, the developmental stage and structure of the stand, tree species, climate, weather conditions, fertilizer type and dose, etc. However, variation in growth response can only partly be explained by these factors (Brantseg et al. 1970, Braastad et al. 1974, Gustavsen and Lipas 1975).

The effect of site fertility on the response to fertilization is obvious. According to Gustavsen and Lipas (1975), the magnitude of the response increases as the site becomes more fertile. Gustavsen and Lipas warn against making far-reaching conclusions from the results dealing with the site index, as in their material there is a solid mutual correlation between the site index and the age of the stand. Rosvall's (1980) results give a contrary dependence. When making the comparison, Rosvall kept the stand factors constant, which tends to falsify the results. If stands at the same developmental stage are compared using Rosvall's model, the response increases with the improvement in the site index.

It is obvious that the response to nitrogen fertilization increases along with the fertility of the site up to a certain point, and then starts to decrease as fertility improves further. At this point, either nutrients other than nitrogen or else growth factors apart from nutrients begin to limit growth (see Malm et al. 1974).

The developmental stage of the stand influences the magnitude of the response to fertilization. Very young stands cannot fully utilize the applied nutrients, hence the response remains quite small (Viro 1966). The growth of the stand at fertilization is generally regarded to correlate best with the response to fertilization (Viro 1967, Möller 1972, Keltikangas and Seppälä 1973). The stand requires the greatest amounts of nutrients during its most intensive stage of growth, i.e. at the age of 30—50 years (Mälkönen 1974). At this stage, fertilization will produce the greatest response (Gustavsen and Lipas 1975, Rosvall 1980, Kreutzer 1981). As the stand ages the capacity and need to use nutrients decreases, it thus being impossible to obtain as good results through fertilization as in a younger stand. However, the response in a mature stand may be of great economic value (e.g. Haveraaen 1981).

The stand volume has not usually been found to correlate very well with the response to fertilization in mature stands (Brantseg et al. 1970, Möller 1972, Gustavsen and Lipas 1975). On the other hand, Viro (1967) successfully used the mean height and volume to explain the response in young stands. Similarly, Keltikangas and Seppälä (1973) employed volume to predict the response. The reason for the discrepancy in the results may be that the correlation between needle area and volume is clearer in the early developmental stages of stands than in mature stands, since volume increases with age, but maximum needle biomass is reached when the stand is still young and it either remains at that level or decreases (Switzer et al. 1968, Albrektsson 1980).

Mälkönen (1977) concluded that logging waste left after thinning is an important source of nutrients and is partly responsible for the positive response of trees to thinning. However, nutrients become released from logging waste only in the course of time, whereas the nutrients given as fertilizer are immediately available to trees. Consequently, fertilization and thinning should be carried out simultaneously (Brix 1971, Haapanen et al. 1979, Möller and Pettersson 1980). On the other hand, both thinning and fertilization make trees more vulnerable to wind damage (Laiho 1980), and their simultaneous effect even enhances the risk of damage.

The total growth response brought on by nitrogen fertilization is roughly of the same order of magnitude in pine as in spruce stands (Brantseg et al. 1970, Mälkönen 1979, Rosvall 1980), although the timing of the response is different. The initial effect of fertilization on growth is greater in pine than in spruce stands, but the duration of the effect is longer in spruce stands (e.g. Möller and Rytterstedt 1975, Puro 1977, Rosvall 1979). This is due to differences in the length of the needle rotation period in these two species. As the needle rotation period in spruce is twice as long as in pine, the increased needle biomass brought about by fertilization is available to the trees for a longer time and prolongs the effect of fertilization (e.g. Westman 1975). If the response during the first five year period is marked with 100, the overall response is 150 in a pine stand and 170 in a spruce stand (Rosvall 1979). The corresponding figures, according to Pettersson (1980), are 115—125 for pine stands in southern Sweden and 135—145 in Norrland (northern Sweden). The figures for spruce stands are 140—150 in southern Sweden and 160—170 in Norrland.

The growth response is affected by the growing conditions, which vary according to the geographical location. The response decreases to some extent towards the north according to the still unpublished results of Laakkonen et al. According to Pettersson (1980), the response increases slightly towards northern Sweden. The conflict between Finnish and Swedish results may be partly due to the fact that the material of Laakkonen et al. extends north of the Arctic Circle, while that in Pettersson's investigation is concentrated more to the south. Pettersson (1980) points out that the response is also affected by the elevation above sea level. In southern Sweden the response did not depend on the elevation below a height of 150 m a.s.l., but above this level it increased strongly. The corresponding elevation in northern Sweden is 250 m a.s.l. (see also Eriksson and Jansson 1981). According to Rosvall (1980), the optimum elevation is 200—300 m.

A number of experiments have been carried out to find the most suitable type of nitrogen fertilizer (Viro 1966, 1972, Brantseg et al. 1970, Gustavsen and Lipas 1975, Malm and Möller 1975, Lipas and Levula 1980, Päivinen and Salonen 1981). Urea has usually resulted in a smaller growth response than NPK fertilizer, ammonium nitrate with lime or ammonium sulphate (Gustavsen and Lipas 1975, Malm and Möller 1975). No differences have been found between the effects of ammonium nitrate with lime and ammonium sulphate (Mälkönen 1979). Urea has been found to be easily affected by the weather conditions prevailing at the fertilization time (Overrein 1970, Gustavsen and Lipas 1975, Levula 1976, Nömmik 1976, Derome 1979, Lipas and Levula 1980).

The fertilizer dose clearly influences the magnitude of the growth response. Brantseg (1967) pointed out that the response was almost directly proportional to the nitrogen dose applied. Gustavsen and Lipas (1975) reported a linear dependence when the nitrogen dose varied between 72—180 kg/ha. According to Swedish results (Friberg 1971), the dependence is linear over the range 120—240 kg N/ha. Subsequently, the response in relation to the nitrogen dose diminishes, but the absolute response increases up to 600 kg N/ha (Erken 1970, Friberg 1971, 1973, Ericson et al. 1972, Jonsson 1978). In northern Finland, nitrogen doses of 150 kg/ha are enough to cause frost damage under unfavourable conditions (Norokorpi 1977).

Many different views have been expressed about the best time for refertilization, but owing to the fact that such experiments are still in their infancy very few concrete facts are available. Karsisto (1972) suggested that a suitable refertilization time would be the year when the effect of the previous fertilization has culminated. This suggestion is based on the idea that the assimilation machinery of trees, i.e. the foliage, has become enlarged and so the trees are immediately able to utilize the applied nutrients. On the other hand, at the culmination point of the response more nutrients are available to the tree stand than at primary fertilization, and there is no such shortage of the applied nutrients as at primary fertilization. Consequently, the response to refertilization is weaker than that to the primary one. Viro (1972) recommended that fertilization be repeated 6—8 years after the previous fertilization (see also Brantseg 1967), at the time when the effect of the previous fertilization has practically stopped. Päivinen and Salonen (1978) concluded on the basis of their material that refertilization five years after the primary fertilization would have given the best result. In the long run, the intensity of fertilization — i.e. the size of the individual doses and the interval between fertilizer applications — is an economic question and the alternative which provides the greatest yield is not necessarily the most profitable one.

Growth does not explain the response after refertilization as well as at primary fertilization (Lipas 1979). Puro (1977) pointed out that the response to the second fertilization was the stronger, the greater the response given by the first fertilization. Eriksson and Jansson (1981) used either the predicted or measured response to primary fertilization as an independent variable in their model depicting the response obtainable through repeated fertilization. When nitrogen fertilization is repeated more than once, the nutrient status of the soil changes. Part of the fertilizer nitrogen is bound in the humus and increases its nitrogen reserves (e.g. Nömmik and Möller 1981). The increased growth of the trees promotes the binding of nutrients, which may lead to a deficiency of other macronutrients (Viro 1967) or micronutrients (Veijalainen 1977).

Forest fertilization has been carried out on a practical scale for so long in Finland that some forests have already been fertilized twice, some even more. Unfertilized stands and those already fertilized earlier should be arranged in order of their potential value as fertilization objects.

The purpose of this investigation is to determine which factors contribute to the growth response obtained by repeated fertilization. The main methodical goal is to develop a model which can be used for analyzing experimental material treated with diverse fertilization regimes and which makes the results easily adaptable to practical forestry.

2. MATERIAL AND MEASUREMENTS

21. General features

The Department of Soil Science of the Finnish Forest Research Institute established the experiments in 1955—65. The aim was to investigate the effect of N, P, K and Ca application on the growth of tree stands. Most of the experiments were arranged using a factorial design (Fig. 1, see Lipas 1981 a). The majority of the factorial experiments consisted of 8 sample plots representing combinations of three nutrients: in southern Finland N, P and Ca and in northern Finland N, P and K. Experiments with four nutrients (N, P, K and Ca) had 16 or 17 plots, the latter containing two unfertilized plots. All the nutrients investigated had been applied in the primary fertilization. Since then, only nitrogen fertilization had been repeated except for a few cases where phosphorus was given, too (see App. 1).

As lime is not used in practical forest fertilization, it was omitted from this investigation. According to the preliminary investigation, the growth in limed pine stands did not differ considerably from that of unlimed ones. Liming had, however, decreased the growth of spruce stands so much that the limed spruce plots were excluded from the investigation. They will be dealt with in a separate investigation on the effect of liming. As there was no response to either phosphorus or potassium, these plots were combined with the control plots (for details see Chapter 4).

The stands to be included in the material had to fulfil the following conditions:

— dominant height at least 4 m at the time of establishment,
— age at least 20 years at the time of establishment,
— dominant tree species pine or spruce,
— pine growing on a dry, dryish or moist site,
— spruce growing on a moist or herb site,
— at least two nitrogen applications.

Plots where the data from successive measurements deviated too much from one another for unexplainable reasons were excluded from the material at the calculation stage. The final material contained 63 experiments distributed throughout Finland as shown in Fig. 2.

The mean length of the period studied was 13 years, varying from 9 to 19 years. The material was from years 1955—77. During this period the weather, from the point of view of the growth of pine, was at first worse

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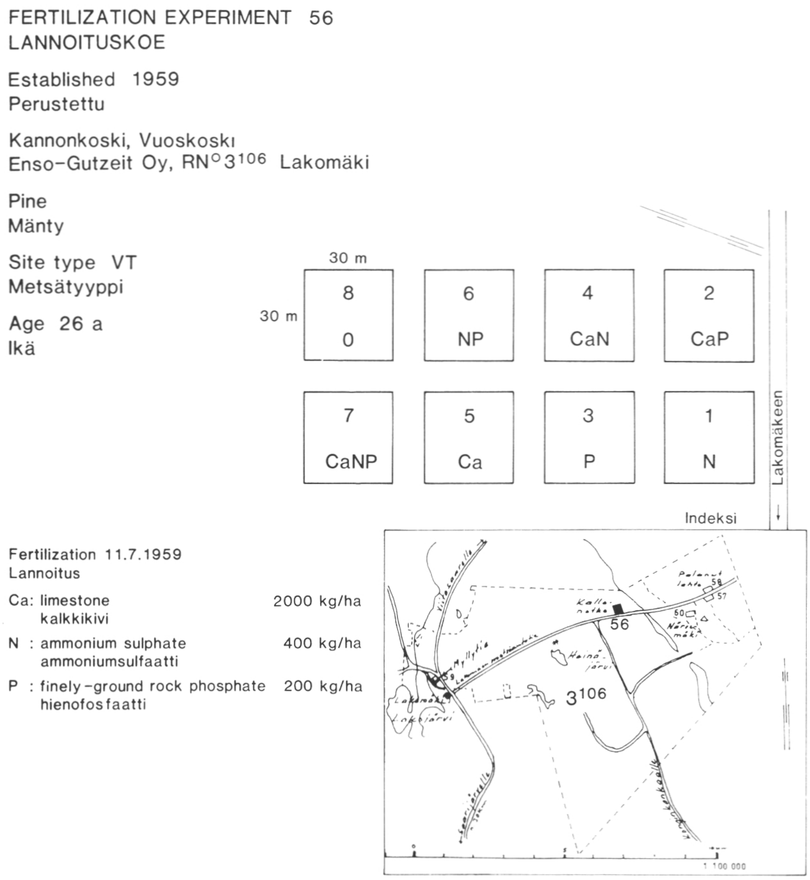


Fig. 1. Example of the layout of the factorial fertilization experiments.
Kuva 1. Esimerkki faktoriaalisen lannoituskokeen koejärjestelystä.

than the average, but at the end of the period the long-term means were surpassed (Tiihonen 1979). In northern Finland the growth of pine was the worst during the first few years of the 1960s. The radial growth index for spruce in southern Finland was, throughout the period under study, below the average level and in northern Finland above the average for almost the entire period.

The material was divided into 2 parts (northern and southern Finland), the limit being the temperature sum of 1000 dd. The largest part-material was that for pine in southern Finland. The mean ages of the different part-materials at the time of establishment were:

— pine, southern Finland, 50 years
— pine, northern Finland, 54 years
— spruce, southern Finland, 47 years
— spruce, northern Finland, 96 years

Table 1 gives information about the stands at the time of establishment. There were no considerable differences between the tree stands on the unfertilized plots and those fertilized with nitrogen when the experiments were set up. However, the growth on the unfertilized plots was slightly better than on the fertilized ones. It should be borne in mind when studying the results, that the youngest stands were growing on more fertile sites than the oldest ones. In spite of restrictions put on the site, the material covers almost the whole distribution of site index.

Table 2 presents the distribution of plots into age and volume classes at the time of establishment. The southern part-material dealing with pine represents well the age and volume range normally considered suitable for practical fertilization. In fact, the results dealing with this part-material can be considered to be the most representative in the investigation. The pine material from northern Finland contains no middle-aged stands and the volume of the standing crop is low from the point of view of fertilization. As a whole the spruce material is smaller than the pine material. The material of southern Finland forms two separate parts, young stands and mature stands. The middle-aged stands are poorly represented. The northern spruce material is narrow and one-sided.

22. Thinnings

An attempt had been made to eliminate the effect of thinning, if possible, as it interferes with the investigation of the effect of fertilization. However, as it is

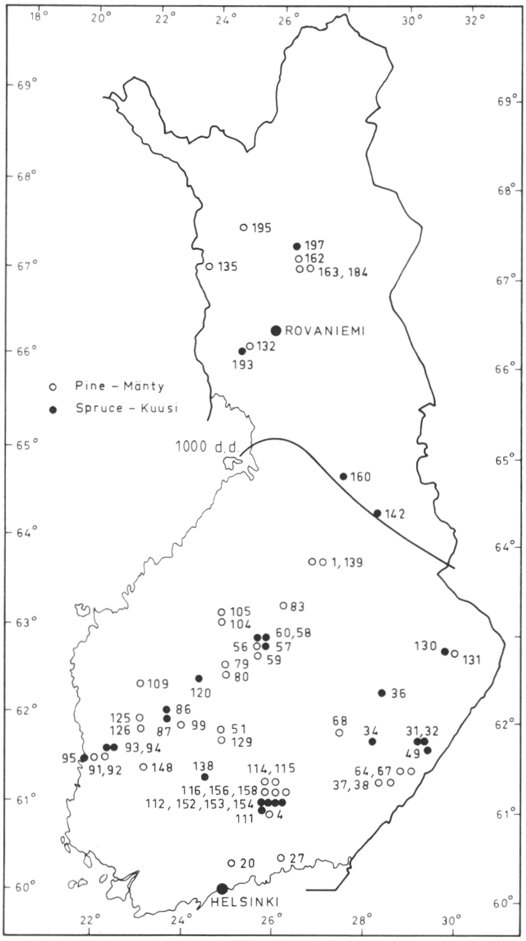


Fig. 2. Location of the experiments. The material was divided into southern and northern part-materials according to the temperature sum curve shown in the figure.

Kuva 2. Kokeiden sijainti. Aineisto on jaettu Etelä- ja Pohjois-Suomen osa-aineistoihin kuvan lämpösummakäyrän perusteella.

impossible to avoid thinnings in permanent experiments, they were carried out carefully with the emphasis on low thinning.

An experimental stand was considered to have been thinned if the average removal of the plots was over 10 % of the basal area. Pine experiments treated in this way numbered 11, two of which had been subjected to thinnings twice during the period under study. Thinned spruce experiments numbered 5, one of which had been thinned twice. Dead or dying trees, and those damaged in various ways, had been removed from several other experiments.

Thinning had been carried out according to the principle that the same percentage of basal area would be removed from all the plots in the same experiment. When the groups of plots fertilized with nitrogen are compared with the unfertilized ones (see Table 3), it is apparent that this was largely succesful. The thinning yield was very small in some pine experiments and the treatments more moderate on average than in the spruce experiments. The pine experiments included both first thinnings and the type of thinnings carried out in maturer forests. The spruce experiments had been subjected to first thinnings. The thinning yield increased as the trees grew in size. A slightly higher yield was regularly obtained from pine plots fertilized with nitrogen than from the unfertilized ones. The opposite situation prevailed with the spruce experiments (Table 3).

23. Fertilizations

At the time the experiments were set up, ammonium sulphate was used as a nitrogen fertilizer in agriculture in Finland. It was naturally also used for the forest fertilization experiments. The idea that urea would be suited for forest fertilization spread in the 1960s (e.g. Viro 1968). This led to a change over to urea in the experiments. The discouraging results obtained with urea fertilization in the late 1960s and early 1970s (e.g. Viro 1972, Malm and Möller 1975) resulted in a new nitrogen fertilizer, ammonium nitrate with lime, being introduced in forest fertilization. The change in opinion about fertilization is clearly apparent in Table 4 which illustrates different successive fertilizations. Most of this material concerns urea applications. According to earlier results concerning different nitrogen fertilizers (e.g. Mälkönen 1979), the fertilizations were divided into urea fertilizations and As/Os fertilizations (ammonium sulphate/ammonium nitrate with lime) for the analysis of the material.

During the course of the period under study, fertilizers were applied in many cases more frequently at the beginning than at the end. After the first few years, however, an attempt was made to maintain the interval between fertilizations in each experiment constant. Information about the fertilization regime for each experiment can be seen in App. 1.

The nitrogen doses used in the first fertilizations were low, below 100 kg/ha. However, the doses were increased later on after it became apparent that low doses of nitrogen do not produce economically profitable results. A nitrogen dose of 150 kg/ha was used in the most recent fertilizations. However, the resulting response was still continuing at the time when the investigated period ended. As the average amount of nitrogen applied during the investigated period was about 300 kg/ha and there were, on the average, three fertilizer applications, the material can be considered to represent a lighter level of fertilization than is presently recommended. The average length of the investigated period, 13 years, is quite short for the follow-up of repeated fertilization, although it covers 2—5 applications.

The first nitrogen applications were carried out between early and mid-summer. The refertilizations took place between spring and early summer. If fertilization was carried out in July or later, it was considered to come within the same group as fertilizations carried out at the start of the following growing season. The reason for this is that fertilization presumably did not have time to affect, to any considerable degree,

Table 1. Means of stand characteristics at the time the experiments were established. Standard deviations of the characteristics are given in parentheses.
Taulukko 1. Puustotunnusten keskiarvoja kokeiden perustamisajankohtana. Suluissa puustotunnusten keskihajonnat.

Tree species and region *Puulaji ja alue*	Characteristic *Tunnus*	Age class — *Ikäluokka* 20—39		40—59		60—79		80—99		≥ 100		Total — *Kaikki*	
		Fertilization — *Lannoitus* 0	N	0	N	0	N	0	N	0	N	0	N
		Mean and standard deviation — *Keskiarvo ja hajonta*											
Pine South Finland	H_{100}	23,8 (2,9)	23,6 (3,0)	25,4 (3,5)	25,4 (4,3)	21,9 (3,8)	21,8 (3,3)	20,6 (1,8)	19,8 (1,6)	17,3 (1,6)	17,4 (1,8)	22,9 (3,8)	22,7 (3,9)
Mänty *Etelä-Suomi*	Stem number (no/ha) *Runkoluku*	1797 (624)	1768 (582)	856 (380)	855 (379)	721 (216)	711 (245)	424 (149)	375 (98)	350 (102)	332 (95)	1171 (743)	1160 (726)
	D_w	9,1 (2,7)	8,9 (2,7)	17,3 (4,1)	17,1 (4,7)	18,2 (4,2)	18,0 (3,6)	22,7 (2,3)	23,0 (2,8)	22,9 (3,0)	22,6 (3,0)	14,7 (6,3)	14,4 (6,4)
	H_{dom}	8,8 (2,5)	8,6 (2,4)	15,8 (3,3)	15,8 (3,9)	17,5 (3,7)	17,3 (3,2)	19,4 (1,8)	18,7 (1,7)	17,8 (1,9)	17,9 (1,8)	13,4 (5,1)	13,2 (5,1)
	V	39 (22)	37 (20)	118 (54)	116 (50)	132 (72)	121 (53)	136 (34)	116 (21)	107 (26)	99 (24)	86 (60)	79 (53)
	$\hat{I}_v$	3,9 (1,6)	3,8 (1,7)	5,1 (1,5)	5,1 (1,6)	4,0 (1,4)	3,9 (1,2)	3,4 (0,6)	3,1 (0,4)	2,0 (0,4)	2,0 (0,5)	4,0 (1,6)	3,9 (1,7)
	Sample plots *Koealoja*	63	66	29	28	25	27	10	9	14	15	141	145
Pine North Finland	H_{100}	22,3 (2,2)	22,5 (2,4)	18,7 (1,3)	18,5 (1,1)	—		—		17,2 (1,4)	17,0 (0,8)	19,6 (2,7)	19,6 (2,8)
Mänty *Pohjois-Suomi*	Stem number (no/ha) *Runkoluku*	1358 (273)	1303 (226)	1083 (131)	1044 (137)	—		—		435 (108)	439 (130)	1020 (408)	990 (382)
	D_w	11,6 (1,8)	11,9 (2,0)	11,0 (1,5)	11,0 (1,2)	—		—		21,5 (2,7)	21,9 (3,0)	13,8 (4,9)	14,1 (5,0)
	H_{dom}	9,7 (2,1)	9,8 (2,3)	10,0 (1,4)	9,9 (1,1)	—		—		17,5 (1,3)	17,3 (0,8)	11,8 (3,7)	11,7 (3,6)
	V	60 (22)	62 (24)	37 (12)	37 (10)	—		—		106 (16)	106 (8)	63 (32)	64 (32)
	$\hat{I}_v$	5,4 (0,9)	5,5 (1,0)	3,1 (0,6)	3,1 (0,5)	—		—		1,7 (0,2)	1,7 (0,3)	3,6 (1,6)	3,7 (1,7)
	Sample plots *Koealoja*	13	12	14	12					9	8	36	32

Spruce South Finland *Kuusi Etelä-Suomi*	H_{100}	26,0 (3,4)	25,4 (3,2)	30,0 (2,9)	28,6 (3,9)	—		19,7 (2,7)	19,4 (2,3)	20,6 (2,4)	21,4 (2,6)	25,4 (4,5)	24,8 (4,2)
	Stem number (no/ha) *Runkoluku*	1922 (667)	1813 (512)	772 (128)	736 (114)	—		624 (293)	655 (297)	459 (164)	434 (173)	1425 (824)	1334 (715)
	D_w	7,7 (3,7)	7,2 (3,7)	20,6 (3,7)	19,4 (4,2)	—		19,1 (4,0)	19,3 (3,7)	23,2 (3,7)	23,2 (3,7)	12,8 (7,4)	12,5 (7,5)
	H_{dom}	7,9 (3,5)	7,5 (3,3)	19,6 (3,3)	18,3 (4,3)	—		18,5 (2,4)	18,3 (1,9)	21,0 (2,1)	21,9 (2,3)	12,5 (6,6)	12,2 (6,7)
	V	42 (49)	35 (43)	206 (71)	168 (84)	—		111 (27)	118 (14)	163 (28)	147 (12)	90 (82)	81 (75)
	$\hat{I}_v$	7,6 (6,3)	6,7 (5,9)	9,9 (1,4)	8,6 (2,7)	—		3,4 (1,3)	3,5 (1,2)	3,5 (1,4)	3,4 (1,2)	7,1 (5,4)	6,3 (5,0)
	Sample plots *Koealoja*	28	26	8	8	—		6	6	4	4	46	44
Spruce North Finland *Kuusi Pohjois-Suomi*	H_{100}	—		—		14,9 (1,0)	15,5 (0,4)	15,9 (1,6)	16,1 (1,1)	13,8 (1,8)	13,6 (2,0)	14,7 (1,8)	14,8 (1,8)
	Stem number (no/ha) *Runkoluku*	—		—		657 (153)	640 (85)	506 (60)	457 (63)	659 (107)	695 (156)	613 (124)	612 (156)
	D_w	—		—		11,4 (0,9)	12,6 (0,8)	19,2 (2,2)	19,8 (1,8)	17,2 (1,6)	16,9 (1,5)	16,4 (3,4)	16,8 (3,0)
	H_{dom}	—		—		9,0 (0,8)	9,5 (0,4)	15,3 (1,6)	15,5 (1,1)	15,3 (1,8)	15,1 (2,0)	13,8 (3,1)	13,9 (2,9)
	V	—		—		16 (5)	20 (4)	61 (10)	61 (10)	79 (31)	80 (30)	59 (33)	60 (32)
	$\hat{I}_v$	—		—		1,5 (0,4)	1,8 (0,3)	2,5 (0,4)	2,5 (0,3)	1,6 (0,4)	1,6 (0,4)	1,9 (0,6)	1,9 (0,5)
	Sample plots *Koealoja*	—		—		4	4	5	5	8	8	17	17

$\hat{I}_v$ is obtained by the model presented in Table 5
I_v on saatu taulukossa 5 esitetyllä mallilla

Table 2. Distribution of the plots into age and volume classes at the time the experiments were established. The number of control plots used to supplement the material is given in parentheses.
Taulukko 2. Koealojen jakaantuminen ikä- ja tilavuusluokkiin kokeiden perustamisajankohtana. Suluissa aineistoa täydentävien vertailukoealojen määrä.

Tree species and region / *Puulaji ja alue*	Volume class (m³/ha) / *Tilavuus-luokka*	Age class — *Ikäluokka* 20—39		40—59		60—79		80—99		≤ 100		Total — *Kaikki*	
		Fertilization — *Lannoitus*											
		0	N	0	N	0	N	0	N	0	N	0	N
Pine	0— 49	42(4)	47	4	4	3	3				1	49(4)	55
South Finland	50— 99	21(1)	19	7	6	5	7	1	2	6	5	40(1)	39
Mänty	100—149	(3)		11	13	10	10	6	6	7	9	34(3)	38
Etelä-Suomi	150—199			5 (2)	4	1	5	2	1	1		9(2)	10
	200—249			2	1	4	2	1				7	3
	250—299					2						2	
Pine	0— 49	4	4	12	12							16	16
North Finland	50— 99	9	8	2 (2)						4(4)	1	15 (6)	9
Mänty	100—149									5	7	5	7
Pohjois-Suomi													
Spruce	0— 49	20 (12)	20		1							20 (12)	21
South Finland	50— 99	3 (2)	3	1	1			2	1			6 (2)	5
Kuusi	100—149	5	3	1	1			3	5	2	3	11	12
Etelä-Suomi	150—199			2	2			1 (1)		1	1	4 (1)	3
	200—249			2	1			(2)		1		3 (2)	1
	250—299			2	2			(1)				2 (1)	2
Spruce	0— 49					4		1		1		6	
North Finland	50— 99							4		4		8	
Kuusi	100—149									3		3	
Pohjois-Suomi													

Table 3. Average information about the thinning treatment on the plots. Minimum and maximum values are given in parantheses.
Taulukko 3. Keskimääräistietoja koealojen harvennuksista. Suluissa minimi- ja maksimiarvot.

Characteristics of the removed trees / *Poistuvan puuston tunnuksia*	Pine — *Mänty*		Spruce — *Kuusi*	
	Fertilization — *Lannoitus*			
	0	N	0	N
Proportion of basal area (%) / *Osuus pohjapinta-alasta*	16,4 (5,9—24,0)	16,4 (5,7—32,3)	20,8 (16,4—26,3)	19,7 (16,7—22,7)
Stem number (no/ha) / *Runkoluku (kpl/ha)*	384 (44—1160)	370 (70—1053)	825 (522—1500)	726 (456—1211)
V	20,2 (1,8—48,9)	21,5 (3,4—54,8)	32,5 (17,6—62,0)	28,8 (15,3—58,9)
D_w	12,5 (5,5—25,6)	12,9 (6,4—21,9)	10,7 (8,0—14,0)	11,0 (9,1—13,9)
Observations — *Havaintoja*	56	61	14	11

growth during the year of application. In some cases, other nutrients had been applied in the autumn preceding nitrogen fertilization, but this was not considered to have any effect on the response to fertilization. In some experiments phosphorus fertilization had been repeated 10 years after the establishment of the experiment. These plots were not separated from those fertilized only once with phosphorus.

The growth response to urea fertilization is known to be affected by weather conditions (e.g. Salonen 1973, Friberg 1974, Lipas and Levula 1980). As all the urea applications were carried out in the spring or early summer, which according to the cited investigations is the most unfavourable time for urea application, the results cannot be compared to the results for urea applications carried out in accordance with present recommendations.

Table 4. Average information about the nitrogen fertilizations. Minimum and maximum values are given in parantheses. Nitrogen fertilizer types: 1 = ammonium sulphate, 2 = urea, 3 = ammonium nitrate with lime.
Taulukko 4. Tietoja typpilannoituksista. Suluissa minimi- ja maksimiarvot. Typpilannoitelajit: 1 = ammoniumsulfaatti, 2 = urea, 3 = oulunsalpietari.

Tree species and region *Puulaji ja alue*	Characteristic *Tunnus*	Nitrogen application time — *Lannoituskerta* 1.	2.	3.	4.	5.	Total *Kaikki*
Pine South Finland	Sample plots *Koealoja*	145	145	113	59	7	145
Mänty *Etelä-Suomi*	Nitrogen fertilizer *Typpilannoitelaji*	1,0 (1—3)	1,8 (1—2)	2,2 (2—3)	2,7 (2—3)	2,0 (2)	1,8 (1—3)
	Dose (kg N/ha) *Typpimäärä*	79,3 (21—82)	91,7 (62—138)	102,2 (92—150)	139,2 (92—150)	150,0 (150)	97,2 (21—150)
	Time since previous fertilization (a) *Aika edellisestä lannoituksesta*	—	4,2 (1—10)	4,6 (2—8)	5,1 (3—7)	9,0 (9)	4,6 (1—10)
	Cumulative fertilizer amount (kg N/ha) *Kumulatiivinen lannoitetyppimäärä*	79,3 (21—82)	171,0 (83—220)	272,4 (175—324)	402,6 (295—462)	498,0 (498)	314,5 (174—498)
Pine North Finland	Sample plots *Koealoja*	32	32	24	4	—	32
Mänty *Pohjois-Suomi*	Nitrogen fertilizer *Typpilannoitelaji*	1,4 (1—2)	2,0 (2)	2,8 (2—3)	3,0 (3)	—	2,0 (1—3)
	Dose (kg N/ha) *Typpimäärä*	85,8 (82—92)	92,0 (92)	145,0 (120—150)	150,0 (150)	—	106,2 (82—150)
	Time since previous fertilization (a) *Aika edellisestä lannoituksesta*	—	4,8 (2—6)	5,0 (4—6)	4,0 (4)	—	4,8 (2—6)
	Cumulative fertilizer amount (kg N/ha) *Kumulatiivinen lannoitetyppimäärä*	85,8 (82—92)	177,8 (174—184)	320,7 (294—334)	444,0 (444)	—	305,3 (184—444)
Spruce South Finland	Sample plots *Koealoja*	46	46	29	10	—	46
Kuusi *Etelä-Suomi*	Nitrogen fertilizer *Typpilannoitelaji*	1,0 (1)	1,9 (1—3)	2,0 (2)	2,4 (2—3)	—	1,6 (1—3)
	Dose (kg N/ha) *Typpimäärä*	86,5 (82—123)	107,9 (82—230)	96,8 (92—120)	120,8 (92—150)	—	98,9 (82—230)
	Time since previous fertilization (a) *Aika edellisestä lannoituksesta*	—	4,8 (1—10)	4,6 (3—8)	4,6 (3—6)	—	4,7 (1—10)
	Cumulative fertilizer amount (kg N/ha) *Kumulatiivinen lannoitetyppimäärä*	86,5 (82—123)	194,4 (164—312)	286,1 (256—404)	436,0 (348—554)	—	281,7 (174—554)
Spruce North Finland	Sample plots *Koealoja*	17	17	8	4	—	17
Kuusi *Pohjois-Suomi*	Nitrogen fertilizer *Typpilannoitelaji*	1,5 (1—2)	2,0 (2)	2,0 (2)	3,0 (3)	—	1,9 (1—3)
	Dose (kg N/ha) *Typpimäärä*	87,3 (82—92)	106,8 (92—120)	120,0 (120)	150,0 (150)	—	105,7 (82—150)
	Time since previous fertilization (a) *Aika edellisestä lannoituksesta*	—	4,1 (3—5)	4,5 (4—5)	4,0 (4)	—	4,2 (3—5)
	Cumulative fertilizer amount (kg N/ha) *Kumulatiivinen lannoitetyppimäärä*	87,3 (82—92)	194,1 (174—212)	294,0 (294)	444,0 (444)	—	285,9 (212—444)

24. Measurements

Tree diameters, with a few exceptions, were measured using one centimetre classes. The sample trees were chosen using the basal area — mean tree method developed by Kuusela (1966). The aim was to find 20 sample trees/plot.

The sample trees were in most cases chosen by the relascope method from the middle of the sample plot by using relascope coefficient one. If there were more than 20 trees, the extra ones were excluded randomly. If there were too few, additional sample trees were chosen with the relascope from each corner of the plot (see Lipas 1979). As the sample trees were not usually permanently marked, the same sample trees were not always measured each time. This leads to higher variation. Especially after thinnings new sample trees were included.

The height of the sample trees was measured to an accuracy of 0,1 m and tapering to that of 1 cm. On most occasions, breast-height increment cores (at least 15 growing seasons) were taken. Bark thickness at breast height and two 5-year-period height growths were measured on the sample trees. The reference point for all the measurements was the topmost root collar, in accordance with the tables drawn up by Ilvessalo (1947). The measurements were repeated every five years irrespective of the fertilization timetable. Measurements carried out in the middle of the growing season were divided into spring (before July 15) and autumn (after July 15) periods (see Ilvessalo 1932, Andersson 1953, Leikola 1969). Thinnings were carried out only in the years when measurements were made.

The annual radial growth during the 15-year-period preceding measurement was determined from increment cores to an accuracy of 0,01 mm in the laboratory.

3. PROCESSING OF THE MATERIAL

31. Checking and correction of the material

Certain measurements or even entire experiments were rejected because of inaccuracies and treatment errors. When comparing the height observations of successive measurements, it was found that height growth had been overestimated when measured using binoculars. As the error had an essential effect on volume growth estimates, the height growths were corrected.

In order to estimate the error, the parameters of the height curve model presented by Näslund (1937) were first calculated for the starting point of each measurement period in two ways (measurement period refers to the interval between two consecutive measurement times):

1) on the basis of the sample trees measured at the end of the measurement period by subtracting the growth during the measurement period from the diameter and height of the sample trees

2) on the basis of the sample trees measured at the start of the measurement period (those trees which remain until the end of the measurement period).

Two estimates for the arithmetic mean height were then calculated for those trees included as sample trees at the end of the measurement period using height curves 1 and 2. The difference between these mean heights was an estimate of the error in the height growth measurements. The average difference over a 5-year-period was 19 cm in the case of pine and 27 cm for spruce, i.e. approximately equal to one year's growth. The overestimate was the bigger, the taller the trees concerned. In order to correct the height growth of the sample trees, the error estimates were classified according to the mean height and height growth estimated through binoculars, and the classwise means then calculated.

As the measured height growth corresponded to total height growth during 5-year-periods, it had to be divided up into growth figures for each year in the measurement period. This was done using the annual values for radial growth. If the growth value for the whole measurement period had been divided evenly, growth in the most favourable years of the period would have been underestimated and that of unfavourable years overestimated. Thus the effect of fertilization would have become distorted in such a way that the response would have been underestimated in the years when it was at its greatest and the duration of the effect would have been overestimated.

The weighted moving averages of radial growth for the individual years in the measurement period were calculated by weighting the radial growth in the year in question with the value 0,25, and in the previous year with 0,75. The height growth for the whole measurement period was distributed between the years in the period in relation to these weighted radial growth figures. The method is based on the fact that height growth is clearly dependent on the weather conditions prevailing during the previous growing season, whereas radial growth is mainly affected by the weather conditions in the current growing season (Mikola 1950).

32. Calculation of stand characteristics

Stand characteristics were calculated using a calculation programme for the sample plots, KPL (Heinonen 1981). They were calculated for the instances when the measurements were carried out, and for each year in the preceding measurement period, by means of the radial growth values and the corrected height growth values of the sample trees. A function based on breast-height diameter and height (Laasasenaho 1982) was selected for calculating the volume of the sample trees. The inclusion of the diameter at a height of 6 m in the volume calculations for the sample trees reduced the compatibility of volume estimates calculated from successive measurements. This result was partly due to missing information about radial growth at that particular height, which therefore had to be estimated by means of the taper curve.

When using the volume function based on the breast-height diameter and height, the assumption has to be made that the form of the trees in this material developed in accordance with this function. However, this is not quite true (Flewelling and Yong 1976, Brix and Ebell 1969, Saramäki 1980). On the other hand, in mature stands fertilization affects the stem form mainly above 6 m (see Saramäki 1980), and so in most cases not even the inclusion of the diameter at 6 m would have revealed any changes. The height observations were smoothed out by applying Näslund's (1937) model.

After the calculation of stand characteristics, the differences in the estimates of characteristics calculated from successive measurements were investigated. The differences were classified according to the mean diameter of the stand, and the classwise mean values and standard deviations of the differences were calculated. The plots where the difference in the basal area, mean height and volume was simultaneously higher than the standard deviation of the difference were rejected. Only one deviating characteristic sufficed for a plot to be omitted if the difference was large. Less than two per cent of the plots were rejected. The omitted plots are not included in the figures presented in Tables 1—4.

The results of successive measurements were collated to form a time series consisting of annual stand data and growth data. The site index for each plot was then estimated using a growth model for dominant height devised by Vuokila and Väliaho (1980). The estimates for site index were calculated according to the dominant height and age at the time the plots were established. The degree of bias of the growth model was investigated on the control plots of each experiment by calculating the site index estimates for other years in the investigated period as well. The ratio between the mean value of the site index estimates for all the years and the site index estimate at the time of establishment was used to correct the site index estimates of the fertilized plots as well. The procedure improves the reliability of site indices especially in young stands.

4. CALCULATION OF THE RESPONSE TO FERTILIZATION

The response to fertilization was defined in the conventional way as the difference between the growth of fertilized and unfertilized stands. As far as repeatedly fertilized stands are concerned, however, the situation is not so clear. As fertilization promotes growth, differences in the stage of development between the fertilized and unfertilized stands will arise in spite of originally being the same kind of stand. This leads to a biased estimate of the response because the growth of stands at different developmental stages deviate from one another even without fertilization (see Lipas 1979). The growth response was calculated annually for each plot. After testing, the plots were divided into groups on the basis of the fertilization treatment as follows:

Pine:	
Control plots	0, Ca, CaP, CaK, CaPK, P, PK, K
N plots	N, CaN, CaNP, CaNK, CaNPK, NP, NPK, NK
Spruce:	
Control plots	0, P, PK, K
N plots	N, NK
NP plots	NP, NPK

The spruce material was divided into three groups owing to the interaction between phosphorus and nitrogen. The effect of phosphorus alone or with potassium was slight. From this point on in the text the plots fertilized with nitrogen will be referred to as fertilized and the other ones as controls.

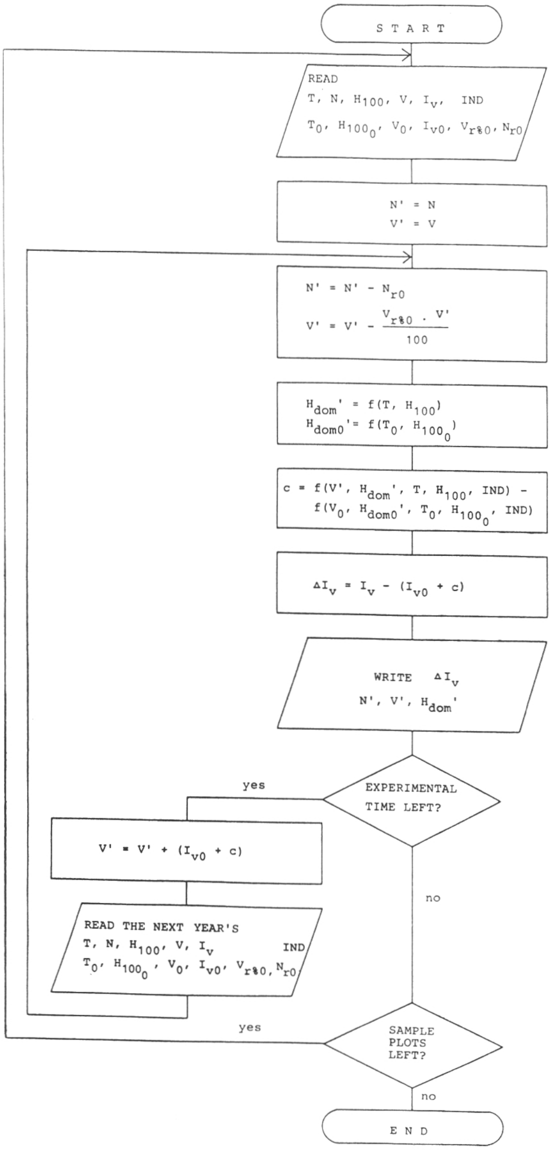
There is always a certain amount of variation as regards the tree stand and site between the plots within the same experiment, leading to errors in calculating the response. Various ways of eliminating the error have been devised (see Lipas 1979). Volume growth models were used in this investigation to eliminate the effect of the variation between the plots. They were constructed to predict the annual growth on the basis of stand characteristics at the start of the growing season, the site index as well as the radial growth index for the growing season (Table 5).

The volume growth model, the growth model for dominant height (Vuokila and

Table 5. Volume growth models which predict the annual growth without fertilization ($y = \ln I_v$), and information about the volume growth. The models are used in the calculation of the corrected response.
Taulukko 5. Korjatun kasvunlisäyksen laskennassa käytetyt tilavuuskasvumallit, jotka ennustavat vuotuista kasvua ilman lannoitusvaikutusta ($y = \ln I_v$) sekä tietoja tilavuuskasvusta.

Variable — *Muuttuja*	Pine — *Mänty*	Spruce — *Kuusi*
	Coefficient — *Kerroin*	
Constant — *Vakio*	34,5044	−1,05445
ln T	1,24491	−0,849837
T	−0,0186792	−0,00658209
ln V	1,00135	0,830715
V	−0,00252132	
$V/\sqrt{T}$		−0,0219825
ln H_{100}	1,68060	0,495856
ln (H_{dom} + 1)	−1,71930	
ln IND	−11,7880	0,380544
IND	0,126190	
Standard error of estimate $\frac{\Sigma(I_v - \hat{I}_v)^2}{n-1} \cdot \frac{100}{\bar{I}_v}$ *Arvion keskivirhe*	23,2	22,4
Coefficient of determination ($y = I_v$) *Selitysaste*	0,74	0,88
Mean of I_v (m³/ha/a) *I_v:n keskiarvo*	4,9	7,4
Standard deviation of I_v (m³/ha/a) *I_v:n keskihajonta*	2,2	4,8
Range of I_v (m³/ha/a) *I_v: vaihteluväli*	0,8—15,4	0,6—23,5
Observations *Havaintoja*	2592	946

Constant includes correction term $s_f^2/2$ (s_f^2 = residual variance)
Vakio sisältää korjaustermin $s_f^2/2$ (s_f^2 = jäännösvarianssi)
If IND < 90 in pine model, index value IND = 90 should be used
If IND > 110 in pine model, index value IND = 110 should be used
Jos mäntymallissa IND < 90, pitäisi käyttää indeksiarvoa IND = 90
Jos mäntymallissa IND > 110, pitäisi käyttää indeksiarvoa IND = 110



Read the stand characteristics at the time of primary fertilization on the fertilized plot and control plot as well as the radial growth index of the growing season in question.

The initial stem number of estimated zero development is the stem number of the fertilized plot, and the initial volume the plot volume.

When the control plot has been thinned, the stem number and volume of the estimated zero development decreases according to the removal from control plot.

Calculate the estimate of dominant height for the estimated zero development and control plot using the model introduced by Vuokila and Väliaho (1980).

Calculate the correction for the growth of the control plot by subtracting the growth prediction of the control plot from that of estimated zero development.

Calculate the response to fertilization as the difference between the growth of fertilized plot and corrected growth of control plot. The corrected growth of control plot is at the same time the predicted growth of the estimated zero development.

Add the predicted growth to the volume of estimated zero development.

Read the stand characteristics at the start of the following growing season.

Fig. 3. Flowchart of the calculation of the annual responses to fertilization for the fertilized plots of one experiment. The stand characteristics of the fertilized plots are not marked with subindices and the subindex of the control plot is 0. N = stem number, N_r = number of trees removed at thinning, $V_{r\%}$ = percentage of volume removed. If there are several control plots in the experiment, mean values of the characteristics are used:

$\bar{f}(V_0, H_{dom_0}', T_0, H_{100_0}, IND)$, $\bar{I}_{v_0}$, $\bar{H}_{100_0}$, $\bar{V}_{r\%0}$ and $\bar{N}_{r_0}$

"The estimated zero development" refers to the predicted value for unfertilized stand development.

Kuva 3. Kaavio vuosittaisten kasvunlisäysten laskennasta kokeen typellä lannoitetuille koealoille. Lannoitetun koealan puustotunnusten merkinnät ovat alaindeksittömiä ja vertailukoealan tunnusten alaindeksinä on 0. N = runkoluku, N_r = harvennuksessa poistuva runkoluku, $V_{r\%}$ = poistumaprosentti tilavuudesta. Kun kokeella on useita vertailukoealoja, käytetään tunnusten keskiarvoja. Nimitys "estimoitu nollakehitys" tarkoittaa ennustetta siitä, kuinka ko. koealan puusto olisi kehittynyt ilman lannoitusta.

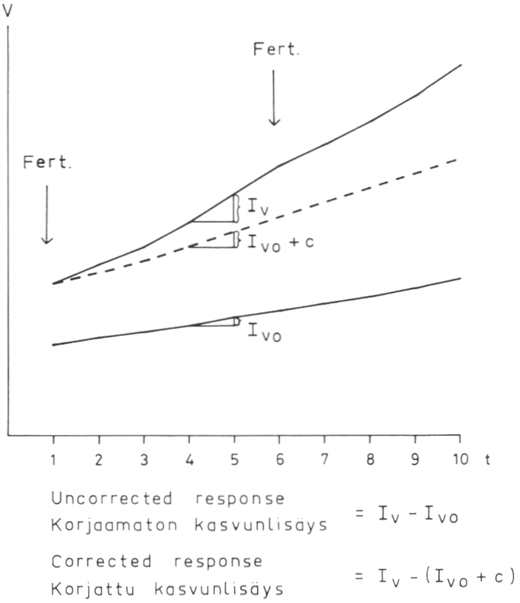


Fig. 4. Principle diagramme illustrating the calculation of corrected response. Markings as in Fig. 3.

Kuva 4. Periaatepiirros korjatun kasvunlisäyksen laskennasta. Merkinnät kuten kuvassa 3.

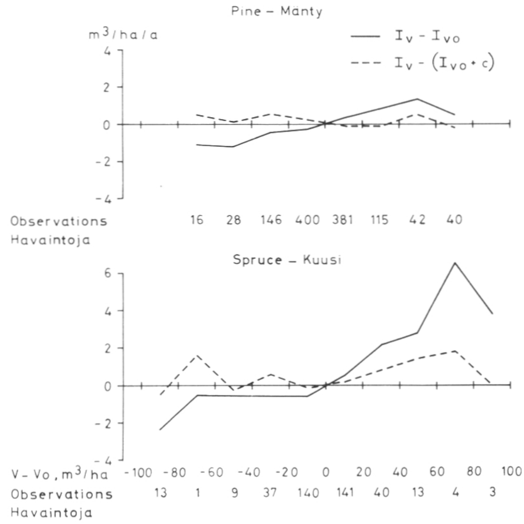


Fig. 5. Testing the method used for calculating the corrected response by means of the control plots. How the effect of the difference in stand volume on the difference in growth can be diminished is studied. Markings as in Fig. 3.

Kuva 5. Korjatun kasvunlisäyksen laskennassa käytetyn menetelmän testausta vertailukoealojen avulla. Tutkittu, kuinka puustojen tilavuuseron vaikutusta niiden kasvueroon voidaan vähentää. Merkinnät kuten kuvassa 3.

Väliaho 1980) and the data from the control plots of the experiment in question were used to predict how each fertilized plot would have developed without fertilization from the very start of the experiment. The annual response to fertilization was then calculated as the difference between the measured and predicted growth on the plot. The flowchart for the calculation is shown in Fig. 3, and the method is illustrated in Fig. 4.

The data for the volume growth models consisted of the annual growth values for the control plots of the entire material. As the material was partly deficient, additional material for the model was acquired from the control plots of five pine and six spruce experiments (see Table 2). Thus 204 additional annual growth observations for pine and 138 for spruce were obtained.

The reason for the inclusion of the radial growth index in the models as an independent variable was to make sure that the growth variation caused by climate would not interfere with the estimation of the dependence between volume growth and different stand variables. The indices were acquired from the index series based on the National Forest Inventory (Tiihonen 1979). The series for the latter part of the 1970s were supplemented by unpublished indices for pine (introduced by the Department of Forest Inventory and Yield, Division of Forest Yield) and on the basis of radial growth on the unfertilized plots for spruce.

The correction method was tested using the control plots. The control plots of each experiment were divided into two groups and the development of the stand was estimated on the plots of one group, the other acting as the "control". As there is no response to fertilization on the control plots, the corrected growth difference between the plots should be zero irrespective of possible differences in their stand volumes. Figure 5 shows, after experimentation, how the effect of the difference in stand volume on the difference in growth could be diminished.

5. RESPONSE MODEL

51. Background

The amounts and types of fertilizer applied have changed during the course of the experiments. Similarly, the intervals between fertilizer applications have varied in many of the experiments, being shorter at the beginning. Consequently it would have been impossible to divide the material into groups according to the fertilization regime without having to omit several experiments where the interval between fertilizer applications varied during the course of the experiment. This was partly the reason why a model was devised for predicting the annual volume growth response which would facilitate the analysis. The annual response was chosen for the dependent variable so that the observations from irregularly fertilized experiments could also be utilized in estimating the parameters of the model.

When the response model was being made, it was assumed that the response to successive fertilizations during a certain growing season can be predicted separately and then explain the growth difference between repeatedly fertilized and unfertilized stands as a sum of the responses. It was also assumed that "the law of diminishing growth increases" (see Mengel and Kirkby 1978) can be applied when taking into account the effect of previous fertilizations on the response obtained through refertilization. If the nitrogen status of forest soil is good as a result of previous fertilizations — or as a result of natural fertility — then the response is not as great as on nitrogen-poor forest soil. Thus the benefit from refertilization is the smaller, the less time has elapsed since the previous fertilizer applications and the greater the amount of fertilizer given the previous times. On the other hand, if the previous fertilizer applications no longer have any effect, then the response to refertilization will be the same as that to primary fertilization in the same type of stand.

A separate model was devised for pine and spruce stands using the experiments in southern Finland as the material. The distribution of the response between the individual years during the post-fertilization period was first modelled, followed by the influence of stand factors and previous fertilizations on the response. The parameters were estimated using a BMDP statistical programme PAR for nonlinear regression analysis (Table 6).

The model for the response obtained with a single fertilization is presented in two parts. In the first part (FA) the data concerning nitrogen fertilization are used, and in the second (FB) the stand characteristics. In the spruce model phosphorus fertilization is also included in part FB. The estimate of the response, $\Delta\hat{I}_v$, is calculated as the product of the two parts of the model:

$$\Delta\hat{I}_v = FA \cdot FB$$

The parameters of part FA of the model were first estimated. The values of the parameters — except for scaling parameter a_1 — were fixed when the variables of part FB were added to the model. The fertilization factors were included in the model first because they were the most important (Brantseg 1967, Braastad et al. 1974, Malm and Möller 1975, Gustavsen and Lipas 1975, Jonsson 1978). Furthermore, the estimation of parameters $a_2,\ldots,a_9$ had also to be supported by results from other investigations, the stand data for some of which were unsuitable.

52. Fertilization factors in the model

Part FA of the model shows the distribution of the growth response between the different years in the post-fertilization period with different nitrogen doses. The

Table 6. Parameter values of the response model. t = growing season after fertilization; in the first growing season after fertilization t = 1, in the second t = 2, etc.
Taulukko 6. Kasvunlisäysmallin parametrien arvot. t = kasvukausi lannoituksen jälkeen; ensimmäisenä kasvukautena lannoituksen jälkeen t = 1, toisena t = 2, jne.

Parameter *Parametri*	Pine — *Mänty*		Spruce — *Kuusi*	
	Nitrogen fertilizer — *Typpilannoitelaji*			
	As/Os	Urea	As/Os	Urea
	Parameter value — *Parametrin arvo*			
a_1	$3{,}375 \cdot 10^{-6}$	$1{,}718 \cdot 10^{-6}$	$7{,}699 \cdot 10^{-9}$	$2{,}053 \cdot 10^{-9}$
a_2, when $t = 1$ *kun t = 1*	1,0	0,0	0,8	0,0
a_2, when $t > 1$ *kun t > 1*	1,0	1,0	1,0	1,0
a_3	3,0	3,0	7,0	7,0
a_4	−2,38	−2,61	−2,02	−2,09
a_5	0,324	0,39	0,2	0,233
a_6	−0,00072	−0,00083	−0,00045	−0,000495
a_7	7,0	7,0	9,0	9,0
a_8	3,0	4,0	3,0	3,0
a_9	—	—	2,2	2,5
b_1	−0,00005	−0,00005	−0,00004	−0,00004
b_2	1,5	1,5	3,0	3,0
b_3	−0,00564	−0,00564	−0,2	−0,2
b_4	0,055	0,055	—	—
b_5, when N fertilization *kun N-lannoitus*	—	—	0,0	0,0
b_5, when NP fertilization *kun NP-lannoitus*	—	—	0,012	0,012
c	0,20	0,20	0,07	0,07

properties of the different tree species affect the timing of the response (Albrektsson et al. 1977), the most important factor being the length of the needle rotation period (Fagerström and Lohm 1977). Thus the response in pine stands reaches a maximum earlier and the response is of shorter duration than in spruce stands.

The nitrogen compounds in different types of nitrogen fertilizer are bound in the soil in different ways. Urea application does not usually increase growth during the year when fertilization is carried out. In spruce stands, at any rate, the growth may decline temporarily after a high dose of urea (Kukkola 1978). Ammonium sulphate and ammonium nitrate with lime increase growth to some extent even during the first growing season, and the response reaches its maximum sooner than after urea application.

The fertilizer dose affects both the intensity of the response and its timing. With higher doses the response reaches its maximum at a later stage and the response lasts longer (Viro 1972, Päivinen and Salonen 1978, Jonsson 1978). These features have been illustrated using the following model:

$$FA = a_0 x^{a_3} e^{dx}$$

in which $a_0 = a_1 a_2$

$x = t + (\frac{t}{a_7})^{a_8}$ in the model for pine

$x = t + (\frac{t}{a_7})^{a_8} + a_9$ in the model for spruce

t = growing season after fertilization; in the first growing season after fertilization $t = 1$, in the second $t = 2$, etc.

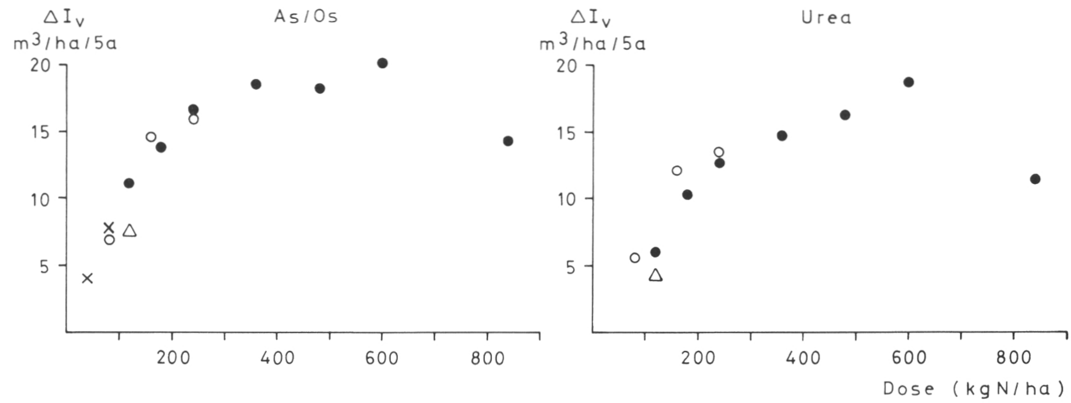
$d = a_4 + a_5 \ln(FN + 1) + a_6 FN$

FN = nitrogen dose applied, kg N/ha

$a_1,\ldots,a_9$ are parameters

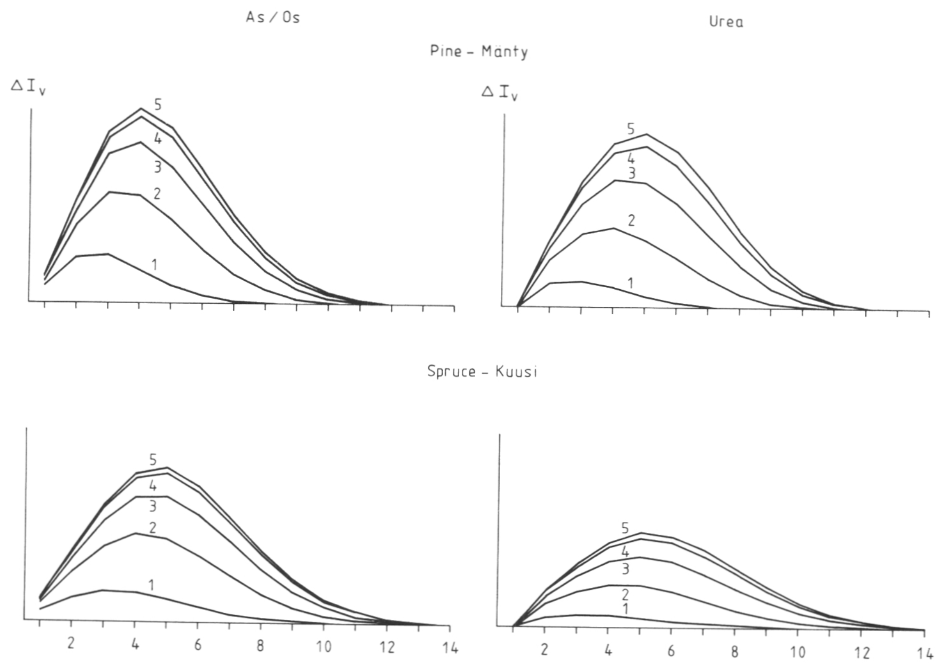
Figure 7 presents examples of the course followed by the model when estimating the responses obtained with different nitrogen doses.

The distribution of the response obtained with As/Os fertilization into separate years during the post-fertilization period was



x authors' data for time between the first and second fertilizations — *oma havainto ensimmäisen ja toisen lannoituksen väliseltä ajalta*
● Malm & Möller 1975
○ Gustavsen & Lipas 1975 (group VIII) — *(ryhmä VIII)*
Δ Laakkonen, Keipi & Lipas (unpublished) — *(julkaisematon)*

Fig. 6. Results from pine stands used for estimating the shape of the dependence between nitrogen dose and response.
Kuva 6. Männiköissä saatuja koetuloksia, joita käytettiin lannoituksen typpimäärän ja kasvunlisäyksen välisen riippuvuuden muodon estimoinnissa.



1 = 50, 2 = 150, 3 = 250, 4 = 350, 5 = 450 kg N/ha.

Fig. 7. Examples of the effect of nitrogen dose on the annual response to fertilization predicted by the model.
Kuva 7. Mallilla laskettuja esimerkkejä lannoituksen typpimäärän vaikutuksesta vuosittaiseen kasvunlisäykseen.

estimated from the data for the years in the period between the primary and the second fertilization. The primary fertilizations where ammonium sulphate had been applied at a level of about 80 kg N/ha were included. The annual response means were calculated and used in estimating the parameters of the model. As the data for the response to urea fertilization concern the period after the second application of nitrogen at the earliest, the timing of the response obtained with urea was estimated on the basis of the annual responses presented by Laakkonen et al. (unpub.) for southern Finland. The amount of nitrogen which had been applied in the material of Laakkonen et al. was 120 kg/ha.

Scaling parameter a_2 was needed for depicting the response in the first growing season after fertilization. Its value depended on the fertilizer type and the time which had elapsed since fertilization. Correspondingly, the model was fitted to the data for the last few years of the response by means of parameters a_7, a_8 and a_9. The value of parameter a_3 was also estimated at the same time.

The effect of the nitrogen dose has been depicted in the model by means of coefficient d, the value of which depends on the dose. As the amount of nitrogen given at primary fertilization varied only slightly, the form of the dependence between the nitrogen dose and the response was also estimated using the results from other investigations (Malm and Möller 1975, Gustavsen and Lipas 1975, Laakkonen et al., unpub.). The response during the 5-year-period following fertilization in pine stands (Fig. 6) was presented in these studies. Parameters a_4, a_5 and a_6 were estimated so that the sum of the annual response predictions calculated for the first five years ($\sum_{t=1}^{5} FA_t$) explained as well as possible the variation in the data presented in Fig. 6. The same data were used for estimating these parameters for the spruce model, since there were not enough results concerning the response to different nitrogen doses available for spruce. Thus it was assumed that the relative change in the response with varying fertilizer doses was the same in both pine and spruce stands. There are, however, indications that the maximum response is attainable with a smaller amount of nitrogen in spruce than pine stands (Malm and Möller 1975). Although parameters a_4, a_5 and a_6 determined the form of the dependence between the nitrogen dose and the response, the absolute response level was finally determined using scaling parameter a_1 which, in turn, was determined on the basis of the entire southern material.

The result of the estimation of the parameters was evaluated both with the residual variance and by comparing it to the results of other investigations. Unpublished material from experiments with different nitrogen doses carried out by the Department of Soil Science were available for this purpose, too.

53. Stand factors in the model

The prediction based on the fertilization data was supplemented by stand data. The stand density influences the extent to which the stand is able to reach the potential growth level. The amount of needle biomass is of prime importance, since the response to fertilization is to a great extent based on a temporary increase in the needle biomass (Brix and Ebell 1969, Brix 1971, Tamm 1974, Albrektsson et al. 1977). On the other hand, the benefit from nutrient application depends on the site quality, i.e. the soil nutrient status and the water conditions. Consequently, part FB of the model describing the effect of stand factors was composed of two parts, one characterizing the standing crop (f1) and the other the site (f2):

$$FB = f1 \cdot f2$$

The stem number and dominant height were chosen for describing the standing crop. The basic assumption was that the capacity of the tree stand to respond improves as the stem number increases, until the point is reached where overdensity starts to weaken it (see Brix and Ebell 1969, Rosvall 1978). The dominant height was assumed to influence the intensity by which the increasing stem number improves the response (Fig. 8). The dependencies were described in the model as follows:

$f1 = N' H_{dom}' e^{b_1 N' H_{dom}'}$

in which N' and H_{dom}' are predicted stem number and dominant height at the start of the growing season in question, assuming that the plot would be unfertilized (see Fig. 3)
b_1 = parameter

The effect of stand age on the response is expressed indirectly in the model by means of stem number and dominant height. However, in very old stands they cannot describe adequately enough the weakening capacity of the stand to respond.

In the present investigation the site quality could only be expressed in terms of the site type and site index describing the joint influence of all site factors. As the site type is a variable with an ordinal scale and is difficult to use in the model, the site index was used to describe the site. One disadvantage of the use of the site index for predicting the response to fertilization is that the importance of climatic factors increases on moving from the south towards the north, and that the same site index in the north does not represent the same fertility and water conditions as in the south. The effect of this was, however, lessened by using only the southern material for the estimation of the parameters.

The most fertile sites have sufficient nutrients. On the other hand, a lack of water is the most important factor limiting growth on infertile mineral soils. The sites suitable for fertilization fall within these

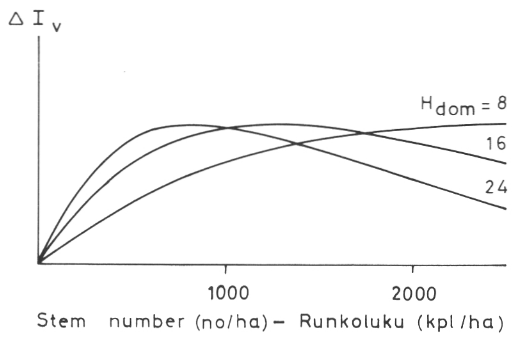


Fig. 8. Effect of stem number on the response predicted by the model at different stages of dominant height.
Kuva 8. Runkoluvun vaikutus mallilla ennustettuun kasvunlisäykseen eri valtapituusvaiheissa.

extremes. This feature is described by the site index in the pine model as follows:

$$f2 = H_{100}^{b_2} e^{b_3 H_{100}^{b_4 H_{100}}}$$

and in the model for spruce:

$$f2 = H_{100}^{b_2} e^{b_3 H_{100}} (1 + b_5 H_{100})$$

in these H_{100} = site index
$b_1, \ldots, b_5$ are parameters
The value of parameter b_5 in the spruce model is different for N and NP fertilizations.

The site index affects the response estimation as shown in Fig. 9, the other variables being kept constant. In the pine

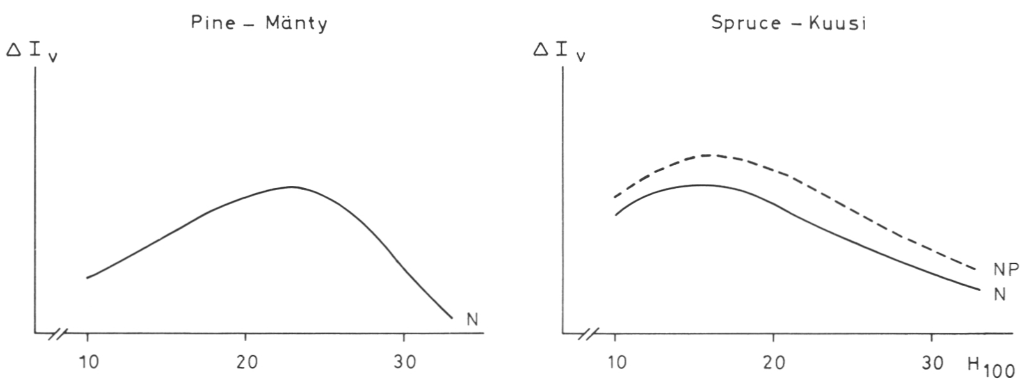


Fig. 9. Effect of site index on the response predicted by the model.
Kuva 9. Pituusboniteetin vaikutus mallilla ennustettuun kasvunlisäykseen.

model the site index does not interact with the other variables. In the spruce model the effect of phosphorus fertilization depends on the site.

The value of parameter a_1 and the parameters of part FB were estimated using all the observations in the southern material. The numer of observations was 2009 in the pine material and 593 in the spruce material. In most of the observations the response was composed of several overlapping fertilization effects. This had to be taken into account when estimating the parameters.

54. Effect of repeated fertilization in the model

The response model could be used in the above-presented form for predicting the effect of the first fertilization. In the case of repeatedly fertilized stands, the response was considered to be composed of the overlapping effects of the successive fertilizations, which were predicted separately. The fact that the preceding fertilizations affect the response to refertilization had to be taken into account. The effect of refertilization refers here to the part of the growth response that was brought about by the refertilization in question. Each of the preceding fertilizations was taken into account by means of a function whose value was affected both by the time which had elapsed since the earlier fertilization in question, and the nitrogen dose applied at that time:

$$FN' = FN \cdot t^{-ct}$$

in which FN = nitrogen dose applied, kg N/ha

t = growing season after fertilization; in the first growing season after fertilization t = 1, in the second t = 2, etc.

c = parameter (see Table 6)

Variable FN′ was assumed to indicate the amount of available nitrogen which had remained bound in the soil and the tree stand after fertilization. The preceding fertilization treatments influence the growth response obtained by subsequent fertilization also in ways other than through the fact that nitrogen remains in the soil and tree stand. The needle biomass may still be enlarged as a result of previous fertilization. This is the reason why the needle biomass cannot, at any rate in a mature stand, increase as effectively as after the primary fertilization. The mutual shading of needles increases as the needle biomass increases, thus diminishing their assimilation (Albrektsson et al. 1977). Such factors affect the value of parameter c, and the nitrogen remaining, FN′, can only be regarded as a technical aid. Parameter c was estimated in conjunction with the estimation of parameters a_1 and $b_1,...,b_5$.

The method is presented stepwise in the following. Supposing we have fertilization time k and the response is predicted for the growing season t_k (t_k indicates the number of the growing season following fertilization k). First of all the amount of nitrogen remaining from the previous fertilizations is estimated at the time of fertilization k, and is added to the nitrogen dose applied at fertilization k:

$$FN_s = FN_k + \sum_{i=1}^{k-1} FN_i'$$

The response estimate is then calculated with amounts FN_s and $FN_s—FN_k$. The effect of fertilization k is obtained as the difference between these two estimates based on ''the law of diminishing growth increases'':

$$\Delta\hat{I}_{vk} = [FA(t_k,FN_s,FS_k) - FA(t_k,FN_s—FN_k,FS_k)]FB$$

in which FS_k = type of fertilizer used at fertilization k

The combined response of fertilization k and the previous fertilizations in the growing season in question is obtained by the sum:

$$\Delta\hat{I}_v = \sum_{i=1}^{k} \Delta\hat{I}_{vi}$$

The details of the method are presented in Fig. 10 and the principles of the method are illustrated in Fig. 11. Fig. 12 contains examples of the course the model takes when predicting the response obtained by repeated fertilization.

55. Reliability of the model

The reliability characteristics of the response model were:

	Pine	Spruce
Coefficient of determination (%)	40	23
Standard error of estimate (%)	69	96

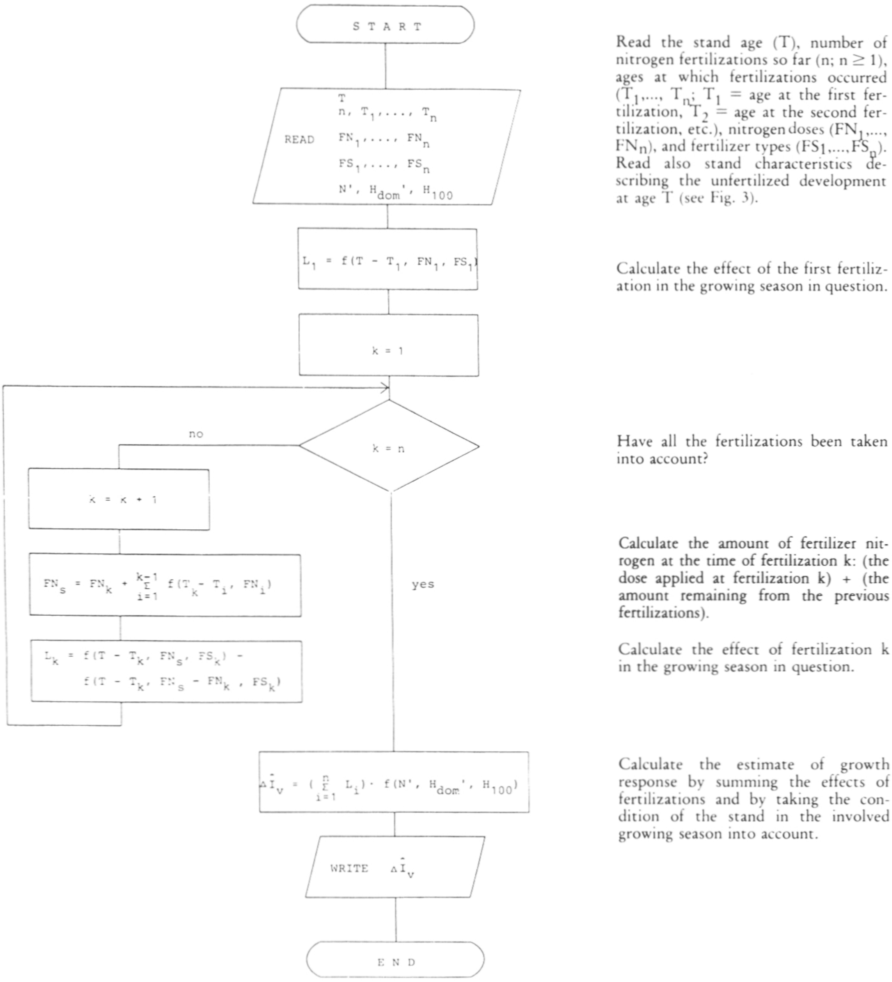


Fig. 10. Flowchart of response prediction for one growing season in a stand which has been fertilized repeatedly.
Kuva 10. Kaavio kasvulisäysennusteen laskennasta yhdelle kasvukaudelle toistuvasti lannoitetussa metsikössä.

The standard error of the estimate was calculated in the same way as in Table 5. The reliability characteristics were also calculated by using the mean values of both the dependent and independent variables of the fertilized plots in each experiment. Thus in the pine material the coefficient of determination was 57 % and the standard error of the estimate 46 % (445 observations). Corresponding figures could not be calculated from the spruce material because of the division into N and NP fertilization. It was possible to explain the variation in the response in the pine material by means of fertilization and stand data as successfully as in the investigations dealing with single applications (Brantseg et al. 1970, Braastad et al. 1974, Gustavsen and Lipas 1975, Rosvall 1980). Information for example about the soil and, especially in the case of urea, about the weather at the time of fertilization is required before the accuracy of the model can be improved. One reason for the high standard error of the estimate is the inaccuracy of the response data. Growth response is only a rather small part of the growth. The average response in pine stands in southern Finland was 23 % and correspondingly in spruce stands 16 % of the mean growth of the fertilized plots.

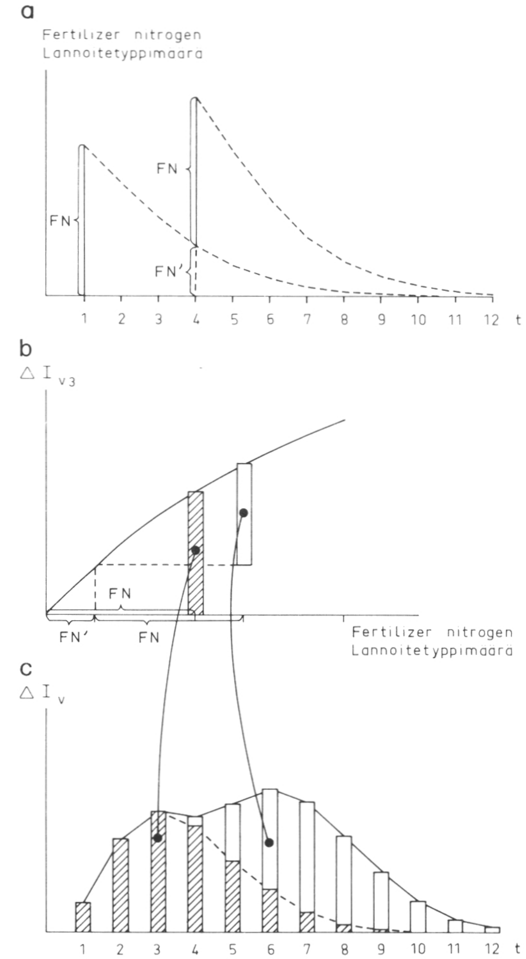


Fig. 11. Diagramme showing the principle of the method used for predicting the response brought on by repeated fertilization.

a) Two fertilizer applications, both with nitrogen dose FN. Amount of nitrogen remaining from the first fertilization is FN' at the time of the second fertilization.

b) As an example the response brought on by the first fertilization (hatched column) and that by the second fertilization (white column) in the third growing season after the fertilization in question. The response given by the second fertilization has been calculated as the difference: (response with dose FN + FN') — (response with dose FN').

c) Annual responses. (The effect of stand development on the response omitted.)

Kuva 11. Periaatepiirros menetelmästä, jolla ennustetaan toistuvan lannoituksen aiheuttama kasvunlisäys.

a) On tehty kaksi lannoitusta ja molemmissa typpiannos on ollut FN. Ensimmäisestä lannoituksesta on typpeä jäljellä toisen lannoituksen ajankohtana määrä FN'.

b) Esimerkkinä ensimmäisen (varjostettu pylväs) ja toisen (valkoinen pylväs) lannoituksen aiheuttama kasvunlisäys kolmantena kasvukautena ko. lannoituksesta lukien. Toisen lannoituksen aiheuttama kasvunlisäys on laskettu erotuksena: (kasvunlisäys määrällä FN+FN') – (kasvunlisäys määräällä FN').

c) Kasvulisäykset vuosittain. (Puuston kehityksen vaikutus kasvunlisäykseen on tässä jätetty huomiotta.)

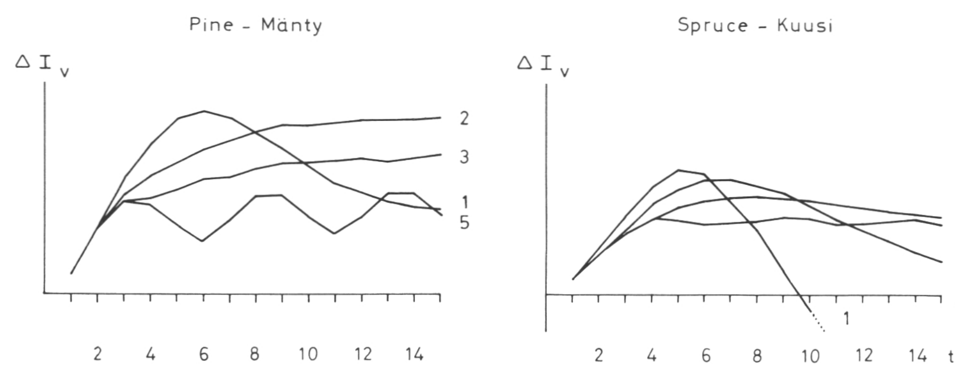


Fig. 12. Effect of the interval between fertilizations on the response. The values in the figure were calculated by means of the model using As/Os fertilizer at single doses of 150 kg N/ha. The figures at the end of the curves indicate the interval between fertilizations in years.

Kuva 12. Lannoitusvälin vaikutus kasvunlisäykseen. Kuvan arvot on laskettu mallilla käyttäen lannoitelajina As/Os:ia ja kerta-annoksena 150 kg N/ha. Numerot kuvaajien päissä ilmaisevat lannoitusvälin vuosina.

Table 7. Comparison between the observed and predicted responses during the most recent measurement period in some experiments in southern Finland. The period is not dealt with in the study.

Taulukko 7. Mallilla lasketun ja havaitun kasvunlisäyksen vertailu eräillä Etelä-Suomen kokeilla viimeisimpänä mittausjaksona. Jakso ei sisälly tutkimuksen varsinaiseen koeaikaan.

Tree species *Puulaji*	Sample plots *Koealoja*	Age (a) *Ikä*	H_{100}	Stem number (no/ha) *Runkoluku (kpl/ha)*	H_{dom} (m)	Growth response ($m^3/ha/a$) *Kasvunlisäys* Observed *Havaittu*	 Predicted *Ennustettu*
Pine — *Mänty*	40	45	21,6	1303	13,2	1,7	1,8
Spruce — *Kuusi*	24	46	24,1	1376	13,7	1,6	1,7

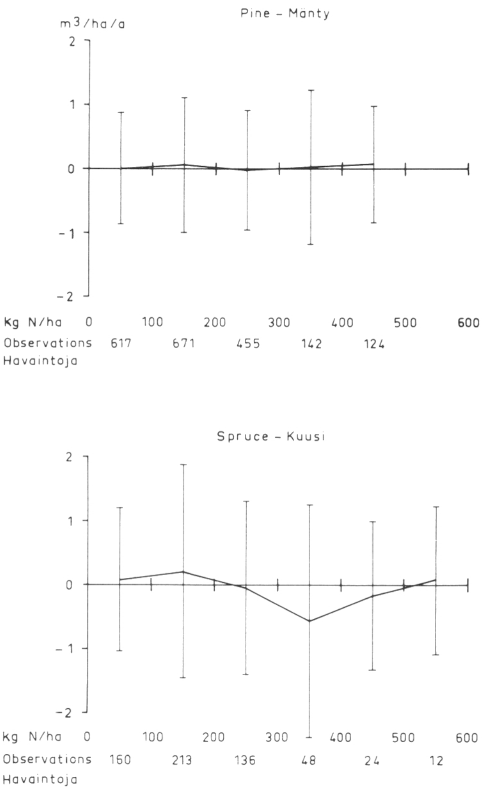


Fig. 13. Residual variance of the response model in the classes of the nitrogen level applied up until the observation date.

Kuva 13. Kasvunlisäysmallin jäännöshajonta havainnon ajankohtaan mennessä annetun typpimäärän luokissa.

The parameters in part FA of the model were estimated for As/Os and urea fertilization separately. The reliability of the model could not, however, be estimated for each fertilizer type separately as in most of the observations the effect of several fertilizer types were involved at the same time. For the sake of illustration, the observations were divided into groups according to the type of fertilizer used in the previous fertilization and the standard error of the estimate was calculated in part-materials. In both the pine and spruce stands it was greater in the years after urea application than after As/Os.

The effect of stand factors in the model was investigated by replacing part FB with a constant. The degree of determination then decreased in the pine material by 10 %-units and in the spruce material by 12 %-units. Thus the information concerning stand, site and phosphorus fertilization was important in addition to fertilization factors, especially in spruce stands.

The residual variance of the model in relation to the nitrogen level applied prior to the year in question is presented in Fig. 13. The cumulative nitrogen level indirectly describes the intensity of the fertilization regime. The predicted values are also compared with the observations in groups of experiments fertilized at different intervals in Figs. 16 and 17.

Some of the experiments in the southern material were measured 3—6 years after the last growing season in the investigated period. The measured responses for these years were compared with the predicted values (Table 7). Nine pine and eleven spruce experiments were available for this purpose. By the time when the last measurement period had started, the plots had been fertilized three times on the average and two of the spruce experiments had also been fertilized during the last measurement period. The last fertilization involved ammonium nitrate with lime and urea at doses of 92, 120 or 150 kg N/ha. On the average the model predicted the responses well. The correlation coefficient between the observed response and the predicted response was 0,64 on the pine plots and 0,56 on the spruce plots.

It was not possible, on the basis of the material, to estimate parameter c separately for different fertilizer types (see Table 6). Thus the model includes the assumption that the effect of previous fertilizations on the response given by refertilization does not depend on the types of fertilizer used in previous fertilizations. The sensitivity of the model to changes in parameter c was tested by calculating the predicted responses with different values of c (Fig. 14). Naturally the effect of parameter c is stronger, the shorter is the interval between fertilizations. In the pine model a change of ±25 % in c had no decisive effect on the predicted response for intervals between fertilizations of over three years, but in the spruce model the effect was distinct. The results presented in Fig. 14 have been calculated with a single dose of 150 kg N/ha. When the dose further decreases, the significance of c also diminishes.

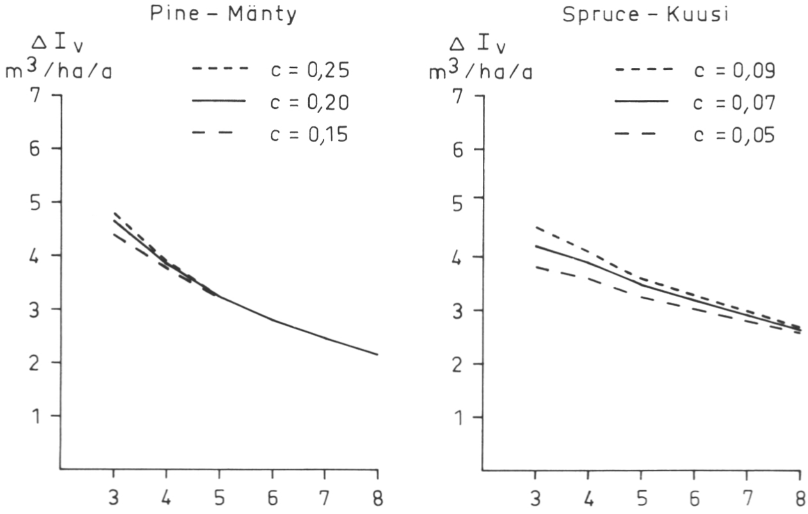


Fig. 14. Example of the effect of a change in the value of parameter c (Table 6) on the predicted response of a young stand with different intervals between fertilizations. N fertilization in pine and NP in spruce stand, fertilizer type As/Os and the single dose 150 kg N/ha.

Kuva 14. Esimerkki parametrin c (taulukko 6) muuttamisen vaikutuksesta nuoren kasvatusmetsikön kasvunlisäysennusteeseen eri lannoitusväleillä. Männikössä N- ja kuusikossa NP-lannoitus, lannoitelaji As/Os ja kerta-annos 150 kg N/ha.

6. GROWTH RESPONSE OBTAINED WITH REPEATED FERTILIZATION

61. Effect of fertilization factors

Fertilizer type

Urea was spread on the experiments in the spring or early summer, which is the most unfavourable spreading time for urea (Lipas and Levula 1980). Thus no far-reaching conclusions should be drawn from the growth response obtained with urea in this study. The distribution of the response into the different growing seasons following fertilization does not, however, necessarily depend on the time when urea is spread. In pine stands about 30 % more nitrogen was needed in urea fertilization to obtain the same response as in As/Os fertilization. The following table presents some combinations of nitrogen doses and intervals between fertilizations which would result in the same average annual response in a pine stand:

Single dose (kg N/ha)/Interval between fertilizations (a)

As/Os	Urea
100/4	100/3
150/7	150/5

In spruce stands almost twice as much nitrogen was required in urea fertilization to produce a response of similar magnitude as in As/Os fertilization (see Fig. 15). The difference may be caused by the fact that the refertilization of a spruce stand often produces a poorer response than the primary fertilization (see Puro 1977) and that urea was almost invariably used in the second fertilizaton in these experiments.

Fertilizer dose and repetition

If not otherwise mentioned, fertilization refers in this part of the text to As/Os application. If the growth response brought on by an intensive fertilization regime is examined at the beginning of the regime, too good a picture is obtained. Examination later on in the regime reveals, however, the negative effect of too heavy fertilization on growth (Fig. 12).

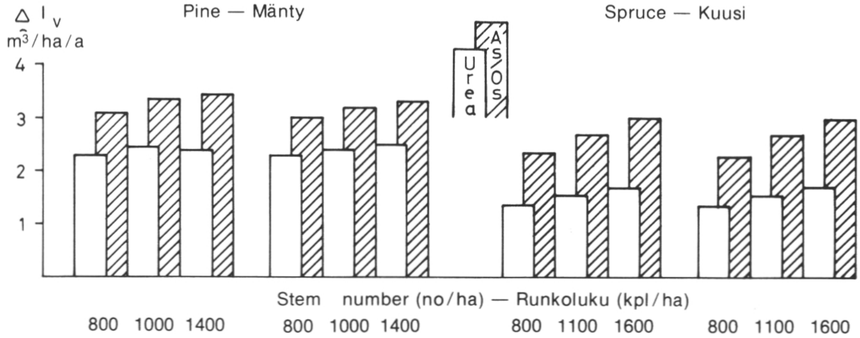


Fig. 15. Average annual response predicted by the model at a site index $H_{100} = 24$ after the first thinning using different stand densities. The predicted value was calculated by including as many complete intervals between fertilizations after the start of the fertilization regime so as to give total of at least 15 years.

Kuva 15. Mallilla laskettu keskimääräinen kasvunlisäys boniteetilla $H_{100} = 24$ ensiharvennuksen jälkeen erilaisin kasvatustiheyksin. Kasvunlisäys on laskettu ottamalla mukaan ensilannoitus-ajankohdasta alkaen täysiä lannoitusvälejä niin, että vuosia tulee vähintään 15.

Pine – Mänty

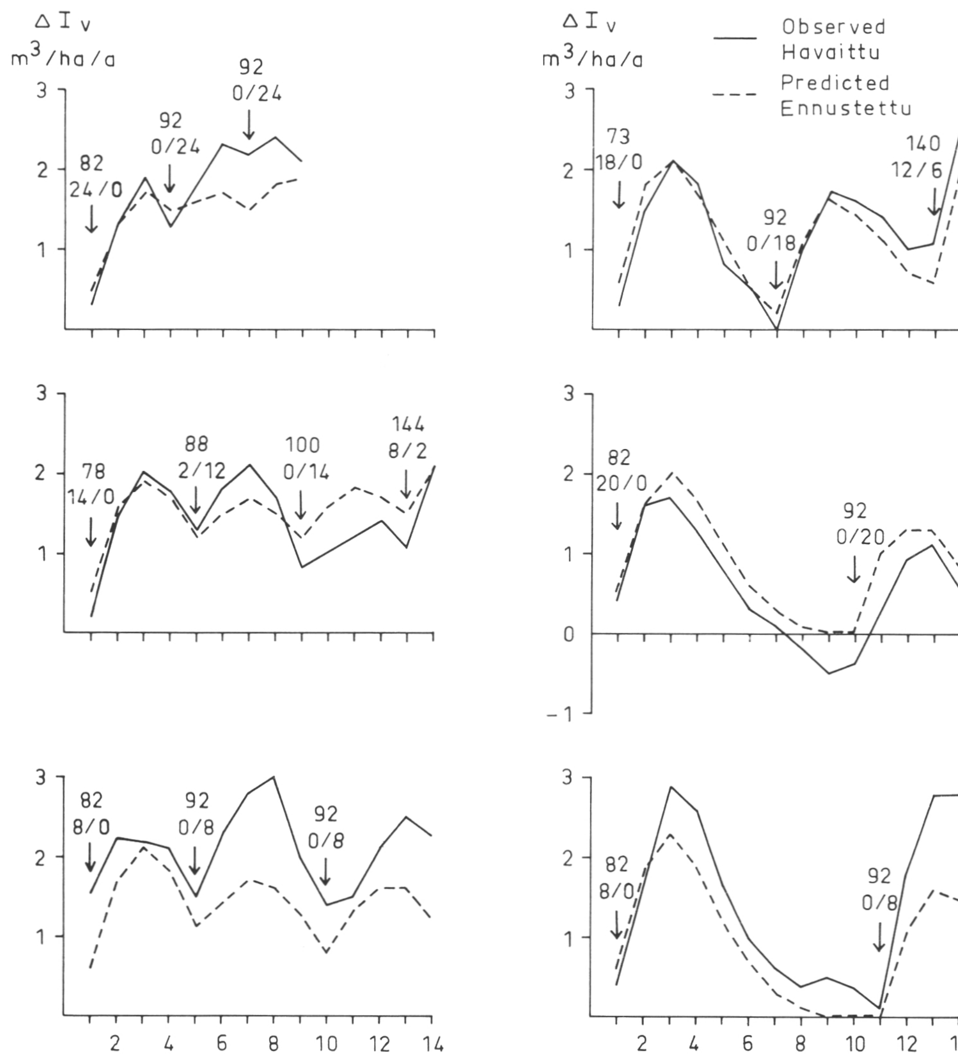


Fig. 16. Observed and predicted responses in the pine experiments in southern Finland fertilized at different time intervals. The fertilization times are marked with arrows and above them on the left is the number of plots fertilized with As/Os and on the right that for urea. The average nitrogen dose (kg N/ha) of the application time in question is marked uppermost.

Kuva 16. Havaittuja ja mallilla laskettuja kasvunlisäyksiä eripituisin aikavälein lannoitetuilla Etelä-Suomen mäntykokeilla. Lannoitusten ajankohdat on merkitty nuolilla ja niiden yläpuolella vasemmalla As/Os:lla ja oikealla urealla lannoitettujen koealojen määrä. Ylimpänä ko. lannoituskerran keskimääräinen typpiannos (kg N/ha).

The mean annual growth responses in those southern experiments which have been fertilized at regular intervals are presented in Figs. 16 and 17. Owing to the fact that only small amounts of fertilizer were given at each application, the mean response was better the shorter was the interval between fertilizations. The figures show that the model for pine better fits the material than the model for spruce. The growth level in the spruce stands was higher and therefore the calculation of the response was less reliable than in the pine stands. This partly explains the great variation in the difference between the observed values and those predicted by the model. The annual means

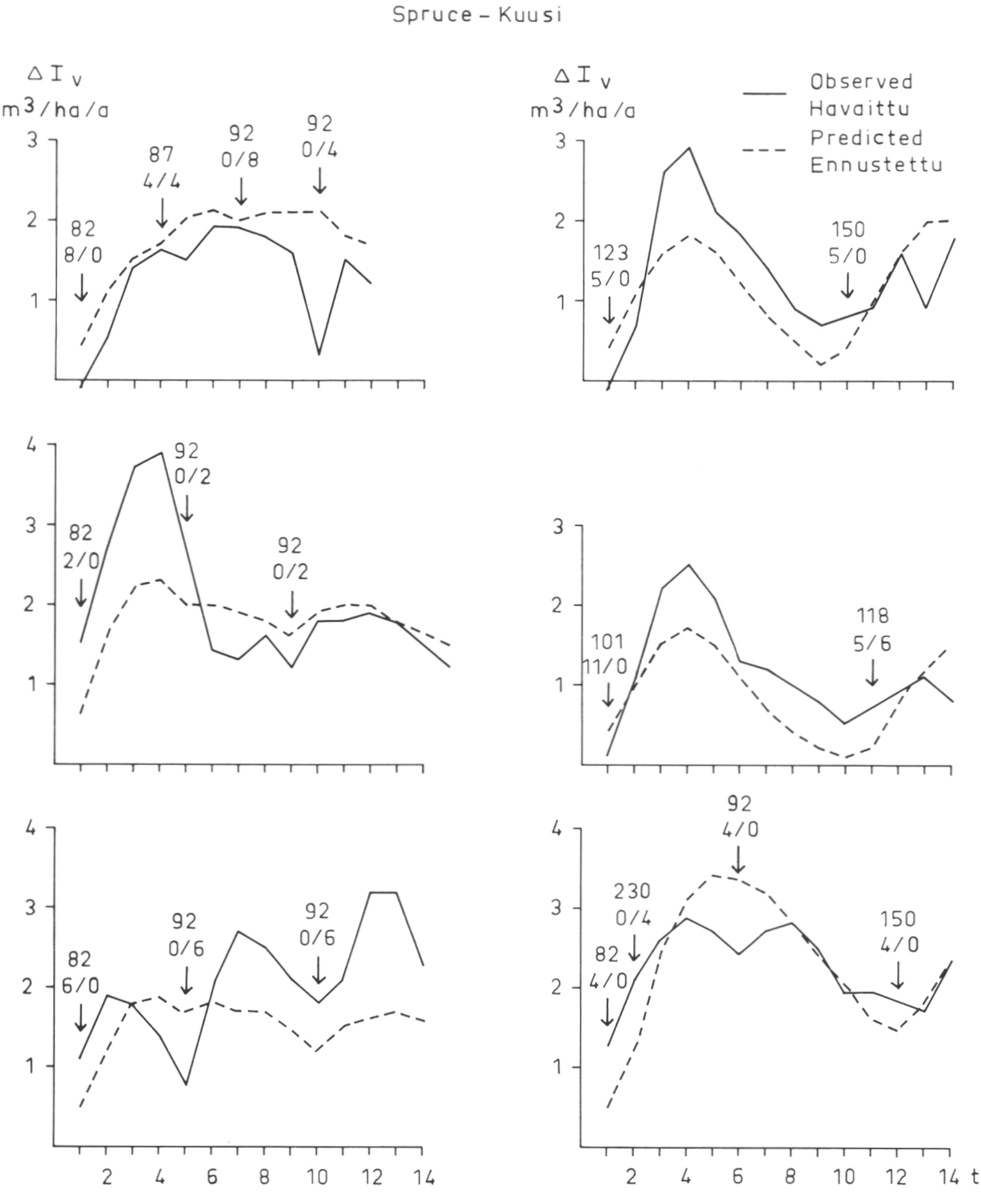


Fig. 17. Observed and predicted responses in the spruce experiments in southern Finland fertilized at different time intervals. Markings as in Fig. 16.

Kuva 17. Havaittuja ja mallilla laskettuja kasvunlisäyksiä eri pituisin aikavälein lannoitetuilla Etelä-Suomen kuusikokeilla. Merkinnät kuten kuvassa 16.

of the responses and predicted values for the entire southern material are presented in Fig. 18. The mean responses calculated from the part-materials are presented in Table 8.

The influence of fertilizer level on fertilization efficiency, i.e. on the response given by one kilogram of nitrogen per hectare, is more pronounced in spruce than pine stands. The efficiency does not vary to any great extent in pine stands when the interval between fertilizations is longer than five years. In spruce stands the efficiency increases when the interval between fertilizations is extended beyond five years (Table 9). For example, a fertilizer dose

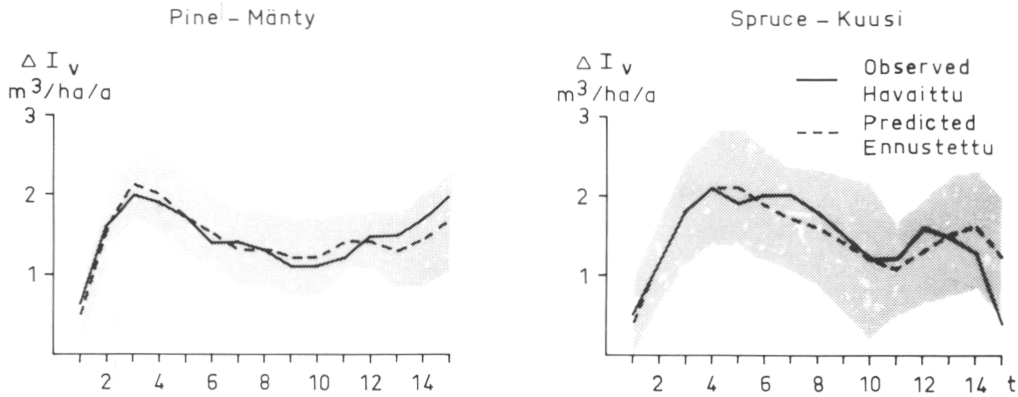


Fig. 18. Annual means of the observed and predicted growth responses in the material for southern Finland. The simple residual variance of the model has been shaded. For average fertilization data see Table 4.

Kuva 18. Havaittujen ja mallilla laskettujen kasvunlisäysten vuosittaiset keskiarvot Etelä-Suomen aineistossa. Mallin yksinkertainen jäännöshajonta on merkitty varjostuksella. Lannoituksia koskevat keskimääräistiedot ovat taulukossa 4.

of 150 kg N/ha every five years produces an effect in pine stands which is 91 % of that obtained when fertilizing every nine years. The corresponding figure in spruce stands is 80 %. If fertilization with 75 kg N/ha is repeated every five years in spruce stands, the efficiency is 12 % greater than for a dose of 150 kg N/ha. In pine stands the corresponding percentage is only 4. There is no difference in the efficiency of these nitrogen doses if fertilization is repeated every nine years.

As is already apparent from the abovementioned figures, the efficiency of fertilization weakens as the interval between fertilizations is shortened. For example, the efficiency obtained by applying a dose of 150 kg N/ha every three years in a pine stand is about 4/5 of that obtainable by applying the same dose every nine years. The corresponding value in a spruce stand is 3/5. On the other hand, if the interval between fertilizations is kept constant, a better fertilization efficiency is reached with smaller single doses.

The change in the fertilization efficiency can also be studied by comparing alternative regimes having the same mean annual nitrogen level. For example, 50/2 (= 50 kg N/ha every 2 years), 100/4, 150/6 and 200/8 all correspond to a mean annual nitrogen level of 25 kg N/ha. In this part of the text the mean annual level is called the nitrogen rate. With low nitrogen rates (e.g. 15 kg N/ha/a) the best efficiency is obtained by repeating fertilization at approximately the time when the response to the previous fertilization has terminated. When the nitrogen rate is increased, the interval between fertilizations leading to the best efficiency is shortened.

Table 8. Average annual response in the part-materials. Standard deviation of the response is given in parentheses. For stand data see Table 1 and for fertilization data Table 4.

Taulukko 8. Osa-aineistojen keskimääräiset vuotuiset kasvunlisäykset. Suluissa kasvunlisäyksen keskihajonta. Puustotiedot ovat taulukossa 1 ja lannoitustiedot taulukossa 4.

Tree species and region *Puulaji ja alue*	Fertilization *Lannoitus* N	NP	Nitrogen fertilizer *Lannoitelaji* As/Os	Urea
	Growth response (m³/ha/a) *Kasvunlisäys*		Proportion of the fertilizer nitrogen (%) *Osuus lannoitetyppimäärästä*	
Pine South Finland *Mänty Etelä-Suomi*	1,43 (1,27)		48	52
Pine North Finland *Mänty Pohjois-Suomi*	0,90 (0,92)		48	52
Spruce South Finland *Kuusi Etelä-Suomi*	1,28 (1,45)	1,74 (1,81)	49	51
Spruce North Finland *Kuusi Pohjois-Suomi*	0,89 (0,73)	1,14 (0,89)	19	81

Table 9. Fertilization efficiency with different fertilization regimes in relation to the result for the most efficient regime (which is given as 100). Efficiency refers to the response in relation to the nitrogen level applied. The single dose is obtained in the different alternatives as a product of the interval between fertilizations and the nitrogen rate. Fertilizer type As/Os.

Taulukko 9. Lannoituksen teho eri lannoitusohjelmilla suhteessa tehokkaimman lannoitusohjelman antamaan tulokseen, jota merkitään 100:lla. Teholla tarkoitetaan kasvunlisäystä suhteessa annettuun typpimäärään. Kerta-annos eri vaihtoehdoissa saadaan toistamisvälin ja typpitason tulona. Lannoitelajina As/Os.

Tree species *Puulaji*	Interval between fertilizations (a) *Lannoituksen toistamisväli*	Nitrogen rate (kg N/ha/a) *Typpitaso*			
		15	20	25	30
		Relative efficiency (%) *Suhteellinen tehokkuus*			
Pine *Mänty*	3	88	87	86	85
	5	95	94	93	91
	7	100	99	97	94
	9	100	98	94	89
Spruce *Kuusi*	3	82	81	78	75
	5	89	87	84	79
	7	100	96	91	84
	9	100	96	90	82

The best efficiencies are produced at different nitrogen rates by the following dose/interval combinations:

Nitrogen rate (kg N/ha/a)	Single dose (kg N/ha) / Interval between fertilizations (a) Pine stand	Spruce stand
15	150/10	150/10
20	160/8	140/7
25	150/6	175/7
30	180/6	(210/7)

The fertilization efficiency weakens more in spruce than in pine stands with inceasing nitrogen rate (Fig. 12, Table 9).

The aim of fertilization is not usually to achieve maximum fertilization efficiency, but only a certain quantitative growth increase. It can be seen from Table 10 that the response becomes smaller as the size of the dose becomes smaller and the interval between fertilizations lengthens. The figures in the table represent responses in the very best fertilization objects in relation to both the site and the developmental stage of the stand. The model can be used to draw up corresponding tables for stands with different standing crops and growing on different types of site. The tables indicate which different combinations of fertilizer dose and interval between fertilizations will produce similar responses. For instance, a response of about 2 m^3/ha/a can be obtained in pine stands with the fertilizers and standing crops presented in Table 10 using the following combinations: 75/4, 100/6, 125/7 and 150/9, and in spruce stands with the following combinations (plus P fertilization): 75/5, 100/7, 125/9 and 150/11. In order to reach the same response level on other sites with different standing crops, a more intensive fertilizer regime is required. The table shows that as the interval between fertilizations lengthens, the response starts to decrease faster in pine stands than in spruce stands.

If the largest possible response is aimed at, although it is not economically sensible, then 100—150 kg N/ha should be applied every 2—3 years. Higher doses applied over the same intervals do not increase the growth further. On the other hand, a larger proportion of the fertilizers is wasted through leaching and volatilization, and the harmful effects increase.

Table 10. Response obtainable with the fertilization regime started after the first thinning. Site index H_{100} = 24, age at the start 40 years, stem number 1000 in pine and 1100/ha in spruce stand. N fertilization in pine and NP in spruce stand, fertilizer type As/Os. The response in calculated for the same period of time as in Fig. 15.

Taulukko 10. Ensiharvennuksen jälkeen aloitetulla lannoitusohjelmalla saatava kasvunlisäys. Boniteetti H_{100} = 24, ikä alussa 40 vuotta, runkoluku männikössä 1000 ja kuusikossa 1100/ha. Männikössä N- ja kuusikossa NP-lannoitus, lannoitelajina As/Os. Kasvunlisäys on laskettu samalta ajanjaksolta kuin kuvassa 15.

Tree species *Puulaji*	Interval between fertilizations (a) *Lannoituksen toistamisväli*	Single dose (kg N/ha/a) *Kerta-annos*			
		75	100	125	150
		Growth response (m^3/ha/a) *Kasvunlisäys*			
Pine *Mänty*	3	2,6	3,3	4,0	4,7
	4	2,0	2,7	3,3	3,8
	5	1,7	2,2	2,7	3,2
	6	1,4	1,9	2,4	2,8
	7	1,3	1,7	2,1	2,5
	8	1,1	1,5	1,8	2,2
	9	1,0	1,3	1,6	2,0
Spruce *Kuusi*	3	2,8	3,5	4,0	4,2
	4	2,3	3,0	3,5	3,9
	5	1,9	2,5	3,0	3,5
	6	1,7	2,3	2,8	3,2
	7	1,5	2,1	2,5	3,0
	8	1,3	1,8	2,2	2,6
	9	1,2	1,6	2,0	2,4

Effect of phosphorus

Before the decision was made to combine the pine plots fertilized with phosphorus and the unfertilized pine plots into one group, the effect of phosphorus on the growth of the pine stands was tested. The average effect of phosphorus both alone and with nitrogen proved to be very small. Phosphorus did not promote the growth of the pine stands, at any rate not during the period under study. Only on the most fertile sites was a slightly positive effect observed.

The effect of phosphorus applied together with nitrogen was distinct in the spruce stands (Fig. 19, Table 8) and became proportionally more important as the fertility of the site increased. However, as the effect of nitrogen simultaneuously weakened, the response to NP fertilization was smaller on fertile than on less fertile sites (Fig. 20). Refertilization with phosphorus was carried out selectively on the most fertile sites, which were presumably suffering from phosphorus deficiency. Phosphorus had increased growth more on these sites than in those experiments with only one phosphorus application.

When As/Os fertilization alone was compared, a better response was obtained in pine than spruce stands. There was a slight difference in favour of spruce when As/Os was applied together with phosphorus (Fig. 20), whereas the effect of urea, even with phosphorus, remained weaker in the spruce than in the pine stands.

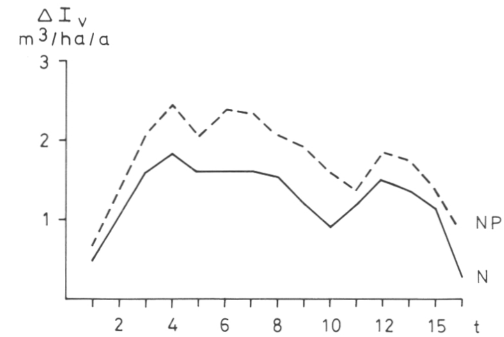


Fig. 19. Annual means of the responses brought on by N and NP fertilization in the spruce experiments in southern Finland.

Kuva 19. N- ja NP-lannoituksen aiheuttamien kasvunlisäysten vuosittaiset keskiarvot Etelä-Suomen kuusikokeilla.

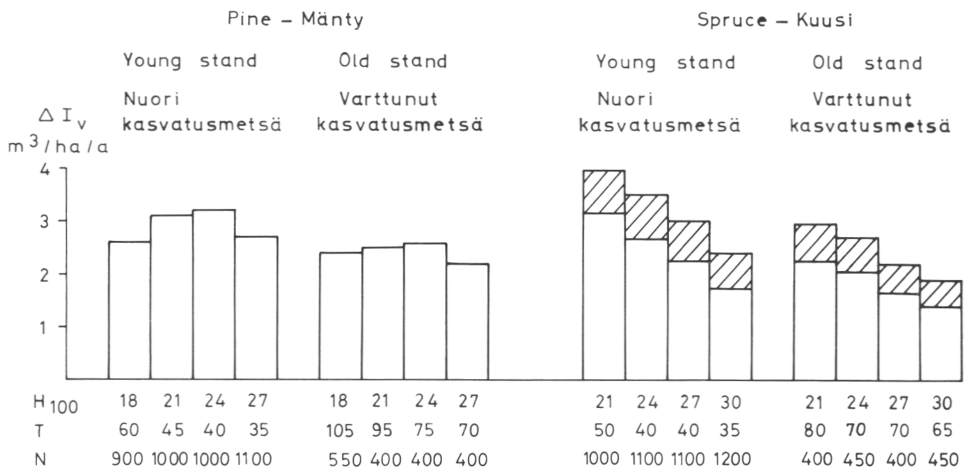


Fig. 20. Dependence of response on site index at different developmental stages of stand. Nitrogen dose of 150 kg/ha at five-year intervals, fertilizer type As/Os. Age (T) and stem number (N) obtained from the investigation of Vuokila and Väliaho (1980). The hatched area indicates the interaction of nitrogen and phosphorus fertilization. The response is calculated starting from each age marked in the figure for the same period of time as in Fig. 15.

Kuva 20. Kasvunlisäyksen riippuvuus pituusboniteetista puuston eri kehitysvaiheissa. Typpiannos 150 kg/ha viiden vuoden välein, lannoitelajina As/Os. Ikä (T) ja runkoluku (N) on otettu Vuokilan ja Väliahon (1980) tutkimuksesta. Varjostettu osa on typpi- ja fosforilannoituksen yhdysvaikutus. Kasvunlisäys on laskettu kustakin kuvaan merkitystä iänkohdasta alkaen samalta ajanjaksolta kuin kuvassa 15.

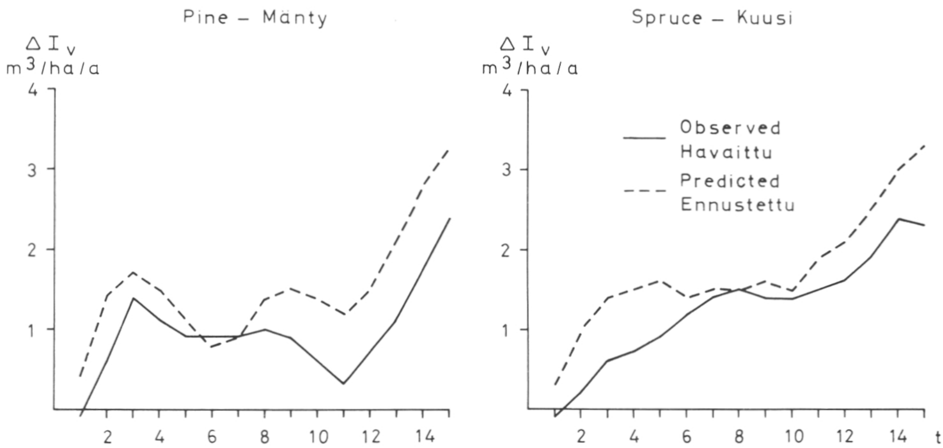


Fig. 21. Annual means of the responses in northern Finland observed and predicted by the model devised for southern Finland.
Kuva 21. Havaittujen ja Etelä-Suomen aineistoon perustuvalla mallilla laskettujen kasvunlisäysten vuosittaiset keskiarvot Pohjois-Suomen aineistossa.

62. Effect of external factors

Geographical location

The northern part-material was omitted from the model as it was too small for a model of its own to be constructed and it could not be combined with the southern material. Differences in the response between southern and northern Finland were studied by using the model to predict responses for the northern experiments and investigating the differences between them and the measured values (Fig. 21). An attempt was also made to apply the model to the northern conditions by calculating a coefficient which would correct the difference between the part-materials. However, the use of the coefficient was not reasonable as the response is slower in the north than in the south (see Pettersson 1980, Laakkonen et al., unpub.). Another obstacle was that the same site index value corresponds to different nutrient conditions in the south and in the north.

The mean growth responses in northern Finland are presented in Table 8. The average response in the northern pine stands was 63 % of that calculated by the model. The corresponding value was 69 % in the spruce stands (Fig. 21). The relative difference seems to remain approximately constant. In northern Finland, too, NP fertilization improved the growth of spruce stands clearly more than nitrogen fertilization alone. The response of northern spruce stands to urea application resembled more closely the response to As/Os fertilization than it did in southern Finland.

According to the residual variance, the growth response in southern Finland proved to be independent of the temperature sum. On the other hand, the model underestimated the response in some experiments situated about 200 m above sea level (see also Rosvall 1980). The good results from these experiments may be accidental, for the experiments had been fertilized with urea in the same years, and favourable weather may have contributed towards this result.

Site and standing crop

The effect of fertility on the response to fertilization is represented in the model by the site index. The site index had a slightly different effect in spruce and pine stands (Figs. 9 and 20). According to the model, the response of the pine stands increased up till a site index value $H_{100} = 24$, above which it decreased abruptly. The spruce stands were most strongly affected at index value $H_{100} = 15$. In the spruce stands the response to nitrogen weakened steadily as the fertility of the site improved. The role of phosphorus, however, became proportionally more important as the site im-

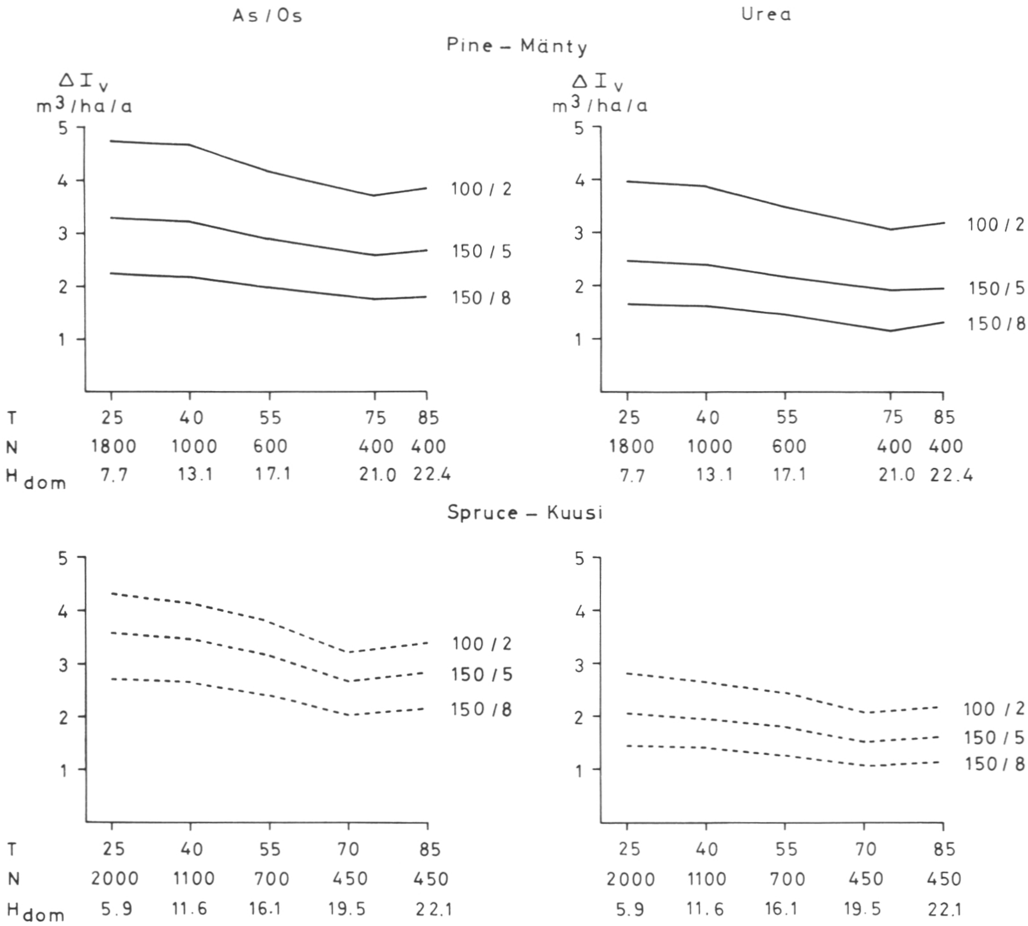


Fig. 22. Response obtainable by repeated fertilization at different developmental stages of the stand according to the model. Fertilization regimes indicated at the end of the lines: single dose (kg N/ha)/interval between fertilizations (a). Age (T), stem number (N) and dominant height (H_{dom}) obtained from Vuokila and Väliaho's investigation (1980) at site index H_{100} = 24. N fertilization in pine and NP in spruce stands. The response is calculated starting from each age marked in the figure for the same period of time as in Fig. 15.

Kuva 22. Toistuvalla lannoituksella saatava kasvunlisäys metsikön eri kehitysvaiheissa mallin mukaan. Viivojen päissä lannoitusohjelma: kerta-annos (kg N/ha)/lannoitusväli (a). Ikä (T), runkoluku (N) ja valtapituus (H_{dom}) on otettu Vuokilan ja Väliahon (1980) tutkimuksesta boniteetilta H_{100} = 24. Männiköissä N- ja kuusikossa NP-lannoitus. Kasvunlisäys on laskettu kustakin kuvaan merkitystä iänkohdasta alkaen samalta ajanjaksolta kuin kuvassa 15.

proved. The effect of site on the response of spruce stands may be distorted in the model. It is possible that the site index has been underestimated in the most infertile sites. Their standing crop is old and has probably earlier been treated with selection felling.

The growth response obtainable through fertilization is greatest in young stands and weakens slowly as the stand matures. The response in the stands approaching final cutting is about 4/5 of that at the first thinning stage (Fig. 22). A higher density improves the response (Fig. 15). If, however, the stand becomes too dense, the response starts to decline again (Fig. 8). Spruce stands which produce the greatest response are probably denser than corresponding pine stands. According to the model, as the volume increases, but the stem number remains constant, the response brought on by fertilization increases.

7. REPEATED FERTILIZATION IN PRACTICE

71. Applications of the investigation

The results of the investigation can be applied to 30 to 100-year-old stands in southern Finland. The northern material is too small to act as the basis of recommendations for either fertilizer rates or stand characteristics. The same fertilization carried out in a similar stand produces a clearly poorer outcome in northern than southern Finland (cf. Keltikangas and Seppälä 1973).

As the material covers a period lasting for approximately 15 years only, conclusions and recommendations can only be made for a similar period of time. The single doses used were lower than those presently recommended, thus making it possible to study the effect of rather small single applications. As the conclusions concerning urea fertilization are based on spring applications, it is not certain how well they reflect the use of urea at other times of the year. According to Lipas and Levula (1980), better results are obtained if urea is spread in the autumn instead of spring. Mälkönen (1979) and Päivinen and Salonen (1981) have arrived at a similar result. Möller (1982) claims, according to a limited material, that the result obtained with urea does not depend on the spreading time. In their investigation, Päivinen and Salonen (1981) found that spreading urea in the autumn gave a slightly poorer result than when ammonium nitrate with lime was used in the spring.

The results for the pine material are the most reliable. The spruce material is too restricted, so the results can only be considered as indicative.

72. Comparison with other investigations

The response model was tested by comparing the predictions given by the model with the results of some other investigations. Gustavsen and Lipas (1975) investigated single fertilizer applications and the model was used to predict the response for the part of their material which corresponded to that used in the model (Table 11). In spruce stands treated with heavy nitrogen fertilization the predicted values were higher than the responses reported by Gustavsen and Lipas. No corresponding feature was found in the case of the pine stands.

The response to a single application predicted by the model was also compared to the response predicted by Rosvall's model (1980). The comparison is difficult owing to the fact that some of the variables used are different. It was, however, found that the predicted values obtained using Rosvall's model were higher in mature stands treated with both As/Os and urea than the values obtained using the model of the present investigation. The comparison between the models as regards the site index was done using stand characteristics in the first-thinning phase. The age, growth etc. were therefore not the same on the different sites. The differences between the predicted values given by these two models were approximately equal on different sites in the case of pine stands. With spruce stands, however, the difference increased sharply as the site index improved, because the response predicted by Rosvall's model increased while according to this investigation it decreased.

Eriksson and Jansson (1981) have presented a model for predicting the response given by repeated fertilization. According to the present investigation, the interval between fertilizations has a more powerful effect on the average annual response than Eriksson and Jansson's model indicates (Fig. 23). The data used by Eriksson and Jansson were based on the average annual response obtained during the first two intervals between fertilizations and they assumed that the response will continue at that level. In the case of fertilization

Table 11. Comparison of the 5-year response measured and predicted using the part-material of Gustavsen and Lipas (1975, groups I—IV, VIII and X). Predicted values were calculated for the NPK fertilized observations using As/Os as the nitrogen fertilizer type, and phosphorus with nitrogen in spruce stands.
Taulukko 11. Gustavsenin ja Lipaksen (1975) osa-aineistolla (ryhmät I-IV, VIII ja X) tehty mitatun ja mallilla lasketun 5-vuotisjakson kasvunlisäyksen vertailu. Y-lannoitetuille havainnoille laskettiin ennusteet käyttäen lannoitelajina As/Os:ia ja kuusikossa fosforia typen ohella.

	Dose (kg N/ha) — *Typpimäärä*					
	60	80	120	160	180	240
	Growth response (m³/ha/a) — *Kasvunlisäys*					
Pine — *Mänty*						
As, Os and Y fertilization *As-, Os- ja Y-lannoitus*						
Observed — *Havaittu*	0,4	1,6	1,5	3,0	2,2	3,5
Predicted — *Ennustettu*	1,0	1,4	1,9	2,5	2,5	3,3
Urea fertilization *Urealannoitus*						
Observed — *Havaittu*	0,4	1,1	0,7	2,4	1,6	2,7
Predicted — *Ennustettu*	0,5	0,8	1,2	1,7	1,7	2,4
Spruce — *Kuusi*	72	90	108	144	180	216
NPK fertilization *NPK-lannoitus*						
Observed — *Havaittu*	2,2	2,1	1,3	2,4	2,6	2,8
Predicted — *Ennustettu*	1,6	1,8	2,4	2,8	3,1	3,8

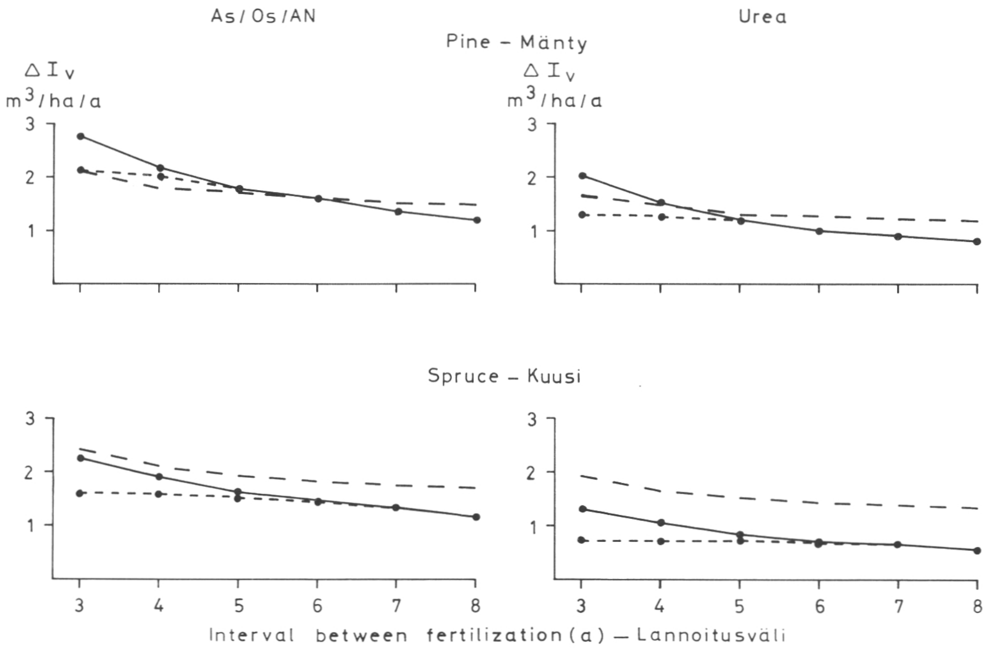
repeated over short intervals the assumption leads to an underestimation of the response, as the response level will continue to rise after the two intervals between fertilizations (see Fig. 12). For the sake of comparison, Fig. 23 includes the average response during the first two intervals between fertilizations calculated using the model of the present investigation. The responses given by As/Os fertilization predicted for pine stands were of the same level. In spruce stands fertilized only with nitrogen, however, the responses predicted by Eriksson and Jansson's model were clearly higher than those obtained using the model of the present investigation.

The model was also tested by predicting the responses for the experimental stands of Päivinen and Salonen (1978) and Burgtorf (1981), and then comparing the responses with the results introduced by the same authors. The experiments carried out by Päivinen and Salonen had been fertilized twice at an interval of six years and each time the nitrogen dose was 100, 200 or 400 kg/ha. In the case of the smallest single dose in the pine experiments, the predicted value was 62 % of that reported by Päivinen and Salonen and for the two largest single doses 92 % and 106 % respectively. In the spruce experiments, the predicted values were lower in the case of all the nitrogen doses and the differences were most distinct with low nitrogen doses.

As Burgtorf's material consisted of four old pine stands situated in central and northern Sweden, part of it was not in the same climatic region as the data for the present model. The fertilization regime had been intensive: initially 60 kg N/ha was applied every two years five times in succession and later on 120 kg N/ha every three years on four occasions. The predicted values calculated for the four successive 5-year-periods were 102, 82, 95 and 103 % of the mean values of Burgtorf's results.

73. Choice of fertilization objects

When searching for a site suitable for fertilization, it should be borne in mind that the greatest growth response for spruce stands is obtained on a poorer site index than for pine stands. The greatest response in pine stands was obtained at a site index $H_{100} = 24$. When converting the site index values into site types as introduced by Vuokila and Väliaho (1980), the greatest antici-



●—● = according to the model of the present investigation, the calculation period including as many complete intervals between fertilizations after the start of the fertilization regime so as to give total of at least 15 years.
tämän tutkimuksen mallin mukaan, kun laskentajaksoon on otettu mukaan täysiä lannoitusvälejä niin, että vuosia tulee vähintään 15.

●--● = according to the model of the present investigation, the calculation period including the first two complete intervals between fertilizations, as done by Eriksson and Jansson.
tämän tutkimuksen mallin mukaan, kun laskentajaksona on kaksi ensimmäistä täyttä lannoitusväliä kuten Erikssonilla ja Janssonilla.

----- = according to Eriksson and Janssons's model (1981)
Erikssonin ja Janssonin (1981) mallin mukaan.

Fig. 23. Effect of interval between fertilizations on the response. Single dose 100 kg N/ha.
Kuva 23. Toistamisvälin vaikutus lannoitusreaktioon. Kerta-annoksena on 100 kg N/ha.

pated response was on sites of the *Vaccinium vitis-idaea* site type. In middle-aged stands the differences between *Vaccinium vitis-idaea* and *Vaccinium myrtillus* site types are not large in spruce stands.

Several investigations (e.g. Möller 1972, Gustavsen and Lipas 1975, Rosvall 1980) have used the growth at the time of fertilization to predict the response. However, the growth at the time of primary fertilization does not very well explain the response obtained with repeated fertilization (see Lipas 1979). On the other hand, the estimation of growth on the basis of increment cores is such a laborious process in practice that it is usually carried out using stand characteristics (e.g. Nyyssönen and Mielikäinen 1978) as in this investigation when explaining the magnitude of the response.

One of the aims in growing a stand is to produce large-diameter timber, which is achieved by regulating the growing density. Stands approaching the final cutting stage are therefore not dense enough from the point of view of obtaining the greatest response to fertilization. When the greatest possible response is aimed at, the stands which are fertilized should be slightly denser than they are at present. The greatest response occurs during the period after the first thinning. The ability to respond decreases as the stand ages (see Gustavsen and Lipas 1975, Rosvall 1980).

One may suspect, differing from the assumption in the model, that the greatest response in spruce stands is obtained using smaller amounts of fertilizer than in pine stands (Malm and Möller 1975). This is probably partly due to the fact that spruce sites are more fertile on average than pine sites. Compared to As/Os fertilization, urea led to a relatively poorer response in spruce than in pine stands (see also Rosvall 1978). As the addition of phosphorus together with nitrogen clearly increased the response in spruce stands, it is recommended that NP fertilization be used with spruce (see also Brantseg et al. 1970, Lipas 1981b). Pine stands do not seem to require phosphorus application, not at least during such a fertilization period as covered by this investigation.

74. Choice of fertilization regime

From the point of view of the wood production, the effect of fertilization can be studied as volume units (m³/ha/a) and also as the biological input output ratio of fertilization (dm³/kg N/a).

Alternative regimes suitable for different situations are given in Fig. 24. These alternative fertilization regimes can be arranged in an order of biological efficiency by means of Fig. 25. These figures present the response in stands which are at their optimum with regard to the response to fertilization, thus the other stand and site factors produce a lower response and weaker efficiency. However, the mutual order of preference of the fertilization regimes remains unchanged. The figures also include areas which are clearly not covered by the study material. They are not meant as a basis for decision making, but they do illustrate in principle the response with different fertilization regimes. When the goal is to reach a certain response level, there is a fairly large number of alternatives which lead roughly to the same result.

The best efficiency for each single-dose level is obtained by repeating fertilization when the effect of the previous one is about to cease (Fig. 25). The results of previous investigations (Friberg 1971, 1973, Gustavsen and Lipas 1975, Jonsson 1978) indicate that the response in relation to the nitrogen dose diminishes when the single application exceeds 200 kg N/ha. As the nutrients given in the previous fertilizer application are usually still exerting an effect when fertilization is repeated, it is better to apply

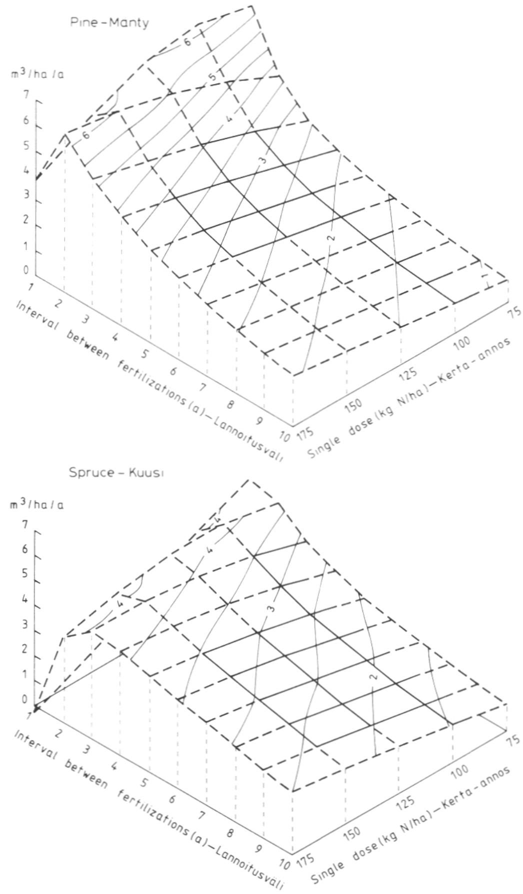


Fig. 24. Effect of single dose and interval between fertilizations on the response obtainable through fertilization in a young stand. Site index H_{100} = 24, age at the start 40 years, stem number 1000 in pine and 1100/ha in spruce stand. N fertilization in pine and NP in spruce stand, fertilizer type As/Os. The response is calculated for the same period of time as in Fig. 15. The area drawn with solid lines indicates the range of the observation material.

Kuva 24. Kerta-annoksen ja toistamisvälin vaikutus lannoituksella saatavaan kasvunlisäykseen nuoressa kasvatusmetsässä. Boniteetti H_{100} = 24, ikä alussa 40 vuotta, runkoluku männikössä 1000 ja kuusikossa 1100/ha. Männikössä N- ja kuusikossa NP-lannoitus, lannoitelajina As/Os. Kasvunlisäys on laskettu samalta ajanjaksolta kuin kuvassa 15. Yhtenäisillä viivoilla piirretty osa kuvaajasta ilmaisee aineiston vaihtelualueen.

smaller doses than if fertilization is carried out only once. Owing to the volatilization losses of urea nitrogen and its strong binding in the humus, urea could be applied in slightly larger nitrogen doses than As/Os.

The ratio between the stem and root volume of trees increases as the site becomes

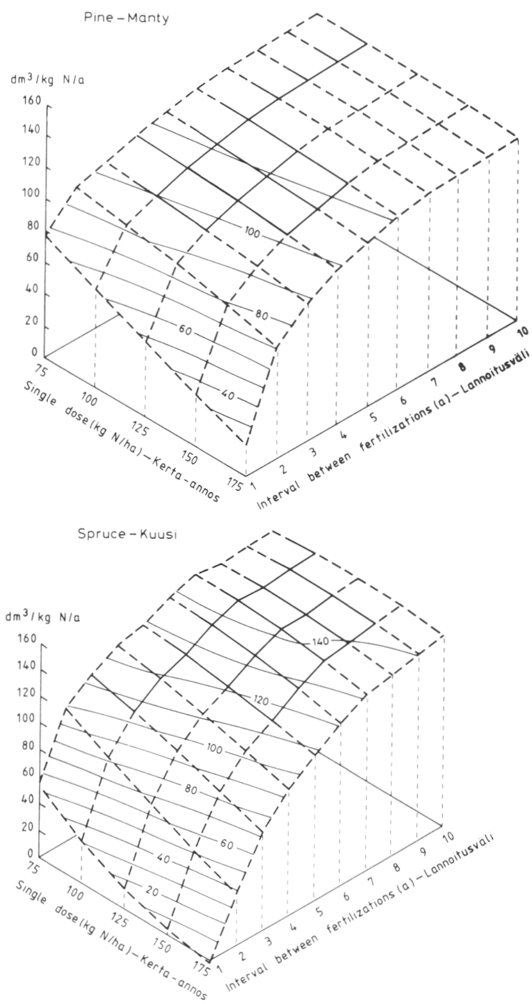


Fig. 25. Effect of single dose and interval between fertilizations on the response obtainable per kilogram of nitrogen in a young stand. Stand and fertilization data as in Fig. 24. The response is calculated for the same period of time as in Fig. 15. The area drawn with solid lines indicates the range of the observation material.

Kuva 25. Kerta-annoksen ja toistamisvälin vaikutus typpikilolla saatavaan kasvunlisäykseen nuoressa kasvatusmetsässä. Puusto- ja lannoitustiedot ovat samat kuin kuvassa 24. Kasvunlisäys on laskettu samalta ajanjaksolta kuin kuvassa 15. Yhtenäisillä viivoilla piirretty osa kuvaajasta ilmaisee aineiston vaihtelualueen.

more fertile (Laitakari 1927). Correspondingly, it it obvious that fertilization temporarily alters the internal growth ratios of the tree, promoting the growth of stemwood (Tölle 1969, Tamm 1979, Axelsson 1981). When the effect of fertilization terminates, the growth of stemwood declines temporarily since the tree is engaged in strengthening its root system (cf. Lipas 1975). In order to maintain a constant pattern of internal growth and to prevent the decline in stemwood growth after fertilization, refertilization should be carried out while the previous fertilization effect is still going on. As the response lasts longer in spruce stands than in pine stands (see Fig. 7, Möller and Rytterstedt 1975), spruce stands require less frequent fertilization than pine stands.

The response to repeated fertilization depends on much the same factors as the response to primary fertilization. One may agree with Puro (1977) who states that the response to refertilization is the better, the greater the response to primary fertilization has been (see also Eriksson and Jansson 1981).

It would thus appear that in southern Finland the interval between fertilizations should be confined to 4—8 years and the size of single doses to 100—150 kg N/ha. If the goal is to obtain the greatest quantitative growth response within these fertilization regime limits, the shortest interval should be used with the biggest single dose (Fig. 24). If the goal is to obtain the greatest response per kilogram nitrogen, the longest possible interval is used with a small dose (Fig. 25). Outside the given ranges there are intensive fertilization regimes that produce more than the above mentioned ones, at least at the beginning. However, it is better not to use them because of increased risk of harmful effects.

REFERENCES

ALBREKTSSON, A. 1980. Tallens biomassa. Storlek — utveckling — uppskattningsmetoder. Summary: Biomass of Scots pine (*Pinus sylvestris* L.). Amount — development — methods of mensuration. Sveriges Lantbruksuniversistet, Institutionen för Skogsskötsel. Rapporter 2:1—189.

— , ARONSSON, A. & TAMM, C.O. 1977. The effect of forest fertilisation on primary production and nutrient cycling in the forest ecosystem. In: Nutrient cycle in tree stands. Nordic symposium. Silva Fenn. 11(3):233—239.

ANDERSSON, S-O. 1953. Om tidpunkten för den årliga diametertillväxtens avslutande hos tall och gran. Summary: On the date of completion of annual diametral growth in pine and spruce. Medd. Statens Skogsforskn. Inst. 43(5):1—27.

AXELSSON, B. 1981. Site differences in yield — differences in biological production or in redistribution of cabon within trees. Sveriges Lantbruksuniversitet, Institutionen för ekologi och miljövård. Rapport 9:1—11.

BRAASTAD, H., FRIBERG, R. & GUSTAVSEN, H.G. 1974. The volume growth increase after fertilization. Föreningen Skogsträdsförädling, Institutet för skogsförbättring. Årsbok 1973:124—138.

BRANTSEG, A. 1967. Kovien maiden metsänlannoitus. Summary: Fertilisation of firm forest land. Metsätaloudellinen Aikakauslehti 2:44—50,64.

— , BREKKA, A. & BRAASTAD, H. 1970. Gjødslingsførsok i gran- og furuskog. Summary: Fertilizer experiments in stands of *Picea abies* and *Pinus silvestris*. Medd. Norske Skogforsøksv. 27:537—607.

BRIX, H. 1971. Effects of nitrogen fertilization on photosynthesis and respiration in Douglas-fir. For. Sci. 17(4):407—414.

— & EBELL, L.F. 1969. Effects of nitrogen fertilization on growth, leaf area, and photosynthesis rate in Douglas-fir. For. Sci. 15(2):189-196.

BURGTORF, H. 1981. Effekten av växtnäringstillförsel till några tallbestånd på näringsfattig mark i kyliga klimatlägen. Summary: The effects of supply of plant nutrients to some pine stands on poor and cold sites. Sveriges Lantbruksuniversitet, Institutionen för skoglig marklära. Rapporter i skogsekologi och skoglig marklära 37:1—41.

DEROME, J.R.M. 1979. Urea hydrolysis and ammonia volatilization from urea pellets spread on top of the litter layer. Seloste: Urean hydrolysoituminen ja ammoniakin haihtuminen karikekerroksen päälle levitetyistä urearakeista. Commun. Inst. For. Fenn. 97(2):1—22.

ERICSON, B., FRIBERG, R. & NÖMMIK, H. 1972. Ett doseringsförsök i tall. Summary: A trial with different amounts of fertilizer in a stand of *Pinus silvestris*. Föreningen Skogsträdsförädling, Institutet för skogsförbättring. Årsbok 1971:87—110.

ERIKSSON, A. & JANSSON, G. 1981. Gödslingsintervallets betydelse för tillväxtökning och gödslingsekonomi. Föreningen Skogsträdsförädling, Institutet för skogsförbättring. Årsbok 1980:41—58.

ERKEN, T. 1970. Gödsling med höga kvävegivor. Föreningen Skogsträdsförädling, Institutet för skogsförbättring. Årsbok 1969:144—152.

FAGERSTRÖM, T. & LOHM, U. 1977. Growth in Scots pine (*Pinus silvestris* L.). Mechanism of response to nitrogen. Oecologia (Berl.). 26:305—315.

FLEWELLING, J.W. & YONG, C.Y. 1976. Tree volume table growth relationships possibly affected by fertilization. For. Sci. 22(1):58—60.

FRIBERG, R. 1971. Gödsling med höga kvävegivor. Institutet för skogsförbättring. Information, Gödsling 1971/72(1). 4 p.

— 1973. Gödsling med höga kvävegivor II. Summary: Fertilization with high amounts of nitrogen. Institutet för skogsförbättring. Information, Gödsling 1973/74(1). 4 p.

— 1974. Resultat från årstidsgödslingsförsök. Summary: Results from fertilization trials with applications at different times of the year. Institutet för skogsförbättring. Information, Gödsling 1973/74(5). 3 p.

GUSTAVSEN, H.G. & LIPAS, E. 1975. Lannoituksella saatavan kasvunlisäyksen riippuvuus annetusta typpimäärästä. Summary: Effect of nitrogen dosage on fertilizer response. Folia For. 246:1—20.

HAAPANEN, T., HARI, P. & KELLOMÄKI, S. 1979. Effect of fertilization and thinning on radial growth of Scots pine. Seloste: Lannoituksen ja harvennuksen vaikutus männyn sädekasvuun. Silva Fenn. 13(2):184—189.

HAVERAAEN, O. 1981. Tilvekst og lønnsomhet ved gjødsling av et eldre granbestand. Summary: Increment and profitableness by fertilizing and old spruce stand. Tidsskrift for skogbruk 89(3):195—204.

HEINONEN, J. 1981. Koealojen peruslaskenta. [Programme for calculating stand characteristics]. Metsäntutkimuslaitos. (Finnish For. Res. Inst.), Matemaattinen osasto. Moniste. 38 p.

ILVESSALO, Y. 1932. The establishment and measurement of permanent sample plots in Suomi (Finland). Selostus: Pysyvien koealojen perustaminen ja mittaus Suomessa. Commun. Inst. For. Fenn. 17(2): 1—39.

— 1947. Pystypuiden kuutioimistaulukot. Summary: Volume tables for standing trees. Commun. Inst. For. Fenn. 34(4):1—149.

JONSSON, S. 1978. Resultat från en tioårig försöksserie med höga kvävegivor. Summary: Results from a ten-year old series of trials with high doses of nitrogen fertilizer. Föreningen Skogsträdsförädling, Institutet för skogsförbättring. Årsbok 1977:79—128.

KARSISTO, K. 1972. Lannoituksen vaikutuksen kestoajasta suometsissä. Summary: On the duration of the effect of fertilizer application to peatland forests. Suo 23(3—4):49—56.
KELTIKANGAS, M. & SEPPÄLÄ, K. 1973. Metsänlannoituksen edullisuuden vaihtelu. Summary: Variations in the profitability of forest fertilization. Silva Fenn. 7(3):192—235.
KREUTZER, K. 1981. Der Einfluss der Düngung auf die forstliche Produktion und die dadurch entstehenden Umweltprobleme. Allg. Forstzeitschr. 32:816—821.
KUKKOLA, M. 1978. Lannoituksen vaikutus eri latvuskerrosten puiden kasvuun mustikkatyypin kuusikossa. Abstract: Effect of fertilization on the growth of different tree classes in a spruce stand on *Myrtillus*-site. Folia For. 362:1—15.
KUUSELA, K. 1966. A basal area-mean tree method in forest inventory. Seloste: Pohjapinta-alakeskipuumenetelmä metsäninventoinnissa. Commun. Inst. For. Fenn. 61(2):1—32.
LAAKKONEN, O., KEIPI, K., & LIPAS, E. Typpilannoituksen kannattavuus varttuneissa kangasmetsissä. Summary: Profitability of nitrogen fertilization in mature forests on mineral soils. Folia For. (1983— in print).
LAASASENAHO, J. 1982. Taper curve and volume functions for pine, spruce and birch. Seloste: Männyn, kuusen ja koivun runkokäyrä- ja tilavuusyhtälöt. Commun. Inst. For. Fenn. 108:1—74.
LAIHO, O. 1980. Aarnomyrskyn tuhot erilaisissa metsiköissä. Metsäntutkimuslaitos. Parkanon tutkimusaseman tiedonantoja 9:1—8.
LAITAKARI, E. 1927. Männyn juuristo. Morfologinen tutkimus. Summary: The root system of pine (*Pinus silvestris*). A morphological investigation. Acta For. Fenn. 33(1):1—380.
LEIKOLA, M. 1969. The influence of environmental factors on the diameter growth of forest trees. Auxanometric study. Acta For. Fenn. 92:1—144.
LEVULA, T. 1976. Urean levitysajankohdasta Pohjois-Suomessa. Metsäntutkimuslaitos. Rovaniemen tutkimusaseman tiedonantoja 13:1—10.
LIPAS, E. 1975. Metsän kasvu lannoitusvaikutuksen loputtua. Leipä Leveämmäksi 3:24—25.
— 1979. Alternative methods for calculating growth response to fertilization. Seloste: Vaihtoehtoisia menetelmiä lannoitusreaktion laskemiseksi. Commun. Inst. For. Fenn. 97(7):1—56.
— 1981a. Faktoriaalisen lannoituskokeen tulosten tulkinta. Summary: Interpretation of the results from factorial fertilization experiments. Folia For. 482: 1—15.
— 1981b. Fosforin tarve kangasmetsissä. Leipä Leveämmäksi 3:21.
— & LEVULA, T. 1980. Urealannoitus eri vuodenaikoina. Abstract: Urea fertilization at different times of the year. Folia For. 421:1—14.
MALM, D. & MÖLLER, G. 1975. Skillnader i volymtillväxtökning efter gödsling med urea resp ammoniumnitrat. Summary: Differences in volume growth increase after fertilization with urea and ammonium nitrate fertilizer. Föreningen Skogsträdsförädling, Institutet för skogsförbättring. Årsbok 1974:46—74.
— , MÖLLER, G. & NÖMMIK, H. 1974. Gödslingseffektens samband med växtnäringsinnehåll i mark och barr. Summary: Relation between growth response to nitrogen application and nutrient content in soil and needles. Föreningen Skogsträdsförädling, Institutet för skogsförbättring. Årsbok 1973:48—75.
MENGEL, K. & KIRKBY, E.A. 1978. Principles of plant nutrition. International Potash Institute. Berne. 593 p.
MIKOLA, P. 1950. Puiden kasvun vaihteluista ja niiden merkityksestä kasvututkimuksissa. Summary: On variations in tree growth and their significance to growth studies. Commun. Inst. For. Fenn. 38(5): 1—131.
MÄLKÖNEN, E. 1974. Annual primary production and nutrient cycle in some Scots pine stands. Selostus: Vuotuinen primäärituotos ja ravinteiden kiertokulku männikössä. Commun. Inst. For. Fenn. 84(5):1—87.
— 1977. Betydelsen av helträdsutnyttjandet i skogens näringshushållning. Skogsbruket 6:124—125,136.
— 1979. Kangasmaiden lannoitustutkimus. Summary: Research on forest fertilization on mineral soils. In: Results and tasks in forest fertilization research. Proceedings of the Finnish Forest Research Institute symposium on forest fertilization research. February 15, 1979. Folia For. 400:20—28.
MÖLLER, G. 1972. Tillväxtökning genom gödsling. Analys av äldre gödslingsförsök. (Summary.) Föreningen Skogsträdsförädling, Institutet för skogsförbättring. Årsbok 1971:50—86.
— 1982. Gödslingstidpunktens betydelse för gödslingseffekten. Summary: The influence of the time of fertilizer application on growth response. Föreningen Skogsträdsförädling, Institutet för skogsförbättring. Årsbok 1981:46—84.
— & PETTERSSON, F. 1980. Samspelseffekter mellan gödsling och gallring. Summary: Interaction between fertilization and thinning response. Föreningen Skogsträdsförädling, Institutet för skogsförbättring. Årsbok 1979:131—144.
— & RYTTERSTEDT, P. 1975. Gödslingseffektens varaktighet och förlopp hos tall och gran. Summary: Duration and course of response to nitrogen fertilizer in pine and spruce stands. Föreningen Skogsträdsförädling, Institutet för skogsförbättring. Årsbok 1974:75—97.
NOROKORPI, Y. 1977. Epätasainen lannoitus ja männiköiden pakkasvauriot. Metsä ja Puu 4:15—17.
NYYSSÖNEN, A. & MIELIKÄINEN, K. 1978. Metsikön kasvun arviointi. Summary: Estimation of stand increment. Acta For. Fenn. 163:1—40.
NÄSLUND, M. 1937. Skogsförsöksanstaltens gallringsförsök i tallskog. Zusammenfassung: Die Durchforstungsversuche der Forstlichen Versuchsanstalt Schwedens in Kiefernwald. Medd. Stat. Skogsförsöksanst. 29(1):1—169.
NÖMMIK, H. 1976. Further observations on ammonia loss from urea applied to forest soil with special reference to the effect of pellet size. Plant and Soil 45:279—282.
— & MÖLLER, G. 1981. Nitrogen recovery in soil and needle biomass after fertilization of a Scots pine stand, and growth responses obtained. Stud. For. Suec. 159:1—37.
OVERREIN, L.N. 1970. Nitrogengjødsling i skog. Saertrykk av Norsk Skogbruk nr 10, 11/12, 13/14, 15/16, 17, 22 — 1969 og 2 — 1970.
PETTERSSON, F. 1980. Gödslingseffektens fördelning över tiden. Summary: Duration and time

course of fertilization growth response. Institutet för skogsförbättring. Information, Gödsling 1979/80(3). 6 p.
PURO, T. 1977. Operaatio metsänlannoitus II. Tuloksia uusintalannoituksesta. Summary: Resulsts of the second fertilization with nitrogen. Folia For. 304:1—15.
PÄIVINEN, L. & SALONEN, K. 1978. Eri typpimäärien sekä fosforin ja kalin vaikutus kangasmetsien kasvuun Etelä-Suomessa. Summary: The effect of different amounts of nitrogen and that of phosphorus and potassium on pine and spruce stands. Kemira Oy. Metsätutkimuksia 1978(1). 4 p.
— 1981. Urea- ja ammoniumnitraattitypen levitysajan vaikutuksesta puiden kasvuun kangasmailla. (Summary.) Kemira Oy. Metsätutkimuksia 1981(1). 4 p.
ROSVALL, O. 1978. Öka årsringen-serien. Resultat från södra Sverige. Summary: Operation forest fertilization. Institutet för skogsförbättring. Information, Gödsling 1978/79(2) 5 p.
— 1979. Prognosinstrument för gödslingseffekter. Summary: Predictive equations for the estimation of fertilizer responses in Sweden. Institutet för skogsförbättring. Information, Gödsling 1979/80(1) 9 p.
— 1980. Prognosfunktioner för beräkning av gödlingseffekter. Summary: Functions for the prediction of fertilizer responses in Sweden. Föreningen Skogsträdsförädling, Institutet för skogsförbättring. Årsbok 1979:70—130.
SALONEN, K. 1973. Eri vuodenaikoina annetun typpilannoituksen vaikutuksesta kangasmetsissä. Summary: On the response of mineral-soil forests to nitrogen application during different seasons of the year. Suo 24(6):99—105.
SARAMÄKI, J. 1980. Typpilannoituksen vaikutus männyn runkomuotoon. Summary: The effect of nitrogen fertilization on the stem form of Scots pine. Commun. Inst. For. Fenn. 99(4):1—46.
SWITZER, G.L., NELSON, L.E. & SMITH, W.H. 1968. The mineral cycle in forest stands. In: Forest fertilization — theory and practice. Papers presented at the Symposium on Forest Fertilization. Gainesville, Florida. April 1967. pp. 1—9. Tennessee Valley Authority. National Fertilizer Development Center, Muscle Shoals, Alabama.
TAMM, C.O. 1974. Experiments to analyse the behaviour of young spruce forest at different nutrient levels. In: Structure, functioning and management of ecosystems. Proceedings of the First International Congress of Ecology. The Hague, The Netherlands. September 8—14, 1974. pp. 266—272.
— 1979. Nutrient cycling and productivity of forest ecosystems. In: LEAF, A.L. (ed.) Proceedings. Impact of intensive harvesting on forest nutrient cycling. State Univ. of New York, College of Enviromental Science and Forestry. Syracuse, N.Y. pp. 2—21.
TIIHONEN, P. 1979. Kasvun vaihtelu valtakunnan metsien 6. inventoinnin aineiston perusteella. Summary: Variation in tree growth in Finland based on the results of the 6th National Forest Inventory. Folia For. 407:1—12.
TÖLLE, H. 1969. Feinwurzelausbildung in mittelalten Kiefernbeständen in Abhängigkeit von Standort und Düngung. In: Forest fertilization. Proceedings. 3rd International Conference on Forest Yield. Prague. June 1969. pp. 291—301.
VEIJALAINEN, H. 1977. Use of needle analysis for diagnosing micronutrient deficiencies of Scots pine on drained peatlands. Seloste: Neulasanalyysi männyn mikroravinnetilanteen määrityksessä turvemailla. Commun. Inst. For. Fenn. 92(4):1—32.
WESTMAN, C.J. 1975. Metsänlannoituksen perusteet. Helsingin yliopisto, Metsänhoitotieteen laitos. Moniste. 50 p.
VIRO. P.J. 1966. Kangasmaan taimiston lannoitus. Summary: Manuring of young plantations. Commun. Inst. For. Fenn. 61(4):1—30.
— 1967. Forest manuring on mineral soils. Medd. Norske Skogforsøksv. 23:111—136.
— 1968. Metsän lannoitus. Metsätaloudellinen Aikakauslehti 4:116—121,137.
— 1972. Die Walddüngung auf finnischen Mineralböden. Folia For. 138:1—19.
VUOKILA, Y. & VÄLIAHO, H. 1980. Viljeltyjen havumetsiköiden kasvatusmallit. Summary: Growth and yield models for conifer cultures in Finland. Commun. Inst. For. Fenn. 99(2):1—271.

Total of 80 references

SELOSTE

Toistuvalla lannoituksella saatava kasvunlisäys kivennäismaiden männiköissä ja kuusikoissa

Tutkimuksen tarkoitus

Kertalannoitusreaktioon vaikuttavista tekijöistä on tehty pohjoismaissa lukuisia selvityksiä (esim. Viro 1967, Brantseg 1967, Brantseg ym. 1970, Möller 1972, Braastad ym. 1974, Gustavsen ja Lipas 1975, Rosvall 1980). Lannoitustutkimusten nuoruuden takia toistuvasta lannoituksesta on vasta vähän tutkimuksiin perustuvaa tietoa (esim. Puro 1977, Päivinen ja Salonen 1978, Eriksson ja Jansson 1981, Haveraaen 1981, Burgtorf 1981). Kuitenkin metsänlannoitus on Suomessa ollut käytännön toimintaa niin kauan, että metsiä on lannoitettu jo toiseen kertaan, osin useamminkin. Uusintalannoitukset on tehty tuntematta toistuvalla lannoituksella saavutettavaa kasvunlisäystä. Lannoituskohteiden valintaa varten tulisi sitä paitsi lannoittamattomat ja aiemmin lannoitetut metsiköt pystyä asettamaan suosituimmuusjärjestykseen.

Tämän tutkimuksen tarkoituksena on selvitellä tekijöitä, jotka vaikuttavat toistuvalla lannoituksella saavutettavaan kasvunlisäykseen. Keskeisenä menetelmällisenä tavoitteena on kehittää malli, jolla voidaan analysoida vaihtelevilla lannoitusohjelmilla käsiteltyä koeaineistoa ja jonka avulla tuloksia voidaan soveltaa joustavasti käytännön metsätaloudessa.

Aineisto

Aineisto koostuu Metsäntutkimuslaitoksen maantutkimusosaston vuosina 1955—65 perustamista, pääasiassa faktoriaalisista lannoituskokeista (kuva 1). Aineistoon hyväksyttiin mänty- ja kuusikokeita, jotka olivat perustamisvaiheessa iältään vähintään 20 vuotiaita ja valtapituudeltaan vähintään 4 m. Kaikkiaan aineistossa oli 63 koetta (kuva 2). Aineisto jaettiin Etelä- ja Pohjois-Suomen osa-aineistoihin käyttäen rajana lämpösummaa 1000 dd. Kokeiden perustamisajankohdan keskimääräiset puustotiedot ovat taulukossa 1 ja koealojen jakaantuminen ikä- ja tilavuusluokkiin taulukossa 2.

Tutkitun jakson keskimääräinen pituus oli 13 vuotta, vaihdellen välillä 9—19 vuotta. Tutkimusjakson aikana oli harvennettu 11 männikkö- ja 5 kuusikkokokeen puustoa. Harvennukset olivat olleet lieviä (taulukko 3).

Kokeet oli lannoitettu perustamisen yhteydessä kaikilla koejäseninä olleilla ravinteilla. Jatkossa oli uusittu ainoastaan typpilannoituksia ja joillakin kokeilla myös fosforilannoituksia (liite 1). Ensilannoituksissa oli käytetty typpilannoitteena ammoniumsulfaattia. Toistettaessa lannoituksia oli käytetty useimmissa tapauksissa ureaa ja tutkimusjakson lopussa oulunsalpietaria (taulukko 4). Aiemmin saatujen tulosten perusteella (esim. Mälkönen 1979) lannoitukset jaoteltiin aineistoa analysoitaessa urealannoituksiin ja As/Os-lannoituksiin (ammoniumsulfaatti/oulunsalpietari).

Kerralla annetut typpimäärät olivat olleet tutkimusjakson alussa pieniä ja kasvaneet jakson loppua kohti. Tutkimusjakson aikana oli typpilannoitetuille koealoille levitetty kaikkiaan typpeä keskimäärin noin 300 kg/ha ja lannoituskertoja oli ollut keskimäärin kolme (taulukko 4). Lannoitusten toistamisväli oli vaihdellut yhdestä kymmeneen vuoteen keskiarvon ollessa noin viisi vuotta.

Puiden läpimitat oli mitattu senttimetrin tasaavalla luokituksella. Koepuut oli valittu Kuuselan (1966) esittämän pohjapinta-alakeskipuu -menetelmän perusteella. Koepuiden tavoitelukumääränä oli ollut 20 puuta/koeala. Koepuut olivat vaihtuneet jonkin verran mittauskerrasta toiseen. Koepuista oli mitattu pituus desimetrin ja kapeneminen senttimetrin tarkkuudella. Niistä oli myös mitattu kiikarilla kahden 5-vuotisjakson pituuskasvu, kairattu 15 lustoa sisältävä lastu ja määritetty laboratoriossa vuotuiset sädekasvut 0,01 mm:n tarkkuudella.

Metsikkötunnusten ja kasvunlisäysten laskenta

Epäselvyyksien ja käsittelyvirheiden vuoksi hylättiin kokeiden tiettyjä mittauksia tai koko koe. Peräkkäisten mittausten pituushavaintoja verrattaessa ilmeni, että kiikarilla mitaten pituuskasvuja oli yliarvioitu. Kun virhe vaikutti oleellisesti tilavuuskasvun laskennassa korjattiin pituuskasvuja. Pituuskasvut oli mitattu viisivuotisjaksoittain ja jakson kasvu jaettiin sen vuosille käyttäen hyväksi vuosittaisia sädekasvuja.

Metsikkötunnukset laskettiin Metsäntutkimuslaitoksen koealojen peruslaskentaohjelmalla KPL (Heinonen 1981). Peruslaskennan jälkeen tarkasteltiin peräkkäisistä mittauksista samaan ajankohtaan laskettujen puustotunnusestimaattien eroja. Erohavainnot luokiteltiin puuston keskiläpimitan perusteella ja hylättiin koealat, joilla sekä pohjapinta-alan, keskipituuden että tilavuuden osalta eron itseisarvo oli suurempi kuin eron keskihajonta ko. läpimittaluokassa. Hylkäämisen syyksi riitti myös poikkeama vain yhden tunnuksen kohdalla, jos poikkeama oli suuri. Peräkkäisten mittausten tuloksista koostettiin vuosittaiset puusto- ja kasvutiedot sisältävä aikasarja.

Testausten perusteella jaoteltiin koealat lannoituksen suhteen seuraavasti:

Mänty:	
Vertailukoealat	0, Ca, CaP, CaK, CaPK, P, PK, K
N-koealat	N, CaN, CaNP, CaNK, CaNPK, NP, NPK, NK
Kuusi:	
Vertailukoealat	0, P, PK, K
N-koealat	N, NK
NP-koealat	NP, NPK

Tässä tutkimuksessa koealojen välisten kasvupaikka- ja puustoerojen vaikutusta kasvunlisäyksen laskennassa pyrittiin vähentämään siten, että tilavuuskasvumallin (taulukko 5), Vuokilan ja Väliahon (1980) esittämän valtapituuden kasvumallin sekä kokeen vertailukoealojen avulla ennustettiin, kuinka kukin lannoitettu koeala olisi kehittynyt ilman lannoituksia ensimmäisen lannoituksen ajankohdasta lähtien. Kasvureaktio laskettiin sitten vuosittain koealan mitatun ja ennustetun kasvun erotuksena (kuva 3 ja 4). Tilavuuskasvumallien havaintoina käytettiin vuotuisia kasvuja koko maan aineiston vertailukoealoilta sekä lisäaineistona käytettyjen viiden mäntykokeen ja kuuden kuusikokeen vertailukoealoilta (ks. taulukko 2).

Kasvunlisäysmalli

Mallin perustelut

Aineistoa ei olisi voitu jakaa selviin ryhmiin lannoitusohjelman mukaan hylkäämättä monia kokeita vaihtelevan lannoitusohjelman takia. Osaksi tämän vuoksi aineiston analysoinin apuvälineeksi laadittiin vuosittaista tilavuuskasvun lisäystä ennustava malli. Siten voitiin hyödyntää epäsäännöllisestikin lannoitettujen kokeiden havaintoja mallin parametreja estimoitaessa.

Oletettiin, että eri lannoitusten aiheuttamat kasvureaktiot tiettynä kasvukautena voidaan ennustaa erikseen ja selittää sitten toistuvasti lannoitetun ja lannoittamattoman metsikön kasvuero kasvureaktioiden summana. Lisäksi oletettiin, että ns. "vähenevän kasvunlisäyksen lakia" (s. Mengel ja Kirkby 1978) voidaan soveltaa otettaessa huomioon edeltävien lannoitusten vaikutus uusintalannoituksen aiheuttamaan kasvureaktioon. Siten hyöty uusintalannoituksesta on sitä pienempi, mitä vähemmän edellisistä lannoituksista on aikaa ja mitä suurempi on ollut niiden lannoitemäärä. Toisaalta, kun edellinen lannoitus on lakannut vaikuttamasta, reaktio uusintalannoitukseen on samanlainen kuin ensilannoitusreaktio vastaavanlaisessa metsikössä.

Malli laadittiin erikseen männikölle ja kuusikolle ja aineistona olivat Etelä-Suomen kokeet. Vuotuisia kasvunlisäyshavaintoja oli mäntyaineistossa 2009 ja kuusiaineistossa 593. Parametrit estimoitiin BMDP-ohjelmiston epälineaarisella regressioanalyysillä PAR (taulukko 6).

Kertalannoituksen aiheuttaman kasvureaktion malli jakautuu kahteen osaan. Ensimmäisessä niistä (FA) muuttujina ovat typpilannoitusta koskevat tiedot ja toisessa (FB) metsikköä kuvaavat tunnukset sekä lisäksi kuusen mallissa tieto fosforilannoituksesta. Lannoitusreaktion ennuste, $\Delta\hat{I}_v$, lasketaan mallinosien tulona:

$$\Delta\hat{I}_v = FA \cdot FB$$

Mallinosan FA parametrit estimoitiin ensin eikä niiden arvoja — lukuunottamatta skaalausparametria a_1 — enää muutettu lisättäessä mallinosan FB muuttujia malliin.

Mallin lannoitus- ja puustotekijät

Mallinosa FA ilmaisee kasvureaktion jakautumisen lannoituksen jälkeisille vuosille. Jakautumiseen vaikuttavista tekijöistä on mallissa mukana typpilannoitelaji ja annettu typpimäärä. Lisäksi puulajien ominaisuudet vaikuttavat kasvureaktion ajoittumiseen (Albrektsson ym. 1977) ja malli laadittiinkin erikseen männiköille ja kuusikoille. Kuvassa 7 on esimerkkejä mallin käyttäytymisestä ennustettaessa eri typpimäärillä saatavia reaktioita.

Metsikkötekijöiden vaikutusta kuvaava mallinosa FB koostettiin puustoa kuvaavasta osasta (f1) ja kasvupaikkaa kuvaavasta osasta (f2):

$$FB = f1 \cdot f2$$

Puustoa kuvaaviksi muuttujiksi valittiin kokeilujen jälkeen runkoluku ja valtapituus. Perusoletus oli, että puuston reaktiokyky paranee runkoluvun lisääntyessä, kunnes ylitiheys alkaa heikentää sitä (ks. Brix ja Ebell 1969, Rosvall 1978). Valtapituuden oletettiin vaikuttavan siihen kuinka voimakkaasti runkoluvun lisääntyminen parantaa kasvureaktiota (kuva 8).

Kasvupaikan viljavuutta kuvattiin pituusboniteetin avulla. Viljavimmilla kasvupaikoilla ravinteita on riittävästi. Toisaalta karuilla kangasmailla veden puute rajoittaa voimakkaimmin kasvua. Näiden äärirajojen välillä ovat lannoituksen kannalta soveliaat kasvupaikat (kuva 9).

Lannoituksen toistumisen vaikutus mallissa

Edeltävät lannoitukset vaikuttavat uusintalannoituksen aiheuttamaan reaktioon. Kukin aikaisempi lannoitus otettiin huomioon funktion avulla, jonka arvoon vaikutti aika lannoituksesta ja siinä annettu typpimäärä. Funktion ajateltiin ilmaisevan sen, paljonko lannoituksesta on jäljellä puille käyttökelpoista typpeä maahan ja puustoon sitoutuneena. Edeltävät lannoitukset vaikuttavat uusintalannoituksen aiheuttamaan kasvureaktioon muutenkin kuin jäljellä olevan typen välityksellä, ja siksi funktion avulla laskettua typpijäämää onkin pidettävä vain laskentateknisenä apuvälineenä.

Menetelmän yksityiskohdat ilmenevät kuvasta 10 ja sitä havainnollistaa periaatepiirros 11. Kuvassa 12 on esimerkkejä mallin käyttäytymisestä ennustettaessa toistuvan lannoituksen aiheuttamaa kasvunlisäystä.

Mallin luotettavuus

Kasvunlisäysmallin luotettavuustunnukset olivat seuraavat:

	Mänty	Kuusi
Selitysaste (%)	40	23
Arvion keskivirhe (%)	69	96

Arvion keskivirhe on laskettu samoin kuin taulukossa 5. Mallin olennainen tarkentaminen vaatii tietoja mm. metsämaasta sekä etenkin urealannoituksen osalta lannoitusajan säästä. Osasyynä suureen arvion keskivirheeseen on myös kasvunlisäyshavaintojen epätarkkuus. Kasvureaktio muodostaa vain pienehkön osan kasvusta. Tässä tutkimuksessa keskimääräinen kasvunlisäys oli männiköissä 23 % ja kuusikoissa 16 % lannoitettujen koealojen keskikasvusta.

Havainnot jaoteltiin edeltävän lannoituksen lannoitelajin mukaan ja todettiin, että arvion keskivirhe oli sekä männiköissä että kuusikoissa suurempi urealannoituksen jälkeisinä havaintovuosina kuin As/Os-lannoituksen jälkeen. Kun mallinosa FB korvattiin vakiolla, pieneni selitysaste mäntyaineistossa 10 ja kuusiaineistossa 12 prosenttiyksikköä. Puusto-, kasvupaikka- ja fosforilannoitustiedot olivat siten tärkeitä muuttujia mallissa.

Kuvassa 13 on esitetty kasvunlisäysmallin jäännöshajonta havainnon ajankohtaan mennessä annetun typpimäärän suhteen ja kuvissa 16 ja 17 on ennusteita verrattu havaintoihin eri tavoin lannoitetuissa koeryhmissä. Eräitä aineiston Etelä-Suomen kokeista on mitattu 3—6 vuotta viimeisen tässä tutkimuksessa käytetyn kasvukauden jälkeen. Keskiarvoisesti malli ennusti tämän jakson kasvunlisäykset hyvin (taulukko 7).

Toistuvalla lannoituksella saatava kasvunlisäys

Lannoitustekijäin vaikutus

Jos lannoitus tehdään keväällä tai alkukesällä kuten tämän tutkimuksen koealoilla, tarvitaan typpeä ureaa käytettäessä männiköissä noin kolmannes enemmän kuin As/Os:ia käytettäessä saman reaktion saavuttamiseen. Kuusikoissa urealla lannoitettaessa typpeä tarvitaan lähes kaksi kertaa niin paljon kuin As/Os:lla lannoitettaessa samaan kasvunlisäykseen pääsemiseksi (kuva 15). Kun kevät on urealle epäedullisin levitysaika, ei urealannoituksesta saatuja tuloksia ole syytä yleistää.

Kuvissa 16 ja 17 esitetään erilaisia Etelä-Suomen aineiston puitteissa olevia lannoitusväliyhdistelmiä. Osa-aineistojen keskimääräiset kasvunlisäykset ovat taulukossa 8.

Tarkasteltaessa mallin avulla typpimäärän ja toistamisvälin vaikutusta lannoituksen tehokkuuteen ts. yhtä typpikiloa kohti saatavaan kasvunlisäykseen todetaan lannoitusohjelman intensiivisyyden vaikuttavan lannoituksen tehokkuuteen selvemmin kuusikossa kuin männikössä. Männiköissä tehokkuus ei parane merkittävästi lannoitusvälin kasvaessa yli viiden vuoden, mutta kuusikoissa se lisääntyy vielä selvästi lannoitusvälin pidetessä viidestä kymmeneen vuoteen (taulukko 9). Toistamisvälin lyhetessä lannoituksen tehokkuus heikkenee. Esimerkiksi 150 typpikilon As/Os-kerta-annoksella on kolmen vuoden toistamisvälein saatava teho männiköissä noin 4/5 yhdeksän vuoden lannoitusvälillä saatavasta, kuusikossa vastaava arvo on 3/5. Pidettäessä lannoitusväli vakiona paranee lannoituksen tehokkuus kerta-annoksen pienetessä.

Lannoitettaessa ei ole useinkaan tavoitteena maksimaalinen kasvunlisäys typpikiloa kohti, vaan tietty määrällinen kasvunlisäys. Taulukko 10 osoittaa kasvunlisäyksen pienenevän kerta-annoksen pienetessä ja toisaalta lannoitusvälin pidetessä. Kasvunlisäys pienenee männiköissä nopeammin kuin kuusikoissa toistamisvälin pidetessä. Suurilla kerta-annoksilla ja tiheillä lannoitusväleillä voidaan lisätä edelleen jonkin verran kasvua, mutta samalla lannoituksen tehokkuus heikkenee ratkaisevasti ja lannoituksen ympäristölle ja puustolle aiheuttamien haittojen riski kasvaa.

Fosforin vaikutus oli männiköissä hyvin pieni. Kuusikoissa fosfori oli yhdessä typen kanssa annettuna lisännyt kasvua selvästi (kuva 19, taulukko 8). Fosforin vaikutuksen suhteellinen osuus kasvunlisäyksestä lisääntyi kasvupaikan viljavuuden parantuessa. Kun kuitenkin typen vaikutus heikkeni samanaikaisesti, NP-lannoituksen vaikutus oli viljavilla kasvupaikoilla pienempi kuin karuilla (kuva 20).

Ulkoisten tekijöiden vaikutus

Pohjois-Suomen osa-aineistolle ei tehty sen pienuuden vuoksi omaa mallia, vaan Etelä- ja Pohjois-Suomen eroja tarkasteltiin laskemalla Etelä-Suomen aineistoon perustuvalla mallilla Pohjois-Suomen kokeille kasvunlisäysennusteet ja tarkastelemalla niiden ja mitattujen arvojen eroja (kuva 21). Pohjois-Suomessa männiköiden kasvureaktio oli keskimäärin 63 % ja kuusikoiden 69 % mallilla lasketusta. Suhteellinen ero näytti pysyvän koko tutkimusjakson likimain vakiona.

Kasvupaikkaa kuvaavan pituusboniteetin vaikutus oli hieman erilainen männiköissä ja kuusikoissa (kuva 9 ja 20). Mallin mukaan männiköissä saadaan paras tulos boniteetilla $H_{100} = 24$. Kuusikoissa maksimi oli boniteettiarvolla $H_{100} = 15$.

Tiheyden lisääntyminen suurentaa kasvunlisäystä (kuva 15). Kuusikoissa parhaan kasvunlisäyksen antava metsikön tiheys on todennäköisesti suurempi kuin männiköissä. Talousmetsän normaalitiheyksillä kasvunlisäys oli suurimmillaan nuorissa metsiköissä ja heikkenee hitaasti iän lisääntyessä (kuva 22). Päätehakkuuta lähestyvien metsiköiden kasvunlisäys on noin 4/5 ensiharvennusvaiheen metsiköiden kasvunlisäyksestä.

Toistuva lannoitus käytännössä

Tutkimuksen sovellutusalueet

Tutkimuksen tuloksia voidaan soveltaa Etelä-Suomessa sijaitseviin 30—100-vuotiaisiin metsiköihin. Pohjois-Suomen aineisto on niin pieni, ettei sen perusteella pystytä antamaan ohjeita sen enempää lannoitemäärän kuin puustotekijöidenkään suhteen. Samoilla lannoitus- ja puustotekijöillä pohjoisessa saadaan kuitenkin selvästi heikompi tulos kuin Etelä-Suomessa (vrt. Keltikangas ja Seppälä 1973).

Koska aineisto kattaa vain noin 15 vuoden pituisen lannoitusjakson, päätelmiä ja suosituksiakin voidaan tehdä vain vastaavalle ajanjaksolle. Käytetyt kerta-annokset olivat nykysuosituksia pienempiä, joten aineisto mahdollistaa pienehköjen kerta-annosten vaikutusten tarkastelun. Ureaa koskevat päätelmät perustuvat keväällä ja alkukesällä tehtyihin lannoituksiin eikä ole varmuutta siitä kuinka hyvin ne pätevät muina aikoina tehtyihin levityksiin. Lipas ja Levula (1980) ovat todenneet urean syyslevityksillä saatavan parempia tuloksia kuin kevätlevityksillä. Vastaavaan tulokseen ovat päätyneet myös Mälkönen (1979) sekä Päivinen ja Salonen (1981). Möller (1982) esittää kuitenkin suppeaan aineistoon perustuen urealla saatavan tuloksen olevan levitysajasta riippumaton. Päivisen ja Salosen (1981) tutkimuksessa urean syyslevityksen vaikutus jäi hieman jälkeen oulunsalpietarin kevätlevityksen vaikutuksesta.

Luotettavimpia ovat mäntyä koskevat tulokset. Kuusiaineisto on vajavainen, mistä syystä sen perusteella saatuja tuloksia on pidettävä suuntaa antavina.

Vertailu muihin tutkimuksiin

Kasvunlisäysmallia testattiin vertaamalla mallilla saatuja ennusteita eräiden muiden tutkimusten tuloksiin. Gustavsen ja Lipas (1975) ovat tutkineet kertalannoituksia ja mallilla ennustettiin kasvunlisäykset heidän aineistonsa sille osalle, joka oli mallin sovellutusalueelta (taulukko 11). Suurilla typpimäärillä lannoitetuissa kuusikoissa ennusteet olivat suurempia kuin Gustavsenin ja Lipaksen esittämät kasvunlisäykset. Männiköissä vastaavaa piirrettä ei ollut.

Mallilla ennustettua kertalannoituksen aiheuttamaa kasvureaktiota verrattiin Rosvallin (1980) mallilla ennustettuun kasvureaktioon. Malleissa käytetään osin eri muuttujia ja vertailu on siksi hankalaa. Voitiin kuitenkin todeta, että Rosvallin mallilla saadut ennusteet olivat varttuneissa puustoissa sekä As/Os:lla että urealla suurempia kuin tämän tutkimuksen mallilla saadut. Boniteetin osalta malleja verrattiin käyttäen ensiharvennusvaiheen metsikkötietoja. Siten ikä, kasvu jne eivät ole samat eri boniteeteilla. Männikössä ennusteiden tasoero oli boniteetista riippumaton. Kuusikossa boniteetin parantuessa ero kasvoi jyrkästi, koska Rosvallin mallilla ennustettu kasvunlisäys suureni ja tämän tutkimuksen mukaisesti se pieneni.

Eriksson ja Jansson (1981) ovat esittäneet toistuvalla lannoituksella saatavaa kasvunlisäystä ennustavan mallin. Käsillä olevan tutkimuksen mukaan lannoitusväli vaikuttaa keskimääräiseen vuotuiseen kasvureaktioon voimakkaammin kuin Erikssonin ja Janssonin mallin mukaan (kuva 23). Eriksson ja Jansson ovat käyttäneet havaintoinaan koetuloksia kahden ensimmäisen lannoitusvälin keskimääräisestä kasvunlisäyksestä ja olettavat, että kasvunlisäys on jatkossakin samaa tasoa. Oletus johtaa lyhyillä toistamisväleillä kasvunlisäyksen aliarviointiin, koska kasvunlisäyksen taso on tällöin vielä kahden lannoitusvälin jälkeen nouseva (ks. kuva 12). Kuvaan 23 on vertailun vuoksi laskettu käsillä olevan tutkimuksen mallilla myös kahden ensimmäisen lannoitusvälin keskimääräinen kasvureaktio. Männikössä mallien antamat kasvunlisäykset olivat samaa tasoa As/Os-lannoituksella. Kuusikossa pelkkää typpeä käytettäessä Erikssonin ja Janssonin mallilla ennustetut kasvunlisäykset olivat selvästi suurempia kuin tämän tutkimuksen mallilla saadut.

Mallia testattiin myös ennustamalla Päivisen ja Salosen (1978) sekä Burgtorfin (1981) koemetsiköille kasvunlisäykset ja vertaamalla niitä heidän esittämiinsä tuloksiin. Päivisen ja Salosen kokeilla oli tehty kaksi lannoitusta kuuden vuoden välein ja typpeä oli kerralla käytetty 100, 200 tai 400 kg/ha. Mäntykokeilla pienimmällä kerta-annoksella ennuste oli 62 % Päivisen ja Salosen esittämästä 10-vuotisjakson kasvunlisäyksestä ja kahdella suurimmalla kerta-annoksella vastaavasti 92 % ja 106 %. Kuusikokeilla ennusteet olivat kaikilla typpiannoksilla pienempiä kuin koemetsiköiden kasvunlisäykset ja erot olivat selvimmät pienillä typpiannoksilla.

Burgtorfin aineistona oli neljä vanhaa männikköä Keski- ja Pohjois-Ruotsista, joten ne olivat ilmastollisesti osittain mallin aineiston ulkopuolelta. Lannoitusohjelma oli ollut tiivis: aluksi viisi kertaa 60 kg N/ha kahden vuoden välein ja myöhemmin neljä kertaa 120 kg N/ha kolmen vuoden välein. Neljälle peräkkäiselle viisivuotiskaudelle lasketut ennusteet olivat 102, 82, 95 ja 103 % Burgtorfin esittämien koetulosten keskiarvoista.

Lannoituskohteen valinta

Etsittäessä lannoituskohteeksi sopivaa kasvupaikkaa voidaan lähteä siitä, että kuusikoissa suurin kasvunlisäys saadaan pienemmän pituusboniteetin kasvupaikoilla kuin männiköissä. Männiköissä saatiin paras tulos boniteetilla $H_{100} = 24$. Muutettaessa pituusboniteettiarvot Vuokilan ja Väliahon (1980) esittämällä tavalla metsätyypeiksi paras kasvunlisäys näyttää olevan odotettavissa puolukkatyypin kasvupaikoilla. Varttuneissa kasvatusmetsissä erot puolukka- ja mustikkatyypin kuusikoiden välillä eivät ole suuria.

Useissa tutkimuksissa (esim. Möller 1972, Gustavsen ja Lipas 1975, Rosvall 1980) on käytetty lannoitushetken kasvua reaktiota ennustettaessa. Ensilannoitushetken kasvu ei kuitenkaan ole kovin käyttökelpoinen toistuvan lannoituksen aiheuttaman kasvunlisäyksen selittäjänä (ks. Lipas 1979). Toisaalta kasvun arvioiminen kairausta käyttäen on niin työlästä, että kasvu arvioidaan käytännössä yleensä puustotunnusten avulla, joita tässä tutkimuksessa on käytetty selittämässä kasvunlisäyksen suuruutta (ks. esim. Nyyssönen ja Mielikäinen 1978).

Puunkasvatuksen eräänä tavoitteena on tuottaa järeätä puutavaraa ja siihen pyritään säätelemällä kasvatustiheyttä. Siten päätehakkuuta lähestyvät metsät ovat suurinta kasvunlisäystä ajatellen liian harvoja. Suurimpaan mahdolliseen kasvunlisäykseen pyrittäessä tulisikin lannoitettavia metsiä kasvattaa hieman nykyohjeita tiheämpinä. Parhaan kasvunlisäyksen antava metsikön kehitysvaihe on ensiharvennuksen jälkeinen aika. Puuston ikääntyessä kasvunlisäys heikkenee (ks. Gustavsen ja Lipas 1975, Rosvall 1980).

Toisin kuin mallissa oletetaan on epäiltävissä, että kuusikoissa suurin kasvunlisäys saavutetaan pienemmällä lannoitemäärällä kuin männiköissä (Malm ja Möller 1975). Tässä lienee osasta kyse kuusen kasvupaikoista, jotka ovat keskimäärin viljavampia kuin männyn. Kuusikoissa urealannoituksen tulos verrattuna As/Os-lannoitukseen oli suhteellisesti heikompi kuin männiköissä (ks. myös Rosvall 1978). Kuusikoissa fosforilannoitus paransi selvästi typpilannoituksen vaikutusta, joten niissä on suositeltavaa käyttää NP-lannoitusta (ks. myös Brantseg ym. 1970, Lipas 1981b). Männiköissä fosforin lisäys ei näytä olevan tarpeen ainakaan tutkimusjakson pituisena lannoitusaikana.

Lannoitusohjelman valinta

Puuntuotosmielessä lannoituksen vaikutusta voidaan tarkastella tilavuusyksikköinä (m^3/ha/a) ja toisaalta voidaan tutkia lannoituksen biologista hyötysuhdetta (dm^3/kg N/a).

Kuvasta 24 lannoittaja voi etsiä tavoitteensa mukaiset vaihtoehdot. Saadut vaihtoehtoiset lannoitusohjelmat voidaan asettaa järjestykseen lannoituksen biologisen tehokkuuden suhteen kuvan 25 avulla. Kuvissa puustotekijät ovat kasvunlisäystä ajatellen optimissa, joten muilla puusto- ja kasvupaikkatekijöillä kasvunlisäyksen taso on alhaisempi ja lannoituksen tehokkuus heikompi. Kuitenkin lannoitusohjelmien keskinäinen paremmuusjärjestys säilyy muuttumattomana. Kuviin on piirretty myös alueita, joilla mennään selvästi aineiston ulkopuolelle. Niitä ei ole tarkoitettu käytettäväksi päätöksenteon pohjana, vaan ne kuvaavat periaatteellisesti kasvureaktiota erilaisilla lannoitusohjelmilla. Kun lannoittajan tavoitteena on tietyn kasvunlisäystason saavuttaminen, hänellä on käytettävissään melko laaja joukko likimain saman tuloksen antavia vaihtoehtoja.

Kullakin kerta-annostasolla paras teho saadaan toistamalla lannoitus edellisen lannoituksen vaikutuksen ollessa lopuillaan (kuva 25). Aiemmista tutkimuksista (Friberg 1971, 1973, Gustavsen ja Lipas 1975, Jonsson 1978) tiedetään reaktion kasvun alkavan hidastua kerta-annoksen noustessa yli 200 kg N/ha. Toistettaessa lannoituksia on edellisten lannoituskertojen lannoiteravinnetta usein vielä vaikuttamassa, joten toistuvassa lannoituksessa on syytä tyytyä hieman pienempiin kerta-annoksiin kuin lannoitettaessa vain kerran. Aiheutuen urean typen haihtumisesta ja toisaalta sen voimakkaasta sitoutumisesta humukseen voinevat typpiannokset ureaa käytettäessä olla hieman suurempia kuin As/Os:ia käytettäessä.

Puiden runkotilavuuden ja juuriston tilavuuden suhde suurenee kasvupaikan parantuessa (Laitakari 1927). Vastaavasti on ilmeistä, että lannoitus muuttaa tilapäisesti puun sisäisiä kasvusuhteita runkopuun kasvun hyväksi (Tölle 1969, Tamm 1979, Axelsson 1981). Lannoitusvaikutuksen loppuessa runkopuun kasvu heikkenee tilapäisesti, kun puu vahvistaa juuristoaan (vrt. Lipas 1975), Kasvun sisäisen jakauman vakaana pitämiseksi ja lannoituksen jälkeisen runkopuun kasvun taantuman estämiseksi lannoitus olisi syytä uusia edellisen lannoitusvaikutuksen vielä jatkuessa. Koska kuusen kasvureaktio kestää kauemmin kuin männyn (ks. kuva 7, Möller ja Rytterstedt 1975), voidaan kuusikossa lannoitus toistaa harvemmin kuin männikössä.

Toistuvalla lannoituksella saavutettavan kasvunlisäyksen suuruus riippuu paljon samoista tekijöistä kuin ensilannoituksenkin kyseessä ollen. Voidaan yhtyä Puron (1977) esittämään näkemykseen, että uusintalannoituksen aiheuttama kasvunlisäys on sitä suurempi mitä suurempi ensilannoituksen aiheuttama kasvunlisäys on ollut (ks. myös Eriksson ja Jansson 1981).

Mainitut näkökohdat rajaavat Etelä-Suomessa suositeltavan lannoitusten toistamisvälin 4—8 vuoteen ja kerta-annoksen 100—150 typpikiloon. Kun näissä rajoissa halutaan suurin määrällinen kasvunlisäys käytetään tiheintä toistamisväliä ja suurinta kerta-annosta (kuva 24). Jos tavoitteena on suurin kasvunlisäys typpikiloa kohti, on toistamisväli mahdollisimman pitkä ja annos pieni (kuva 25). Annettujen rajojen ulkopuolella on intensiivisiä lannoitusohjelmia, joilla saadaan ainakin aluksi suurempia kasvunlisäyksiä kuin edellä mainituilla ohjelmilla. Niitä on kuitenkin syytä olla käyttämättä lisääntyneiden haittariskien vuoksi.

KUKKOLA, M. & SARAMÄKI, J. 1983. Growth response in repeatedly fertilized pine and spruce stands on mineral soils. Seloste: Toistuvalla lannoituksella saatava kasvunlisäys kivennäismaiden männiköissä ja kuusikoissa. Commun. Inst. For. Fenn. 114:1—55.

Appendix 1a. Fertilization treatments carried out in the pine experiments. As = ammonium sulphate, HF = finely-ground rock phosphate, Ca = limestone, U = urea, Os = ammonium nitrate with lime, KF = a mixture of finely ground rock phosphate and super phosphate, K = muriate of potash, SF = super phosphate. The number indicates the dose as element kg/ha except Ca where the unit is 1000 kg/ha as limestone. The termination of the investigated period has been marked with a thick vertical line for each experiment.

Liite 1a. Mäntykokeiden lannoitus. As = ammoniumsulfaatti, HF = hienofosfaatti, Ca = kalkkikivijauhe, U = urea, Os = oulunsalpietari, KF = kotkafosfaatti, K = kalisuola, SF = superfosfaatti. Luku merkitsee lannoiteannosta alkuaineena kg/ha paitsi kalkkiannoksessa, joka on kalkkikivijauhetta t/ha. Tutkimusjakson päättymisajankohta kullakin kokeella on merkitty paksulla pystyviivalla.

Exp. number *Kokeen numero*	Growing season — *Kasvukausi* 1: Primary fertilization *Perustamislannoitus*	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
								Refertilizations — *Uusintalannoitukset*												
South Finland — *Etelä-Suomi*																				
4	Os25, KF19, Ca3, K80		As82			U115			U92	**|**										
104	As82, HF29, Ca2			U92			U92						Os150		**|**					
105	As82, HF29, Ca2			U92			U92						Os150, SF44		**|**					
125	As82, KF40, Ca2		U92			U92					Os150			**|**						
126	As82, KF40, Ca2		U92			U92					Os150			**|**						
139	As82, KF40, Ca2, K83			U92			U92, SF35								U150	**|**				
1	As62, KF34, Ca3, K42				As62				U92				U120		**|**					
99	As82, HF29, Ca2				U92				U92						**|**					
109	As82, HF29, Ca2				U92				U92		SF44		Os150		**|**					
148	As82, KF40, K83			U92				U120				Os150		**|**						
56	As82, HF29 Ca2				U92					U92				**|**						
59	As82, HF29, Ca2				U92					U92				**|**						
20	As55, HF34, Ca2, K83						U92						U120		**|**					
68	As82, HF29, Ca2						U92						Os150		**|**					
129	As82, KF40, Ca2						U92						Os150		**|**					
131	As82, KF40 Ca2						U92						Os150		**|**					

79	As82, HF29, Ca2		U92	SF44	
80	As82, HF29, Ca2		U92		
51	As82, HF29, Ca2		U92		
64	As82, HF29, Ca2		U92		
67	As82, HF29, Ca2		U92		
37	As82, HF29, Ca2			U92	
38	As82, HF29, Ca2			U92	
27	As82, HF29, Ca2, K156	As82	U92 U92		U150
83	As82, HF29, Ca2	U92	U92	Os150	
91	As82, HF29, Ca2	U138	U92	Os150, SF44	
92	As82, HF29 Ca2	U138	U92		
114	As82, KF40, Ca2, K83	As82	U92		
115	As82, KF40, Ca2	As82	U120, SF44		
116	As82, KF40, Ca2, K83	As82	Os92	Os150	
156	As82, KF40, Ca1, K83	U92	U92		
158	As82, KF40, Ca2, K83	U92			
North Finland — *Pohjois-Suomi*					
195	U92, KF40, K83	U92	Os150		
132	As82, KF40, Ca2, K83		U92	Os150	
135	As82, KF40, Ca2, K83		U92	Os150	
163	U92, KF40, K83		U92		
184	U92, KF40, K83		U92		
162	As82, KF40, K83	U92	U120	Os150	

Appendix 1b. Fertilization treatments carried out in the spruce experiments. Markings as in App. 1a.
Liite 1b. Kuusikokeiden lannoitus. Merkinnät kuten liitteessä 1a.

Exp. number *Kokeen numero*	1 Primary fertilization *Perustamis-lannoitus*	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		Growing season — *Kasvukausi* / Refertilizations — *Uusintalannoitukset*																		
South Finland — *Etelä-Suomi*																				
31	As82, HF29, Ca2			As82			U92			U92, SF35										
32	As82, HF29, Ca2			As82			U92			U92, SF35										
120	As82, K40, Ca2		U92			U92														
130	As82, KF40, Ca2			U92			U92, SF35													
86	As82, HF29, Ca2				U92				U92											
95	As82, HF29, Ca2				U92				U92, SF35											
57	As82, HF29, Ca2				U92					U92										
58	As82, HF29, Ca2				U92					U92										
60	As82, HF29, Ca2				U92					U92										
138	As82, KF40, Ca2, K83					U92, SF35					Os150									
152	As123, KF40, Ca2					SF35				Os150										
153	As123, KF40, Ca2					SF35				Os150										
154	As123, KF40, Ca2					SF35				Os150										
34	As82, HF29, Ca2										U92									
36	As82, HF29, Ca2										U92, SF35									
49	As82, HF29, Ca2										U92, SF35									

93	As82, HF29, Ca2	U230			U92					Os150, SF44
94	As82, HF29, Ca2	U230			U92					Os150
87	As82, HF29, Ca2		As82			U92				U120, SF44
111	As82, KF40, Ca2, K83		As82			SF70			U120	
112	As82, KF40, Ca2		As82			SF70			U120	
North Finland — *Pohjois-Suomi*										
160	As82, KF40, K83			U92			U120			Os150
142	As82, KF40, K83			U92				U120		
193	U92, KF40, K83				U120					
197	U92, KF40, K83				U120					

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The investigation dealt with the effect of fertilizer dose and the length of the interval between fertilizations on the growth response in different stands. A model was devised for predicting the annual response. The development of the experiments had been followed over a period ranging from 9 to 19 years. The average single fertilizer dose was 100 kg N/ha and the average number of applications three.

Considering the different factors, the recommended interval between fertilizations is 4—8 years and the size of a single fertilizer dose 100—150 kg N/ha in southern Finland.

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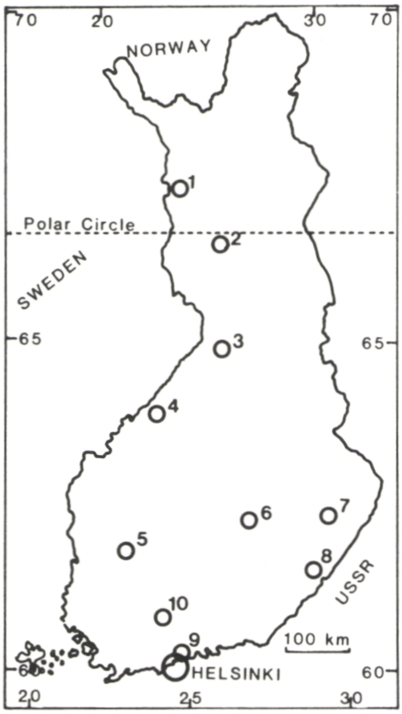

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Total land area: 304 642 km² of which 60—70 per cent is forest land.

Mean temperature, °C:	Helsinki	Joensuu	Rovaniemi
January	-6,8	-10,2	-11,0
July	17,1	17,1	15,3
annual	4,4	2,9	0,8
Thermal winter (mean temp. < 0°C):	20.11.—4.4.	5.11.—10.4.	18.10.—21.4.

Most common tree species: Pinus sylvestris, Picea abies, Betula pendula, Betula pubescens

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