# The predictive accuracy of two Swedish nitrogen forest fertilization functions evaluated on Norwegian fertilization experiments, and preliminary analyses of economic return.

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# Preface

This thesis is written as the completion of my master education in Forestry at the Institute of Ecology and Natural Resource Management (Institutt for Naturforvaltning (INA)) by the Norwegian University of Life Sciences (Universitetet for miljø- og biovitenskap (UMB)).

Throughout my five years of studies I have become especially interested in the directions of forest-production and forest-economy, it has therefore been very motivating, to work on this thesis that combines these two subjects.

Several people have contributed with academic and practical advice on this thesis. Firstly I would like to thank my head supervisor Birger Solberg and co-supervisor Hanne Kathrine Sjølie, for their time, advice and support throughout the work with my thesis. Secondly I would like to thank Bjørn Tveite and the Norwegian Forest and Landscape Institute (Norsk Institutt for Skog og Landskap) for letting me use the long term fertilization data and invaluable help with locating missing data. A special thanks to Sarah Winge-Sørensen for language consultation. Last but not least I would like to thank my parents for their support through these five years of study.

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## Abstract

This thesis paper addresses the accuracy of two Swedish predictive functions for the impact of nitrogen (N) fertilization on tree growth, in relation to the Norwegian fertilization data on Norway spruce (*Picea abies (L.) Karst.)* and Scots pine *(Pinus sylvestris)*. Over the last 60 years a considerable amount of research has been conducted on the impact of nitrogen fertilization on tree growth in conifer forests in Norway. However predictive functions estimating tree growth response to N fertilization has only been made at an early juncture of the research on very limited data and with low predictive accuracy (Brantseg et al. 1970). In the present study the evaluation of the functions predicting the response over the first five years revealed an overall low predictive accuracy. The function produced by Rosvall (1980) and Pettersson (1994 (a)) explained 23 % and 27 % of the variation in the response respectively. The observed growth response was in average 15 % lower than the predicted response for the function produced by Rosvall (1980) and 20 % lower for the function produced by Pettersson (1994 (a)). Both functions explained more of the variation in pine-dominated stands than spruce-dominated stands. In addition, predictions in spruce-dominated stands accounted for a large part of the overestimation in the response. For both functions and tree species' the overestimation increased with increasing dose of nitrogen from 100 kg N $ha^{-1}$. In the Norwegian field data the total growth response was only evaluated in pine dominated stands. When the function predicting the total response produced by Pettersson (1994(b)) was evaluated isolated from the predicted response the first five years, the function explained 86 % of the variation in response. However the observed growth response was on average 21 % lower than the predicted. Based on the observed growth response an application of 150 kg N $ha^{-1}$ gave the highest internal rate (IRR), ranging from 2,9 to 9,6 % p.a, considerably lower than estimates from the two Swedish functions. Further research on the response in practical fertilization with the currently used fertilizer could determine if there is a need for new predictive functions based on the Norwegian experiments, or if the current predictive functions could be adapted to fit the expected response in Norwegian forests.

# Sammendrag

Denne masteroppgaven tar for seg nøyaktigheten av to svenske gjødslingsfuksjoner i forhold til norske gjødslingseksperimenter i bestand dominert av gran (*Picea abies (L.) Karst.)* og furu *(Pinus sylvestris)*. De siste 60 årene er det blitt utført en betydelig mengde gjødslingseksperimenter i Norge. Og det er en etablert oppfatning at nitrogen (N) er det eneste næringsstoffet som kan gi en tilvekstrespons når det blir brukt alene. Til tross for de mange gjødslingsforsøkene, har det kun blitt utarbeidet norske funksjoner for å estimere gjødslingsrespons på et tidlig stadium (Brantseg et al. 1970). Disse funksjonene ble basert på et begrenset datamateriale og forklarte lite av variasjonen i respons.

Begge de to svenske funksjonene produsert for å estimere gjødslingsresponsen etter 5 år, viste seg å forklare en relativt liten del av variasjonen i respons i det norske materialet, henholdsvis 23 % og 27 % for funksjonene produsert av Rosvall (1980) og Pettersson (1994(a)). Den observerte gjødslingsresponsen for de første 5 årene var i tillegg 15 % lavere enn estimert for funksjonen produsert av Rosvall (1980) og 20 % lavere enn estimert for funksjonen produsert av Pettersson (1994(a)). Begge funksjonene forklarte en større andel av variasjonen i furubestand enn i granbestand. I granbestand var det også en større overestimering av gjødslingsresponsen enn i furubestand. I begge funksjoner og for begge treslag økte overestimeringen med økende dose nitrogen fra doser over 100 kg N $ha^{-1}$. Evalueringen av den totale gjødslingsresponsen ble bare utført for furubestand. Funksjonen produsert for å estimere den totale gjødslingsresponsen forklarte 86 % av variasjonen i respons isolert sett. Den observerte gjødslingsresponsen var imidlertid 21 % lavere enn den estimerte. Analysen av det økonomiske utbyttet viste at 150 kg N $ha^{-1}$ ga den høyeste internrenten for alle alternativer. Internrenten varierte mellom 2,9 % og 9,6 % per år, betydelig lavere en internrenten basert på den estimerte gjødslingsresponsen fra de to svenske funksjonene.

Videre forskning på gjødslingsresponsen ved praktisk gjødsling kan bestemme om det er behov for nye gjødslingsfunksjoner basert på det norske materialet eller om de svenske funksjonene kan tilpasses resultatene fra praktisk gjødsling.

## Contents

# 1. Introduction

A key factor affecting the productivity of forest areas is the amount of available nutrients in the soil. In Norway, forest fertilization on mineral soils has been a part of the silvicultural treatment and research since the beginning of the $19^{th}$ century. The tree growth in much of the boreal forest in the Nordic countries[1] is limited by the available Nitrogen (N) in the soil (Tamm 1991). There is a general consensus in Norwegian research that N fertilization leads to an increase in growth (Brantseg et al. 1970; Brantseg 1980; Haveraaen 1972; Sture 1984). In Norway, several forest fertilization experiments were conducted between the 1950s and 1990s. Some of these experiments, initially published in Norwegian, have since been reviewed and published in English for wider scientific scrutiny (Nilsen 2001).

In the beginning the research was almost exclusively focused on increasing-timber production with an economic incentive. Economic profit has also been the main motive for commercial use of fertilizer. Financial analyses of N fertilization in Norway spruce *(Picea abies (L.) Karst)* and Scots pine *(Pinus sylvestris)* have typically showed a high internal rate of return (Brantseg et al. 1962; Haveraaen 1972; Svendsrud 1998). Nevertheless the practical use of N fertilization as a silvicultural measure has almost been absent in recent years with an annual fertilized are of 0,015 % of the productive forest area (Statistisk Sentralbyrå 2006-2011).

Investments in forestry often have a long term perspective. When the forest owner prioritizes between investments in forest production and alternative investments, the prospect of future timber prices are of great relevance. Recent studies indicate that the demand for raw material from the forest will likely increase within the next decades: As a result of international and national focus, the Norwegian forest conservation status was evaluated in 2002. The report revealed the need for conservation of a substantial amount of new productive forest areas (Framstad 2002). New environmental policy based on this report is calling for an increase in conservation of productive forest (White paper nr. 25. 2002-2003), The current expansion of forest conservation in Norway will likely lead to an increase in the demand for timber from the remaining forest areas and have implications for the timber price (Bolkesjø et al. 2005). In addition the use of wood-based energy in Norway is somewhat underexploited today due to low energy prices and readily available hydroelectric power, but the anticipated growth of the bioenergy sector is expected to raise the demand on forest products in Norway (Trømborg &

[1] In this study the Nordic countries refers to Norway, Sweden, Finland and Denmark but excludes Iceland

Solberg 2010). The profitability of forest fertilization is highly dependent on the value of the increase in growth and thus the timber price.

For forest fertilization in particular focus on climate change and the forests role in binding atmospheric carbon has led to a renewed interest. In the newly published white paper on Norway's future climate policy it is stated that it is important to "*Contribute to increased carbon uptake through targeted fertilization of forests"* (White paper nr. 21. 2011-2012). With precise functions predicting the growth response to N fertilizer the increase in growth and subsequently the net carbon sequestration can be estimated.

Further, predictive functions can help forest owners prioritize their investments and select suitable stands for fertilization. A Finnish study revealed that a high growth response could be obtained by carefully selecting suitable stands based on site class factors (Kukkola & Saramäki 1983). Hence predictive functions could also be used to optimize the growth response. However such functions based on Norwegian experience were created only at an early stage of the research conducted in the 1950s and 1960s (Brantseg et al. 1970). The early functions only explained a small proportion of the variation in response, possibly due to little data, low doses of N and a wide range of different treatments (Brantseg et al. 1970). Due to the lack of good predictive functions based on Norwegian fertilization experiments, the predictive functions currently used in Norwegian forestry are derived from Swedish experiments.

The first Swedish functions predicting the impact of N fertilization on tree growth were presented as predictive curves estimating response for the first 5 years following the first application of fertilizer (Möller, Göran 1973). As more of the results from the experimental sites were revised, new and more precise predictive functions were produced for a full range of site class factors (Rosvall 1980). Subsequent functions, based on the response for the first five years, were produced to predict the duration and total response of the initial fertilization (Pettersson 1980(a)). These functions have been revised and new functions were made based on the assumption that the old functions overestimated the response and that a stricter selection criteria could reduce the residual response (Pettersson 1994 (a); Pettersson 1994(b)).

Despite the large amount of data on the impact of N fertilizer obtained over the last 60 years, little has been done to assess the accuracy of the Swedish predictive functions in relation to the results from the Norwegian fertilization experiments. Potential differences in the response could have implications for the estimation of growth, financial analysis, and predictions of net carbon sequestration. The main objective of this study is therefore to evaluate two important Swedish forest fertilization functions on Norwegian field experiments, addressing the following research questions.

i. To which degree do the Swedish predictive functions explain the variation in response in the Norwegian fertilization experiments?
ii. Does different fertilizer types used in the Norwegian fertilization experiments play an important role for the Norwegian results when compared to the predictions of the Swedish functions?
iii. Is there a need for new predictive functions based on the experience in Norway?
iv. At which dose of N (kg ha $^{-1}$) can the highest internal rate of return of a single shot application be achieved, based on the observed response in the Norwegian field experiments and the predicted response from the two Swedish functions?
v. Could the optimal dose of a single shot application lead to any undesirable environmental impacts?

It has been rather challenging and time consuming to explore and make the Norwegian field experimental data ready for statistical analyses, and the main efforts have therefore been on covering questions i-v.

The report is structured like this: In the next chapter a brief overview of the literature on forest fertilization in the Nordic countries is presented. In Chapter 3 the study methodology is described. The results are presented in Chapter 4 and discussed in Chapter 5, and main conclusions drawn in Chapter 6.

## 2. Literature Review of forest fertilization research in the Nordic countries

The geographic area covering the Nordic countries represents a relatively broad range of climatic conditions, soil types, and the amount of air-pollution. Research on nutrient management in the Nordic countries covers a large range of different experiments with a variety of aims, which have been performed at different stages in the rotation. The following short review of forest fertilization research covers tree growth response to nutrient addition, environmental impacts, economic return, and different predictive functions for estimation of growth response.

### 2.1 Tree growth response to nutrient addition

A large part of the research on forest fertilization in the Nordic countries during the last century has been focused on how trees respond to nutrient addition (Brantseg et al. 1970; Dralle & Larsen 1995; Linder & Bergh 1996; Pettersson 1994 (a); Sture 1984) Most of the Nordic studies on growth response show that forest production will increase as a result of fertilizing.

In Denmark, the main aim of forest fertilization has been to improve the survival rates of Spruce plants and young forest stands on infertile former heathland (Vejre et al. 2001). Results from experiments conducted in the 1950s and 1960s indicated that by applying an NPK[2] mix of 120 kg N $ha^{-1}$ in 5 year intervals, one could increase the production in 30-year-old Spruce stands with 3- 4 $m^3$ $ha^{-1}$ $year^{-1}$. As a direct response to the promising results, the Danish National Forest and Nature Agency (Naturstyrelsen) established a fertilization program on former heathland planted with Spruce on in total 12 000 ha`s were initiated in the spring 1978 and 1979. In order to monitor the growth response, a series of experiments consisting of 78 sample plots in total, were established with the same experimental design as in 1950-1960. However, these results showed a growth response of 0,72 $m^3$ $ha^{-1}$ $year^{-1}$ . The decreased effect of N fertilization registered in Denmark in the 1970-80`s coincided with an increase in N deposition. The Nitrogen deposition over the coniferous forest in Denmark averaged 20-30 kg N $ha^{-1}$ $year^{-1}$ in the 1980s (Dralle & Larsen 1995).

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[2] NPK fertilizer is a three-way fertilizer consisting of a mixture of the main ingredients nitrogen (N), phosphorus (P) and potassium (K)

The discovery of a greater growth response in areas where potassium was added led to the assumption that N fertilization might have induced nutrient imbalance. This could have made potassium and potentially phosphorous limiting nutrients, hence devitalizing the forest (Dralle & Larsen 1995).

A Finish study of N deposition show a decreasing deposition with increasing latitude, In the central and northern parts of Finland the n deposition has been found to be far lower than in Denmark in the year 2000 as low as 1-5 kg N $ha^{-1}$ $year^{-1}$ (Poikolainen et al. 2009). Studies of growth response in Finland have shown that N is the only nutrient that could promote stem growth of conifer trees when added alone (Saarsalmi & Mälkonen 2001). Fertilization with a single dose of 150 kg of N $ha^{-1}$ have usually shown a total growth increase as high as 12-20 $m^3$ $ha^{-1}$ in carefully selected suitable stands (Mälkönen et al. 1997). In Finland, a considerable amount of research has been devoted to establishing criteria for selecting suitable stands for fertilization. The optimal volume increment for Pine was found to be at intermediate productivity and stand age from 30-50 years (Kukkola & Saramäki 1983).

In Sweden, N was also found to be the only nutrient that clearly promotes stem growth when added alone, thus it has become the only nutrient to be utilized commercially. Most of the published literature was derived from experiments in coniferous forest on mineral soil. In a review of a substantial amount of Swedish experiments Pettersson (1994 (a)), found an average growth increase of 15 $m^3$ $ha^{-1}$ after 10 years following a single application of 150 kg N $ha^{-1}$. This was equivalent to an average 30 % higher growth than in the control stands. In these experiments, no evidence was found to indicate that the ongoing N deposition had any influence on the effect of N fertilizer. In addition, no significant differences were found between the northern and southern parts of Sweden (Pettersson 1994 (a)). A much greater increase in volume growth was observed when a mix of NPK was applied annually together with irrigation in the Asa and Flakaliden experiments. In the Asa site, total stem growth as high as 30 $m^3$ $ha^{-1}$ $year^{-1}$ was measured (Tamm 1991). As much as 13-15 $m^3$ $ha^{-1}$ was observed in the Flakaliden experiment, which was three times the production of the control area (Linder & Bergh 1996).

In Norway, there has periodically been a large interest in research on nutrient management. A total of 170 different fertilization experiments were established between 1956 and 1975. A large part of the experiments were performed in old stands of Spruce and Pine (Nilsen 2001). Already at an early juncture it became evident that N fertilization had a positive effect on tree growth. However only a small part of the results were analyzed and published (Nilsen 2001). Brantseg et al. (1970) published results from 30 Spruce and 19 Pine experiments. The general conclusions coincided with the results from Sweden and Finland showing that N is the only nutrient that could promote stem growth when applied alone. During a revision of a large part of the Norwegian fertilization experiments, Sture (1984) found an average expected growth increase of 1-2 $m^3$ $ha^{-1}$ $year^{-1}$ in a 6-8 year time period following a single application of 150 kg N $ha^{-1}$. In cases where P and K were added to the N fertilizer in spruce stands, the data revealed small tendencies to an additional increase in growth, whereas no similar results were found for stands dominated by Pine. In general, the numerous experiments performed over the last few decades on N fertilization of boreal forest in Norway, Sweden, and Finland show that the response to fertilizer is roughly of the same magnitude across the countries.

## 2.2 Environmental impacts

Although fertilization has been shown to influence tree growth, it may also have an impact on the environment. In the Nordic counties fertilization as a silvicultural measure has been under debate because of the risk of undesirable effects on the forest ecosystem (Ingerslev et al. 2001).

One of the concerns regarding N fertilization is its impact on the plant community on the forest floor. The N fertilization impact depend on the community structure and each individual species' competitive status (Kellner 1993). Many plants on the forest floor are N limited and some may utilize the addition of N better than others, thereby changing their competitive status. This might subsequently lead to alterations in the plant community structure and each individual species' relative dominance.

In Sweden Olsson and Kellner (2006) examined three different coniferous experimental sites where the last dose of fertilization was applied 15-18 years earlier. The total dose applied during the course of the experiment ranged from 360 to 2400 kg N $ha^{-1}$. The most pronounced effect was found on a nutrient poor and lichen rich pine site. The results indicated that intensive N fertilization regimes did lead to a long term reduction in the abundance of epigenic lichens and common mosses. Here some species' were reduced by as much as 50%. Despite this impact on individual species' the vegetation type was not altered on any of the three sites nor was there an increase in nitrophilic herbs and grasses (Olsson & Kellner 2006).

The growth of coniferous trees in the Nordic countries is highly dependent on the symbiotic relationship with mycorrhiza fungi. The mycorrhiza grows like small hairs of the roots of the tree. They provide the tree with minerals and water, and receive carbohydrates in different forms in return (Nylund & Unestam 1982). Intensive fertilization with N can have an effect on the mycorrhizal fruit body production and the amount of mycorrhiza on tree roots (Wiklund et al. 1995).

Another commonly addressed issue in forest management research is the undesirable leaching of nutrients. The leaching from fresh clear-cuts accounts for a substantial part of nutrient leaching during a rotation (Ring 2004; Rosén et al. 1996; Smolander et al. 2001). The addition of nutrients through fertilization induces a build-up of the N pool in the soil and might subsequently lead to increased leaching of N when the stand is clear-cut. Results from Swedish experimental sites in central Sweden indicated that there was a total dose threshold in one rotation ranging from 700 - 1000 kg N $ha^{-1}$ in pine stands (Ring 1995; Ring 1996). Total doses over this level have proven to have a significant effect on the soil solution chemistry, with increased levels of $H^+$, total Al, Mn, $NO_3^-$-N, total N and $F^-$, and lower acid-neutralizing capacity, with a subsequently greater nutrient leaching after final felling (Ring 2004). However the results are not uniform. Another heavily fertilized experimental plot in central Sweden had no increase in nitrogen in soil water first two years after, clear cutting when nutrients bound to the soil are expected to be released. Only in the third year minor elevated values of nitrate were observed in plots that had been fertilized with the highest dose ($3 \times 600$ kg N $ha^{-1}$), but not at amounts to suggest that they would have an impact on the aquatic ecosystem in the forest catchment. (Nohrstedt et al. 1994).

## 2.3 Economic return

Forest fertilization has been looked upon as one of the most profitable investments in forestry (Simonsen et al. 2010). Nevertheless, there is little literature published on the subject while there are multiple factors influencing the outcome. In general the financial return of an investment in fertilization is dependent on the increase in tree growth, the quality of stem growth, the time between fertilization and harvest, timber prices and the cost of fertilizing. The value of increased stem growth, timber prices as well as the rate of discount used are not constant over time and will alter according to changes in timber prices, and the price span between different qualities and dimensions. In Sweden the most efficient fertilizing regime, with emphasis on economic return, is found to be within time intervals of 8 to 10 years starting in the latter part of the rotation, 10 to 20 years before planned timber harvest (Ingerslev et al. 2001). The rate of return p.a. has been found to be highest for one single shot application of fertilizer in stands close to maturity, and decrease rapidly when repeated fertilizations is applied (Jacobson & Pettersson 2010). In Norway the internal rate of return of an application of 150 kg N $ha^{-1}$ has previously been found to vary between 8 to 15 % p.a when the stand is harvested 6 to 10 years after the application (Brantseg et al. 1962; Haveraaen 1972; Svendsrud 1998).

## 2.4 Functions predicting the impact of N fertilization on tree growth

There is a need for precise predictive functions in order to predict the impacts of N fertilization on growth. This makes it possible to predict various outcomes, for example the net carbon sequestration or economic return. Predictions can help decision-makers select suitable stands as well as the right type of fertilizer and dose. One of the first functions used to predict tree growth response to N fertilization in Sweden was presented as predictive curves. These functions were based on few variables and limited data, covering a large range of different forest conditions and experimental design (Möller, G. 1973). However, by the late 1970s many results were obtained from fertilization experiments established in the 1950s and onwards. The new results made it possible to make predictive functions that covered a full range of site indices and other site class factors. Even though the predictive function produced by Rosvall (1980) was based on a large number of experiments, field data used for testing the function revealed a large overall variation from the predicted value with a standard deviation of 3, 79 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$(Rosvall 1980). Following a review of the research performed by the former Swedish Institute for Forest Improvement (Instituttet for Skogsförbättring). In the mid1980s, a forest fertilization project consisting of several subprojects was established. The aim of subproject 1 was to produce more precise predictive functions based on the assumption that site class factors could be used to assess the soils natural N supply capacity and thus the response to fertilization. Subproject 2 was aimed to study the effect of weather condition. In the new predictive functions, data from plots with large deviation in site class factors between the control and the experimental plots were excluded. The reanalysis resulted in new predictive functions and when tested with the field data the standard deviation from the predicted value varied by on average 3,53 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$. With the residual effect still being low,Pettersson (1994 (a)) found a lower expected growth increment than Rosvall (1980) especially at sites with a high current annual increment.

# 3. Material and methods

## 3.1 Selection of sample plots

The original material consisted of 68 different experimental sites with a total of 1892 experimental plots established by the Norwegian Forest Research Institute (Norsk Institutt for Skog og Landskap) in the timespan of 1959 to 1971. All of the sites were situated in conifer forest in Norway. The research results have been published by Sture (1984).

### *3.1.1 The initial selection of sample plots for all functions*

For the purpose of this study different data was selected for the different functions studied: estimated response for the first five years, total response, and duration of response. The initial selection refers to selection of data material for analysis of response the first five years after application of N fertilizer hereby called the $E_5$ function.

In the initial selection of plots, plots with a deviating response (negative, weak, or high response relative to dose and/or site class factors) were not excluded based on the assumption that subjective selection of data might skew the average response. Hence the data is treated as if no systematical measurement or calculation errors exist.

The initial criteria for the selection of the sample plots was an application of a N fertilizer for which response data covered a minimum of 5 discrete years prior to the second fertilization. Only the initial fertilization of each individual plot was utilized. In addition the following plots were excluded from the data material: plots with split dose application, plots with application of unknown fertilizer, plots with N doses higher than 250 kg N $ha^{-1}$ or lower than 31 kg N $ha^{-1}$.

After the initial selection in total, 51 experimental sites with a total of 707 plots were chosen for the present study of the response after the first 5 years. Twenty-nine of these sites (413 plots) are dominated by Pine and 22 sites (294 plots) are dominated by Spruce **(Table 1).** The research sites were all situated in conifer forest on mineral soil.

**Table 1:** Range of variables, after the initial selection of data plots.

| **Range of variables** | |
|---|---|
| *All Plots* | |
| Number of sites | 51 |
| Number of plots | 707 |
| Latitude | 58° – 66° N |
| Altitude | 10 - 630 m |
| Dose AN fertiliser | 31 - 250 kg N / ha-1 |
| Dose of urea | 31 - 250 kg N / ha-1 |
| *Pine-dominated plots* | |
| Number of plots | 413 |
| Site index $H_{40}$ | 7,4 - 16,7 m |
| Site Index $H_{100}$ | 12,6- 25,4 m |
| Current annual increment | 0,6 - 10,8 $m^3$ o.b $ha^{-1}$ |
| Age at breast height | 42 - 127 years |
| Basal area | 5,11 - 37,68 $m^2$ $ha^{-1}$ |
| Volume | 23 - 373 $m^3$ o.b $ha^{-1}$ |
| *Spruce-dominated plots* | |
| Number of plots | 294 |
| Site index $H_{40}$ | 6,5 - 17,8 m |
| Site Index $H_{100}$ | 12,7 - 27,9 m |
| Current annual increment | 0,6 - 10,3 m3 o.b $ha^{-1}$ |
| Age at breast height | 57 - 139 years |
| Basal area | 3,3 - 41,2 m2 $ha^{-1}$ |
| Volume | 20 - 483 m3 o.b $ha^{-1}$ |

### *3.1.2 Selection of sample plots for evaluation of total response and duration*

Duration and total response was only analyzed for pine-dominated plots due to lack of sufficient data on the spruce-dominated plots. In order to analyze the total response and duration, further selection criteria had to be applied to the data material after the initial selection. Furthermore only plots that had been observed for a minimum of 9 years, had been fertilized once in the observed period, and no longer responded to the fertilizer at the time of the revision were chosen. The end of the response period was set to include and stop at the year when the response was less than 30 % of the average response in the first 5 years. The predictive functions do not allow the use of negative values, thus all plots with an observed negative response were excluded. The discarded plots relative to the criteria for discarding and the remaining plots is presented in **Table 2**.

**Table 2:** Criteria for discarding plots for functions total response and duration, selections were made after the initial selection and only for the pine-dominated stands.

| **Selections** | | |
|---|---|---|
| *Criterion* | *plots* | *plots discarded* |
| Plots from initial selection | 413 | - |
| Discrete observed resp.< 9 years | - | 316 |
| Negative response | - | 10 |
| Enduring response at revision | - | 15 |
| plots remaining/ excluded | 72 | 341 |

Plots discarded due to negative response or enduring response are presented in **Table 3**. Plots were revised either because of the application of a second dose of N or because there were no more observations in the plot.

**Table 3:** Plots discarded due to negative response or enduring response subdivided into number of years observed after the initial fertilization.

| **Discarding of plots for total response and duration** | | | |
|---|---|---|---|
| *years at revision* | *nr of plots* | *Plots disc. enduring resp.* | *plots disc. negative resp.* |
| 9 | 40 | 5 | 1 |
| 10 | 7 | 5 | 1 |
| 11 | 45 | 4 | 8 |
| 12 | 8 | 1 | 0 |

## 3.2 Calculation of the response to fertilizer

In the results from Norwegian fertilization experiments as presented in Sture (1984) and utilized in the present study control plots were unfertilized plots which was used as a reference for tree growth without addition of nutrients. Experimental plots were fertilized with an N fertilizer. In the block structure of the experiments each experimental plot was connected with a control plot based on the proximity to one another. The growth response to N fertilizer was calculated as the difference between the growth in the control plot and the experimental plot. In order to account for growth differences between the control and experimental plots the quotient method was utilized. In this method differences in basal area growth was found to be the most appropriate variable for adjusting the growth. Hence the growth response was adjusted by the quotient between the basal-area increment of the experimental plot divided by the basal-area increment in the control plot, both 5 years prior to the initial fertilization. The basal-area increment is assumed to be directly proportional to the volume increment,

The calculations were made by Sture (1984) using the following formula (quotient method):

$$Ve = Ivc \times \frac{Dg_5}{Dg_5c}$$

where

Ve = Expected volume increment if not fertilized.

Ivc = the observed volume increment ($m^3$ o.b. $ha^{-1}$ $year^{-1}$) at any given year in the control plot.

$Dg_5$ = basal-area increment ($m^2$ o.b. $ha^{-1}$ $year^{-1}$) in the experimental plot five years prior to treatment.

$Dg_5c$ = basal-area increment ($m^2$ o.b. $ha^{-1}$ $year^{-1}$) in the control plot five years prior to treatment.

The effect of the fertilization on tree growth over five years ($E_5$) ($m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$) is then

$$E_5 = \mathrm{IV} - Ivc \times \frac{Dg_5}{Dg_5c}$$

where:

IV = the observed volume increment on the fertilized plot.

Thus differences in site class factors between the experimental plot and the control lose their significance. The validity of this method is examined by (Mønness 1991). The quotient method was also used in the two Swedish functions evaluated here.

## 3.3 The evaluated predictive functions

The functions are produced based on fertilization experiments were the fertilizer is applied by hand, Due to application-technical differences between practical fertilization and fertilization experiments the functions have been reduced for practical use. The function produced by Rosvall (1980) was reduced by 15 % whereas the function produced by Pettersson (1994 (a)) was reduced by 10 % for the purpose of application in practical fertilization. Since the functions evaluated in the present study was compared with the response in Norwegian fertilization experiments only the functions without reduction were assessed. The site registration from the Norwegian fertilization experiments included all the data required for the functions except from the site index classification which had to be converted from the Norwegian $H_{40}$ to the Swedish $H_{100}$ classification system. In Sweden, the site index is defined as the height at total stand age of 100 years for the 100 trees with the largest stem diameter per ha. The site index classification is tree specific and was used for Pine and Spruce (Hägglünd 1973; Hägglünd 1974). In Norway the site index is defined as the height at stand breast height age of 40 years for the 100 trees with the largest stem diameter per ha tree species specific for Pine and spruce (Braastad 1980; Tveite 1977). The conversion of the $H_{40}$ site index in the Norwegian results to the $H_{100}$ site index as used in the predictive functions was performed using conversion functions (Tveite 1980).

### *3.3.1 Predictive functions for estimation of response the first 5 years*

The predictive functions produced by Rosvall (1980) and Pettersson (1994 (a)) both estimate the effect of N fertilization on growth 5 years following the initial fertilization treatment (**Table 4**).

### *3.3.2 Predictive functions for estimation of total response and duration*

The functions predicting the total response and the duration of the response are taken from Pettersson (1994(b)).The most influential independent variable for the total response function is the predicted response after 5 years hereafter called $E_5$, in addition to the most influential site class factors (**Fig. 5 and 6)**. Unlike the $E_5$ function, no differentiation between type of fertilizer (AN and urea) has been made as it is accounted for in the prediction for the first five years. No differences between the two types have been found in terms of the relative response after the first five year period. In the present study, total response was predicted for three different alternatives, for the variable response after the first five years: based on the $E_5$ functions without reduction for Pettersson (1994 (a)) and Rosvall (1980), and one alternative where the observed response after 5 years was utilized. (in order to isolate the accuracy of the total response function). The predicted total response was compared with the observed total response from Norwegian fertilization experiments in Pine-dominated stands.

**Table 4:** Functions for estimation of growth response to fertilizer after the first five years ($E_5$). Dependent variable log fertilizer response ($m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$) taken from Pettersson (1994 (a)) and Rosvall (1980).

**Functions for estimation of growth response**

| *In dependent variables* | *Rosvall 1980 Coefficient* | *Pettersson 1994 Coefficient* | *Denomination* |
|---|---|---|---|
| Constant | - 4,298110[1)] | -5,067246 [2)] | |
| Log nitrogen dose AN[3)] | + 1,500548 | 1,335267 | log (kg AN-N $ha^{-1}$) |
| Log nitrogen dose urea[3)] | + 1,414132 | 1,226132 | log (kg urea - N $ha^{-1}$) |
| Site index[4)] | - 0,012080 | 0,106000 | m |
| Nitrogen dose * site index AN[3)] | - 0,000105 | -0,000090 | (kg AN-N $ha^{-1}$ x m) |
| Nitrogen dose * site index urea[3)] | - 0,000091 | -0,00057 | (kg urea- N $ha^{-1}$ x m) |
| Latitude | - 0,018376 | - | degrees-54 |
| log latitude | + 0,359554 | - | log (degrees-54) |
| Altitude | - 0,000694 | - | (m + 100) |
| Log altitude | + 0,588503 | 1,719173 | log (m + 100) |
| Log current increment pr anno. | + 0,424878 | - | log ($m^3$ o.b. $ha^{-1}$ $year^{-1}$ |
| Age at b. h. | - 0,003438 | - | years at b. h. |
| Log Age at b. h. | + 0,412783 | - | log (years at b. h.) |
| Proportion of pine | + 0,007016 | - | tenth +1 |
| Northern Sweeden lat. 61 N and above [5)] | - | 0,119126 | |
| Central Sweden lat. 58-61[5)] | - | 0,058646 | |
| Latitude x altitude | - | -0,000030 | degrees x m |
| Log ( latitude x altitude) | - | -0,215528 | log ( degrees x m) |
| Current annual increment P. sylvestris | - | -0,051843 | $m^3$o.b. $ha^{-1}$ $year^{-1}$ |
| Log current annual increment P. sylvestris[6)] | - | 0,781026 | Log ($m^3$o.b. $ha^{-1}$ $year^{-1}$) |
| Log current annual increment P. abies[7)] | - | 0,0306321 | Log ($m^3$o.b. $ha^{-1}$ $year^{-1}$) |

[1)] Rosvall (1980). The constant is without reduction. The constant with reduction for logarithmical bias and 15 per cent reduction of the estimated responses= - 4,368692
[2)] Pettersson (1994(a)). The constant is without reduction. The constant with correction for logarithmical bias and 10 per cent reduction of the estimated responses = - 5,113004
[3)] The respective coefficient for either AN or urea is used.
[4)] Dominant height at age 100.
[5)] The respective coefficient for northern or central Sweden is used.
[6)] The coefficient is used in pine-dominated stands.
[7)] The coefficient is used in spruce-dominated stands.

**Table 5:** Function for estimation of the total response to N fertilization (E). Dependent variable (E), log response ($m^3$ o.b. ha $^{-}$1) taken from Pettersson (1994 (b)).

| **Total response** | | |
|---|---|---|
| *Independent variables* | *Coefficient* | *Denomination* |
| Constant | - 0.115848 [1)] | |
| Log response first 5 years ($E_5$) | +0.973479 | log ($m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$) |
| Latitude | +0.019539 | (degrees-54) |
| Altitude | +0.004166 | (m + 100) |
| Log altitude | -0.359743 | log (m + 100) |
| Latitude x Altitude | -0.000057 | (degrees x m) |
| Site index [2)] | -0.005493 | m |
| P. sylvestris [3)] | -0.105466 | |
| Log Nitrogen dose | +0.314026 | log (kg N $ha^{-1}$) |

[1)] The constant includes correction for logarithmic bias

[2)] Dominant height at age 100

[3)] The coefficient is used in pine-dominated stands

For the duration of response, the most influential independent variable is the relationship between the $E_5$ and total response. The dose of N as well as the most influential site class factors in this case, current annual increment and altitude which have proven to have an impact on the duration. The function is taken from (**Table 6**).

**Table 6:** Predictive function for estimation of the duration of response, dependent variable log duration (year) taken from Pettersson (1994(b)).

| **Duration** | | |
|---|---|---|
| *Independent Variables* | *Coefficient* | *Denomination* |
| Constant | +0.835350[1)] | |
| log total respons ($E_5$) | +0.107194 | log $m^3$ o.b. $ha^{-1}$ $total^{-1}$ |
| Response total /first five years ($E_5$) | -0.192093 | $m^3$ o.b. $ha^{-1}$ $total^{-1}$ / $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$ |
| log response total /first five years ($E_5$) | +1.314621 | log ($m^3$ o.b. $ha^{-1}$ $total^{-1}$ / $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$ |
| log altitude | +0.036374 | Log (m+100) |
| log CAI[2)] | -0.115994 | log ($m^3$ o.b. $ha^{-1}$ $year^{-1}$) |

[1)] The constant includes correction for logarithmic bias

[2)] current annual increment

### 3.4 Economic analyses

The optimal dose of N was evaluated on the basis of the 68 pine-dominated plots with observed total response. This was the same selection of data as utilized for the analysis of predictive accuracy of total response and duration. The only additional selection made was the exclusion of plots fertilized with N doses other than 50, 100, 150 and 250 kg N $ha^{-1}$. Internal rate of return (IRR) was used as criteria for determining the optimal dose. The IRR analysis was performed for the observed total response, and the predicted total response based on the $E_5$ predictive functions produced by Rosvall (1980) and Pettersson (1994 (a)) used in the total response function produced by Pettersson (1994(b)) and assuming one fertilization 10 years before final harvest.

The IRR was calculated by finding the interest rate r which makes the net present value (NPV) zero by using the following formula:

$$NPV = -A + X + I*V*(1-s)/(1+r)^{10}$$

Where

$X = A * s(1 + k)$

A = The invested amount before tax

K = Tax deductible amount when using the forest fund scheme (85 % of invested amount)

s = the marginal income tax rate

The IRR was calculated for three different economic assumptions regarding s and k:

A. First, the national economic return was calculated using the market prices and costs before tax as the marginal costs and benefits caused by the fertilization. This means that s and k was set to zero.
B. Secondly, the IRR was calculated from private forest owner's business point of view assuming marginal income tax s to be 0.28 and k being 0.85.
C. Finally, the IRR was calculated from private forest owner's business point of view assuming marginal income tax s to be 0.358 and k being 0.85.

In all three alternatives the following costs and benefits were assumed:

1. Cost of fertilizing A = 1000 NOK +10 NOK *kg N $ha^{-1}$
2. Net income (before tax) I was set at a fixed 300 NOK per $m^3$
3. The increase in volume V caused by fertilization was calculated as the average 10-years response in $m^3$ o.b. $ha^{-1}$ for the individual doses of N $ha^{-1}$.

### 3.5 Statistical analyses

The statistics and graphs were computed using R statistics (R Development Core Team 2008). A Pearson product-moment correlation coefficient was computed in order to assess the expected linear relationship between predicted and observed response and duration of response to fertilizer. A one way pair-wise ANOVA together with a post-hoc Tukey HSD test was performed to test for differences in response between different types of fertilizer.

## 4. Results

### 4.1 Evaluation of the two Swedish $E_5$ functions

#### *4.1.1 The overall predictive value*

The $E_5$ function produced by Pettersson (1994 (a)) is in the results referred to as function ***a*** whereas the function produced by Rosvall (1980) is referred to as function ***b***. SD= standard deviation.

Although the overall correlation between observed and predicted response for the $E_5$ function was found to be significant, it was low for the function ***b*** ($r^2$ = 0, 23 n= 707, p < 0,001) and somewhat higher for function ***a*** ($r^2$ = 0,27 n= 707, p < 0,001). Function ***a*** overestimated the response by an average of 1,26 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$ (SD=4,01; equivalent to a 20 % lower observed than predicted value). The function ***b*** overestimation of the response was slightly lower with 0,87 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$ (SD= 4,07; equivalent to a 15 % lower observed than predicted value) In order to better understand if there was any significant difference in the parameter estimation, the material was subdivided by fertilizer type urea and ammonium nitrate (AN) in stands dominated by pine and spruce. This gave the following combinations: Pine-AN, Pine –urea, Spruce –AN, and Spruce-urea.

### *4.1.2 Predictive value in Pine-dominated plots fertilized with AN*

For pine stands fertilized with AN fertilizer there was a positive correlation between the predicted and observed response for both predictive functions. The highest level of correlation was found for function ***a*** ($r^2$ = 0,40 , n= 302, p < 0,001). Function ***a*** overestimated the response to fertilizer by an average of 0,84 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$ (SD= 3,72; equivalent to a 13 % lower observed than predicted value). For the predictive function ***b***, the level of correlation was only slightly lower ($r^2$ = 0,38, n= 302 p < 0,001). Function ***b*** overestimated the response by an average of 0,18 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$ (SD = 3,51; equivalent to a 3 % lower observed than predicted value). A scatterplot summarizes the results (**Fig. 1**).

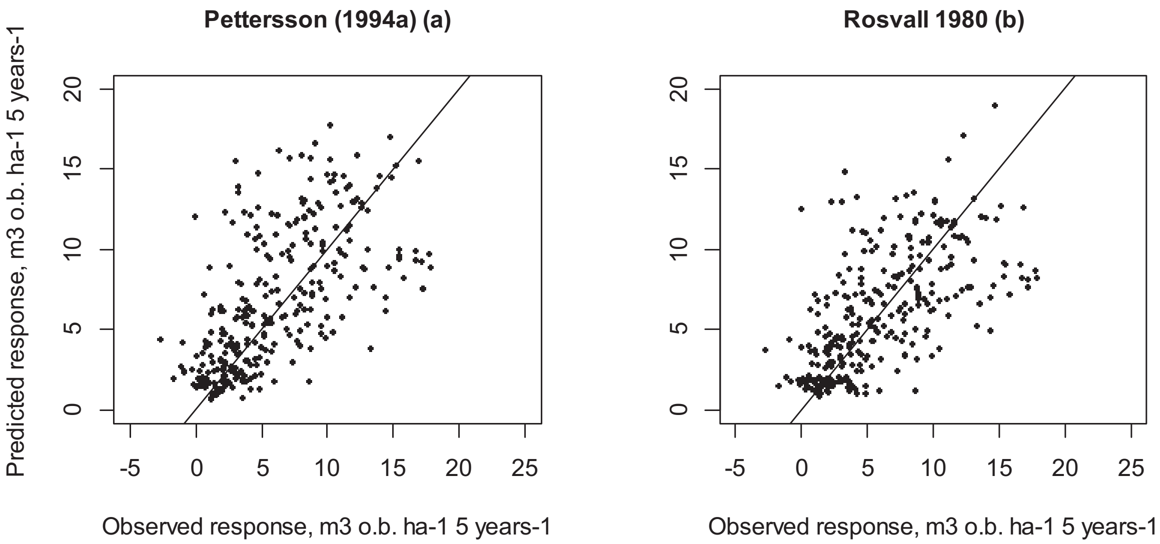


**Figure 1**: Correlation between predicted and observed response in pine plots fertilized with AN for: ***a*** E5 predictive function produced by Pettersson (1994 a) without reduction, ***b*** E5 predictive function produced by Rosvall (1980) without reduction.

### *4.1.3 Predictive value in Pine-dominated plots fertilized with urea*

The growth response to urea fertilizer is in both functions predicted to be less than an equal dose of N applied as an ammonium nitrate mix. For pine-dominated plots fertilized with urea there was a positive correlation between the predicted and observed response for both predictive functions. The same level of correlation was found for function ***a*** ($r^2$ = 0,42, n= 111 p < 0,001) and for the predictive function ***b*** ( $r^2$ = 0,42, n= 111 p < 0,001). For function ***a*** the response was on average overestimated by 0,22 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$ (SD= 3,21; equivalent to a 4 % lower observed than predicted value). Function ***b*** underestimated the response by on average 0,32 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$ (SD=3,13; equivalent to a 6 % higher observed than predicted value) A scatterplot summarizes the results (**Fig. 2**).

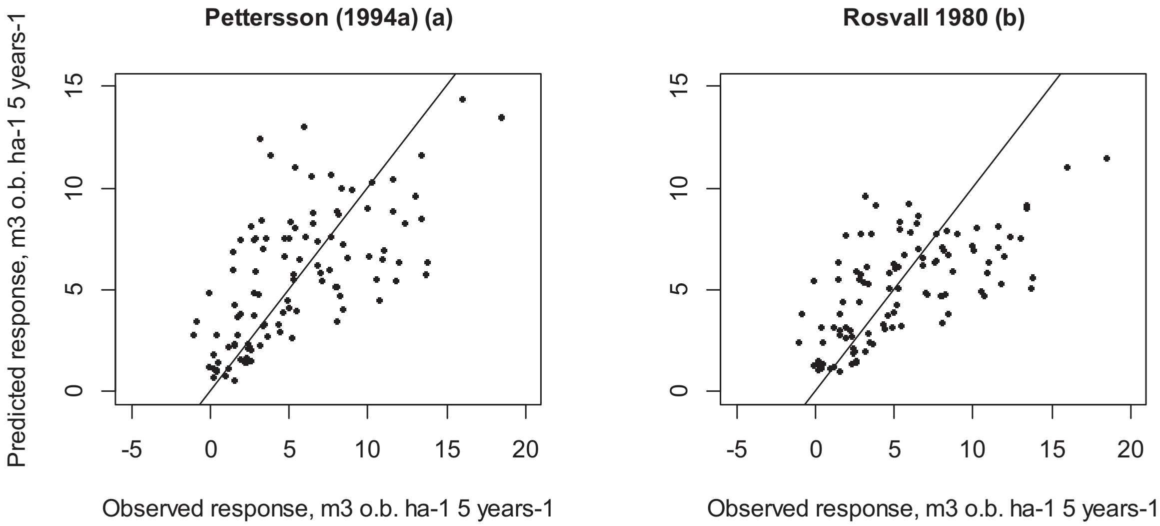


**Figure 2:** Correlation between predicted and observed response in pine plots fertilized with urea for: ***a***, E5 predictive function produced by Pettersson (1994 a) without reduction and ***b***, E5 predictive function produced by Rosvall (1980) without reduction.

### *4.1.4 Predictive value in Spruce-dominated stands fertilized with AN*

For spruce plots fertilized with AN there was a positive correlation between the predicted and observed response. The highest level of correlation was found for the function ***a*** ($r^2$ = 0,12, n= 210 p < 0,001). Here function ***a*** overestimated the response with 1,85 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$ (SD= 4,50; equivalent to a 29 % lower observed than predicted value). For the predictive functions produced by Rosvall 1980 ***b*** , the level of correlation was even lower ( $r^2$ = 0,09, n= 210 p < 0,01) the function ***b*** overestimated the response by on average 1,81 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$ (SD= 4,81; equivalent to a 28 % lower observed than predicted value). A scatterplot summarizes the results **(Fig. 3).**

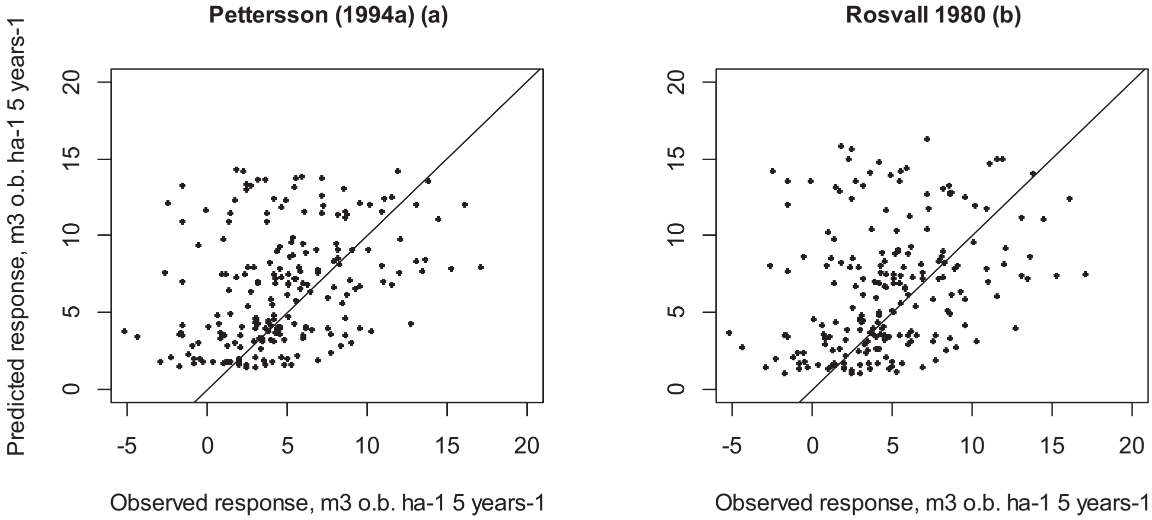


**Figure 3:** Correlation between predicted and observed response in spruce plots fertilized with AN for: ***a***, E5 predictive function produced by Pettersson (1994 a) without reduction and ***b***, E5 predictive function produced by Rosvall (1980) without reduction.

### *4.1.5 Predictive value in Spruce-dominated stands fertilized with urea*

For spruce sites fertilized with urea no positive correlation between the predicted and observed response for any of the predictive functions were found at the 5 % confidence level. Hence the predictive functions are incapable of explaining a significant part of the variation in response. The highest level of correlation was found for function ***a*** ($r^2$= 0, 05, n= 85 p = 0,08). Function ***a*** overestimated the response with an average of 2,74 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$ (SD=4,08; equivalent to a 42% lower observed than predicted value). For function ***b*** the level of correlation was slightly lower ($r^2$ = 0,04, n= 85 p = 0,09). Function ***b*** overestimated the response by on average 2, 65 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$ (SD=4,04; equivalent to a 41 % lower observed than predicted value). A scatterplot summarizes the results **(Fig. 4).**

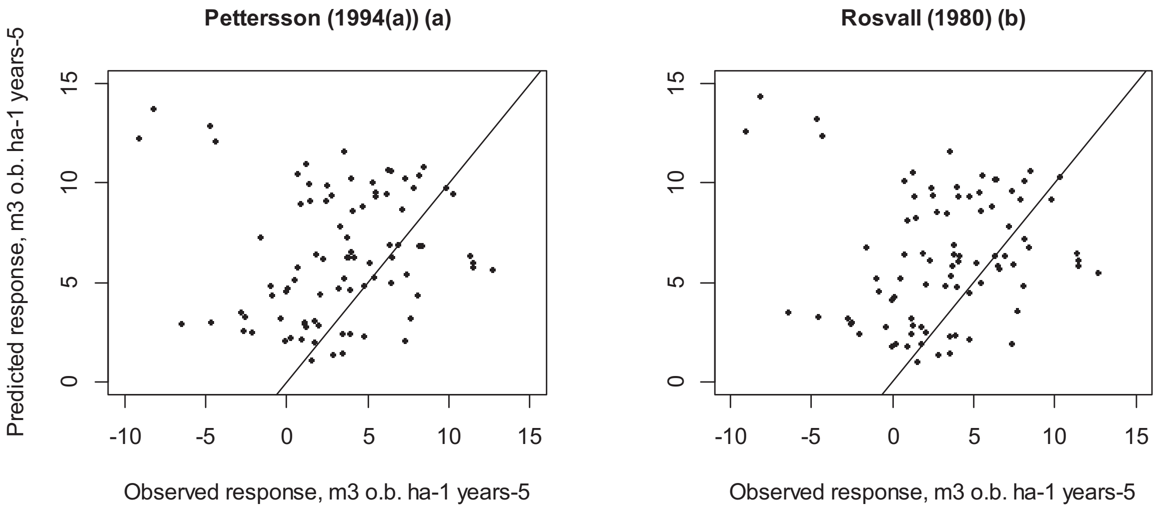


**Figure 4:** Correlation between predicted and observed response in spruce plots fertilized with urea for: ***a***, E5 predictive function produced by Pettersson (1994 a) without reduction and ***b***, E5 predictive function produced by Rosvall (1980) without reduction.

### *4.1.6 Predictive value relative to dose for all stands fertilized with AN*

The overall low predictive value of the predictive models could to a large extent be attributed the lack of correlation between predicted and observed response in spruce stands. In order to better understand were the variation around the response occurs for the respective tree species and fertilizer type, the predictive functions were compared with the observed response at different dose intervals. The analyses were only made for AN fertilizer since it is the current commercially utilized fertilizer and only for the function without reduction. Hence it should be comparable to the observed data were the fertilizer is distributed evenly by hand. A further subdivision into dose gave an overall lower correlation between the predicted and observed, nevertheless the observed response at high doses of N proved to be much lower than the predicted for both functions and tree species' (**Table 7**). For pine dominated stands there are tendencies that response to fertilizer cumulates at doses over 100-150 kg N / ha. A higher than predicted response is observed for doses up to 100 kg /N ha. Spruce sites are underestimated even at low doses and increases with increasing doses for both functions. However there are few plots fertilized with high doses (> 200kg N $ha^{-1}$) of N for both tree species', thus there is a great uncertainty in the correlation analysis at high doses.

**Table 7:** Correlation and descriptive statistics for predicted and observed response after the five first years. Nr. obs = number of observations, mean obser.= mean observed $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$, SD obser. = standard deviation of the observed value, Mean pred = mean predicted $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$, SD pred .= standard deviation of the predicted value, Obser/pred % = the observed response divided on the predicted in percent.

**Correlation and descriptive statistics**

| Tree species. | $E_5$ | Dose N | Nr obs | Mean obser | SD obser. | mean pred. | SD pred. | Obser/pred % | $r^2$ | p- value |
|---|---|---|---|---|---|---|---|---|---|---|
| **Pine AN** | *Pettersson (1994a)* | <51 | 83 | 2.31 | 2.41 | 2.30 | 1.02 | 100.55 | 0.04 | 0.051 |
| | | 51-100 | 99 | 6.93 | 4.79 | 6.10 | 2.23 | 113.57 | 0.25 | < 0.001 |
| | | 101-150 | 74 | 6.89 | 4.20 | 8.87 | 3.00 | 77.69 | 0.08 | 0.011 |
| | | 151-200 | 28 | 9.41 | 3.73 | 13.57 | 1.60 | 69.30 | 0.01 | 0.545 |
| | | 201-250 | 15 | 8.26 | 4.72 | 13.41 | 2.37 | 61.63 | 0.14 | 0.174 |
| | *Rosvall (1980)* | <51 | 87 | 2.31 | 2.41 | 2.07 | 0.91 | 111.55 | 0.07 | 0.014 |
| | | 51-100 | 101 | 6.93 | 4.79 | 5.48 | 1.82 | 126.51 | 0.22 | < 0.001 |
| | | 101-150 | 75 | 6.89 | 4.20 | 8.40 | 2.32 | 82.05 | 0.06 | 0.029 |
| | | 151-200 | 29 | 9.41 | 3.73 | 11.34 | 1.40 | 82.96 | 0.07 | 0.179 |
| | | 201-250 | 15 | 8.26 | 4.72 | 15.07 | 1.71 | 54.84 | 0.10 | 0.251 |
| **Spruce AN** | *Pettersson (1994a)* | <51 | 77 | 2.60 | 3.75 | 2.90 | 0.99 | 89.72 | 0.09 | 0.825 |
| | | 51-100 | 68 | 6.07 | 4.27 | 6.49 | 1.74 | 93.44 | 0.05 | 0.075 |
| | | 101-150 | 46 | 6.20 | 4.19 | 9.68 | 2.21 | 64.12 | 0.00 | 0.689 |
| | | 151-200 | 19 | 3.96 | 6.41 | 13.24 | 1.05 | 29.91 | 0.15 | 0.100 |
| | | 201-250 | 4 | 5.77 | 2.71 | 12.76 | 0.98 | 45.24 | 0.30 | 0.450 |
| | *Rosvall (1980)* | <51 | 77 | 2.60 | 3.75 | 2.58 | 1.02 | 100.91 | 0.00 | 0.855 |
| | | 51-100 | 68 | 6.07 | 4.27 | 6.34 | 1.84 | 95.77 | 0.01 | 0.338 |
| | | 101-150 | 46 | 6.20 | 4.19 | 9.92 | 2.71 | 62.52 | 0.00 | 0.912 |
| | | 151-200 | 19 | 3.96 | 6.41 | 13.76 | 1.67 | 28.79 | 0.24 | 0.330 |
| | | 201-250 | 4 | 5.77 | 2.71 | 14.65 | 1.56 | 39.39 | 0.19 | 0.559 |

## 4.2 Evaluation of the total response function

### *4.2.1 Predictive value of the total response function*

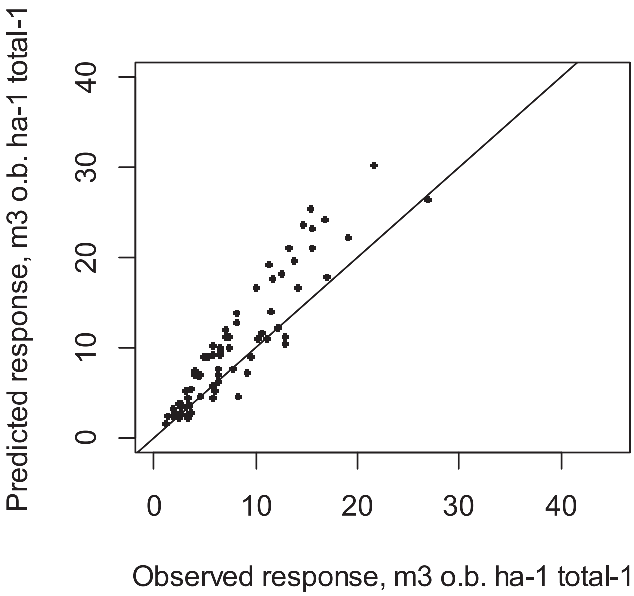


**Figure 5:** Correlation between predicted total response based on the observed response after the first 5 years vs. the observed total response.

Due to the low correlation between the predictive functions and observed response for both urea and AN fertilizer in Spruce-dominated and lack of data on total response in spruce-dominated stand further analyses of the functions built on the predicted response for the first 5 years ($E_5$) as total response and duration was performed only for the pine-dominated stands. The independent variables for the prediction of the total response are shown in **Table 5**. The expected total response is highly dependent on the response to fertilizer the five first years after the initial fertilization. There is a significant positive correlation between the predicted total response based on the observed response after the first 5 years, and the observed total response ($r^2$ =0,855, n=72 p < 0,001). Despite the high level of correlation the total response was overestimated by 2,18 $m^3$ o.b. ha $^{-1}$ total$^{-1}$ (SD= 2,96; equivalent to a on average 21 % lower observed than predicted value). A scatterplot summarizes the results **Figure 5**.

### *4.2.2 Predictive value of total response and $E_5$ functions combined*

When the predicted response for the first 5 years was used in the function the precision was much lower but the skewness towards an overestimation prevailed. When the $E_5$ function ***a*** was used as predictor in the function estimating the total response the correlation was still significant ($r^2$ =0,29 , n=72 p < 0,001). However both functions overestimated the response, function ***a*** by an average of 3,44 $m^3$ o.b. $ha^{-1}$ $total^{-1}$ (SD= 6,65; equivalent to a 30 % lower observed than predicted value). The function ***b*** had a slightly lower level of correlation ($r^2$ =0,27 , n=72 $p < 0,001$), function ***b*** overestimated the response function with an average of 3,80 $m^3$ o.b. $ha^{-1}$ $total^{-1}$ (SD=10,12; equivalent to a 33% lower observed than predicted value). A scatterplot summarizes the results for both functions in **Figure 6**.

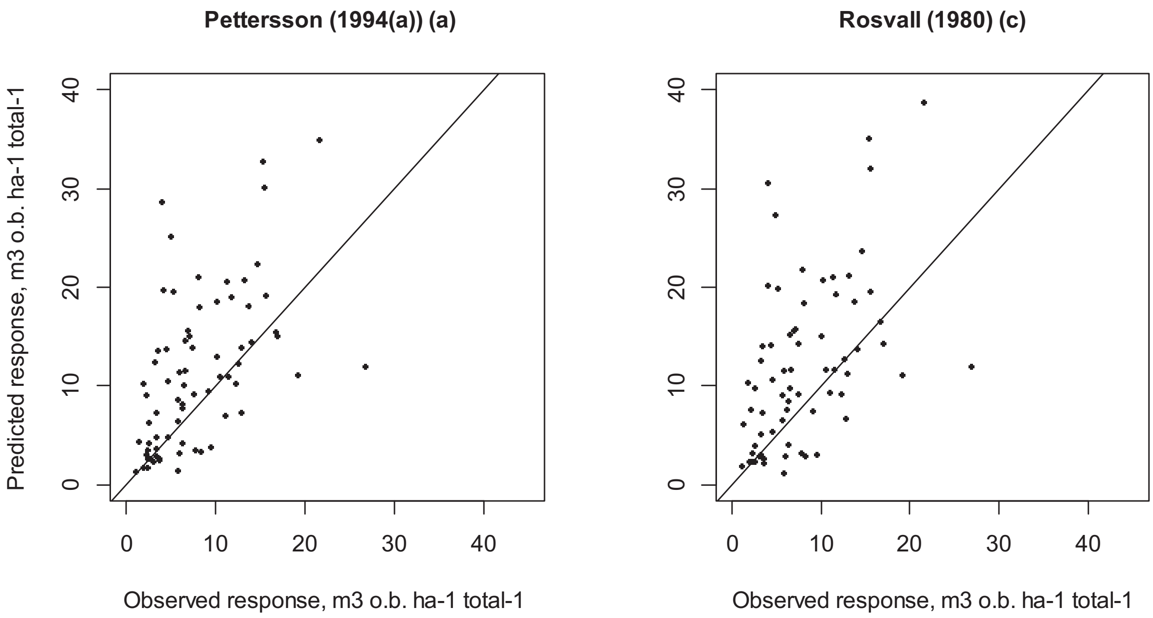


**Figure 6:** Correlation between predicted total response and observed total response with: a, E5 predictive function produced by Pettersson (1994a) without reduction and b, E5 predictive function produced by Rosvall (1980) without reduction as predictors used in the function predicting the total response produced by Pettersson(1994 b).4.3 Evaluation of the duration of response function.

## 4.3 Predictive value of the Duration of response function

The results from the Norwegian fertilization experiments revealed that the duration of the response ranged between 5 to 12 years in pine-dominated stands with an average duration of 7,32 $years^{-1}$ ( SD 1,47). The function estimating the duration of response is highly dependent on the relationship between total response and response after 5 years, in addition to altitude and current annual increment, as shown in **Table 6.** In pine stands fertilized with AN fertilizer a significant correlation between observed and predicted duration was found ($r^2$ = 0,77 , n=72 $p < 0,001$). However only by utilizing the observed response after 5 years and observed total response as variables in the duration function (**Fig. 7)**. The predicted duration was on average 0,42 (SD= 0,70) years longer than the observed (equivalent to a 5 % lower observed than predicted value).

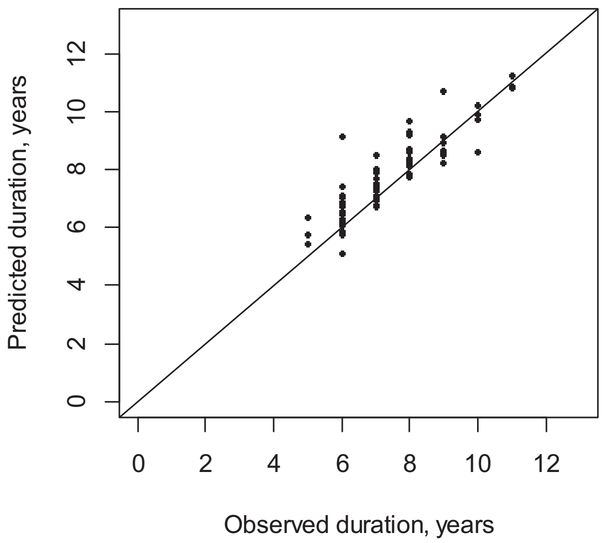


**Figure 7:** Correlation between predicted duration and observed duration with observed response after 5 years and observed total response as predictors.

### *4.3.1 Predictive value of Duration based on $E_5$ and total response functions*

When predicting the duration based on predicted values: $E_5$ functions of Pettersson (1994 (a)), and Rosvall (1980) and predicted total response produced by Pettersson (1994(b)), no significant correlation was found for the function ***a*** ($r^2$ = 0,001, n=72 p = 0,95) or ***b*** ($r^2$ = 0,001 n=72 p = 0,93). The predicted duration of function ***a*** was overestimated by an average of 1,74 years$^{-1}$ (SD =2,04; equivalent to a 19% lower observed than predicted value). For function ***b*** the duration was overestimated by an average of 1,88 years$^{-1}$ (SD =2,18; equivalent to a 20 % lower observed than predicted value). A scatterplot summarizes the results (**Fig. 8**).

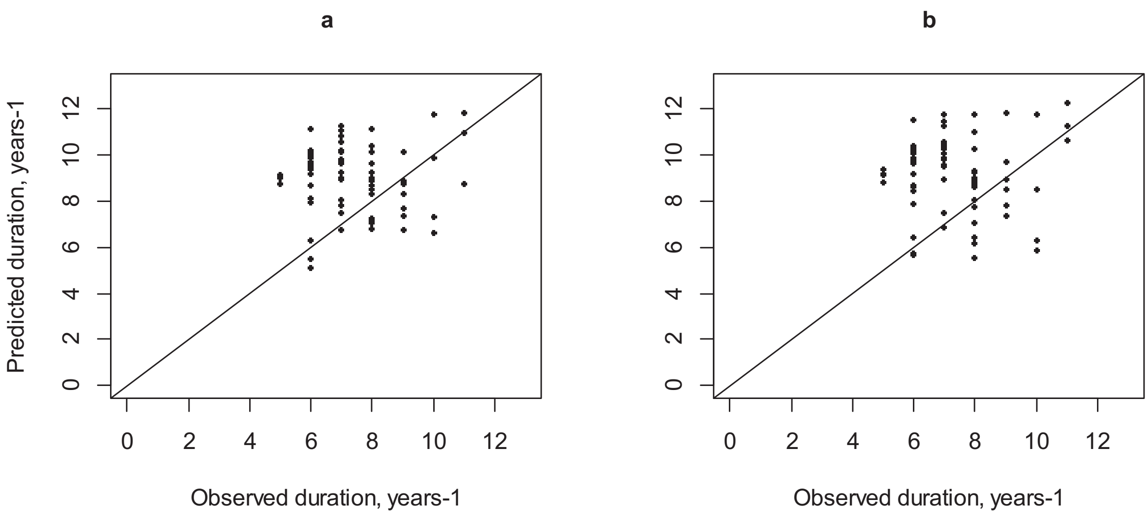


**Figure 8:** Correlation between predicted duration and observed duration with: ***a***, E5 predictive function produced by Pettersson (1994 (a)) without reduction and ***b***, E5 predictive function produced by Rosvall (1980) without reduction used as predictors in the function predicting the duration produced by Pettersson (1994( b)).

## 4.4 Fertilizer type and growth response

There were no statistically significant differences between different fertilizer types based on the observed response after the first 5 years and the doses 100, 150, 200 kg N ha-1 as determined by one-way ANOVA respectively (F=1,718 , p =0,179), (F=0,817 , p=0,487 ), (F= 0,268 , p=0,766 ).

## 4.5 Economic return from a single shot application of N fertilizer

In the present analysis the observed values are exclusive the plots without response which accounted for the 26 % of the plots at 50 kg N ha $^{-1}$. and 3 % of the plots For 100 kg N ha$^{-1}$ . In plots with Doses of 150 and 250 kg N ha$^{-1}$ all of the plots responded to N fertilizer. The observed growth response is higher than the predicted response was greater than the observed response in response was greater in pine plots than spruce plots.

**Table 8:** Total response observed and predicted m$^3$ o.b. ha$^{-1}$

| **Total response observed and predicted** | | | | | | |
|---|---|---|---|---|---|---|
| | ***Observed*** | | ***Pettersson (1994(a))*** | | ***Rosvall (1980)*** | |
| *Kg N ha-1* | *Average* | *SD* | *Average* | *SD* | *Average* | *SD* |
| 50 | 4.31 | 3.97 | 2.59 | 1.44 | 2.68 | 0.88 |
| 100 | 8.95 | 6.38 | 9.59 | 3.66 | 9.88 | 2.99 |
| 150 | 11.04 | 5.16 | 16.24 | 5.56 | 16.93 | 5.10 |
| 250 | 12.66 | 6.23 | 30.14 | 4.82 | 32.74 | 5.62 |

The analysis of IRR revealed large differences between the predicted and observed response to fertilizer in pine dominated stands increasing with dose (**Fig. 8)**.

The IRR was calculated for three different economic alternatives here presented as:

A= The national economic return

B= The business point of view with a tax rate of 28 %

C= The business point of view with a tax rate of 35,8 %

For the observed response the IRR for all for all alternatives A, B, and C was found in stands fertilized with 150 kg N ha$^{-1}$ . For the predicted response there was an increasing IRR with increasing dose up to 250 kg N ha$^{-1}$ which was the highest dose included in this study.

The National economic return alternative without the tax benefits of using the forest fund gave only marginally positive IRR for N doses > 50 kg ha $^{-1}$ peaking at 150 kg N ha$^{-1}$ with an observed IRR of 2,9 % p.a. Estimations of IRR based on the two predictive functions both with the highest IRR at 250 kg N ha$^{-1}$. For the 150 kg N ha$^{-1}$ alternative the predicted response gave a IRR of 6,9 % p.a and 7,3 % p.a for Pettersson (1994 (a)) and Rosvall (1980) respectively (**Fig. 9A**).

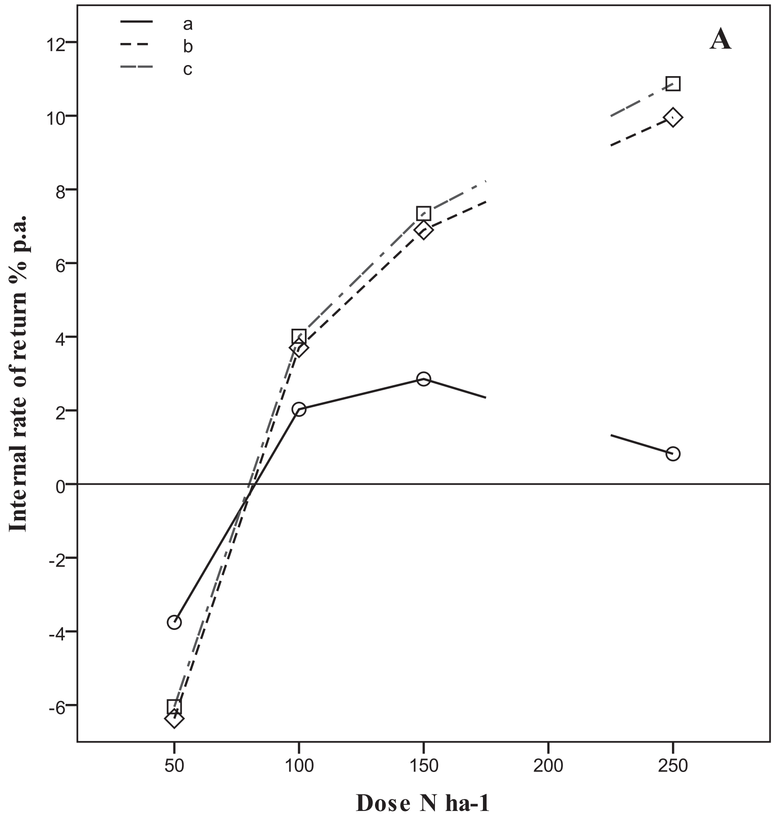


**Figure 9 A:** The national economic return was calculated using the marked price: net timber price 300 NOK / m$^3$and the cost of fertilizing (1000 NOK / ha +10 NOK* kg N ha$^{-1}$) based on: ***a***) the average observed total response, ***b***) the predicted total response based on $E_5$ Pettersson (1994 (a)) and total response (Pettersson (1994( b)) , ***c*** the predicted response based on $E_5$ Rosvall (1980) and the total response (Pettersson (1994(b)) .The IRR was not calculated for N dose 200 kg N ha$^{-1}$ due to insufficient data.

From the private forest owner's business point of view alternative B (28 % tax) including the tax benefits of using the forest fund scheme the observed response gave a positive IRR for all N doses peaking at 150 kg N ha$^{-1}$ with an observed IRR of 7 ,1 % p.a. Estimations of IRR based on the two predictive functions both with the highest IRR at 250 kg N ha$^{-1}$. For the 150 kg N ha$^{-1}$ alternative the predicted response gave a IRR of 11,3 % p.a. and 11,7 % for Pettersson (1994 (a)) and Rosvall (1980) respectively (**Fig. 9 B**).

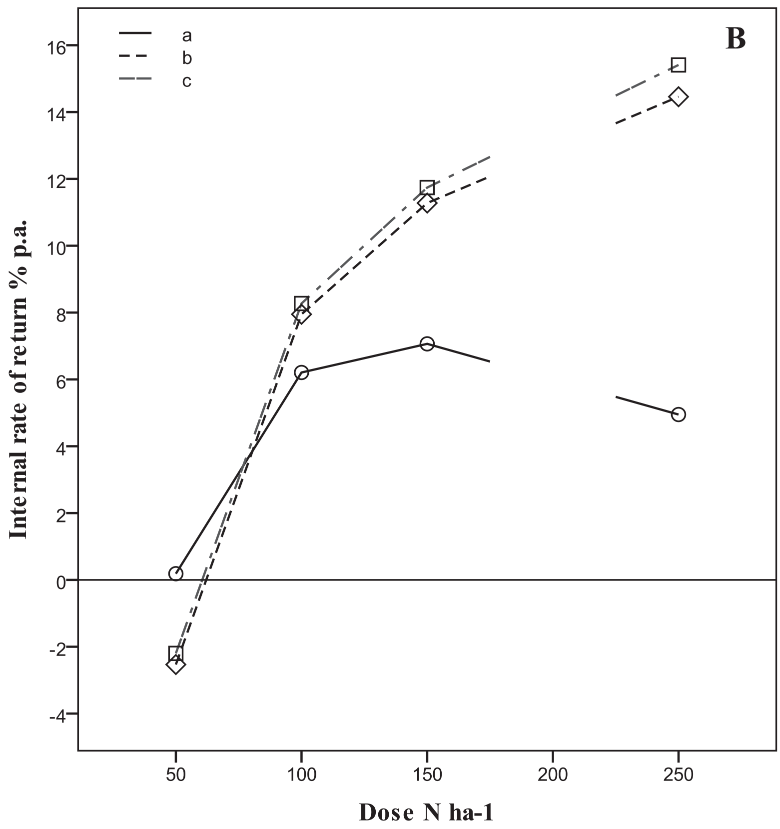


**Figure 9 B:** The IRR from the business point of view was calculated assuming marginal income tax s to be 0.28 and k being 0.85 and the marked price: net timber price 300 NOK / m3and the cost of fertilizing (1000 NOK / ha +10 NOK* kg N ha$^{-1}$) based on average responses for : ***a***) observed , ***b***) the predicted total response based on $E_5$ Pettersson (1994 (a)) and predicted total response (Pettersson (1994( b)) , ***c***) the predicted response based on $E_5$ Rosvall (1980) and total response (Pettersson (1994(b)) .The IRR was not calculated for N dose 200 kg N ha$^{-1}$ due to insufficient data.

From the private forest owner's business point of view return alternative C (35,8 % tax rate ) including the tax benefits of using the forest fund scheme the observed response gave a positive IRR for all N doses peaking at 150 kg N ha$^{-1}$ with an observed IRR of 9,7 % p.a. Estimations of IRR based on the two predictive functions gave the highest IRR at 250 kg N ha$^{-1}$. For the 150 kg N ha$^{-1}$ the predicted response gave an IRR of 14,0 % p.a and 14,5 % p.a for Pettersson (1994 (a)) and Rosvall (1980) respectively (**Fig. 9 C**).

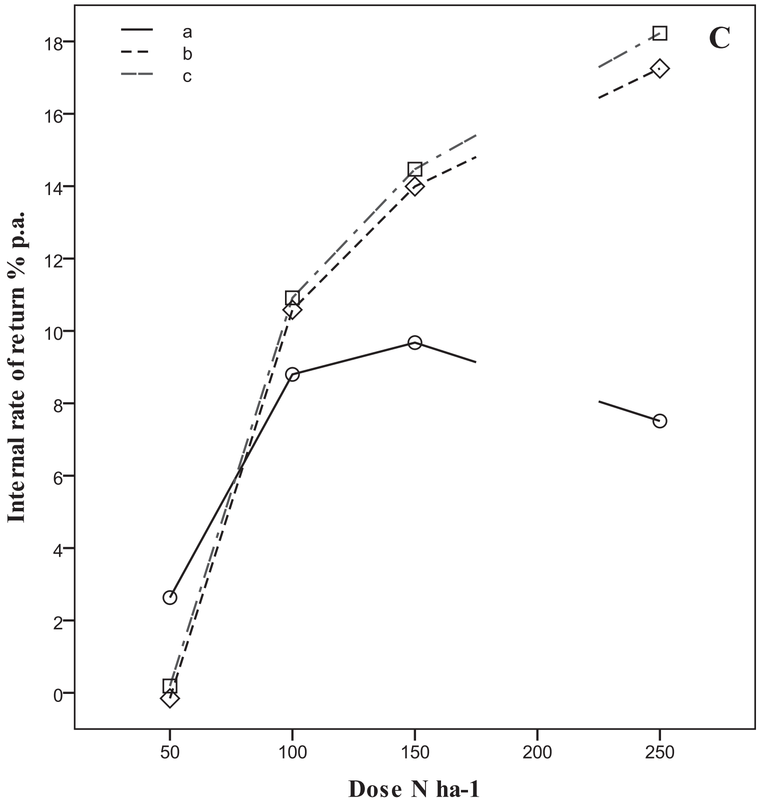


**Figure 9 C:** The IRR from the business point of view was calculated assuming marginal income tax s to be 0.358 and k being 0.85 and the marked price: net timber price 300 NOK / m3and the cost of fertilizing ((1000 NOK / ha) (10 NOK*( kg N ha-1)) based on average responses for : ***a***) observed , ***b***) the predicted total response based on $E_5$ Pettersson (1994 (a)) and predicted total response (Pettersson (1994( b)) , ***c***) the predicted response based on $E_5$ Rosvall (1980) and total response (Pettersson (1994(b)).The IRR was not calculated for N dose 200 kg N $ha^{-1}$ due to insufficient data.

# 5. Discussion

## 5.1 The functions predictive value in relation to the Norwegian fertilization experiments

### *5.1.1 Response over the first five years*

Both predictive functions explained an overall lower part of the variation in the Norwegian fertilization experiment. However the selection of data material used to produce both $E_5$ predictive functions was performed with a stricter selection of plots included in the function than the data used for the correlation analysis in the present study. In the functions produced by Pettersson (1994 (a)), this comprised the exclusion of experimental plots with site class factors that deviated from the adjacent control plots in terms of: basal area, basal area increment immediately prior to the treatment and number of stems per ha. The selections resulted in a field data used to test the function were no plots without response to fertilizer and very few plots with weak response to fertilizer (< 5 $m^3$ o.b. $ha^{-1}$ 5 $years^{-1}$) were included (Pettersson 1994 (a)). In the present study the selection of plots to test the $E_5$ functions did not exclude all plots with a week or no response to N fertilizer. Hence the expected and observed variation around both the functions was greater in the present study than in the initial test of the functions performed by Rosvall (1980) and Pettersson (1994 (a)) respectively. In the present study the main aim was not to fit data to the predictive functions, but to assess the functions ability to predict the response to fertilizer in Norwegian experiments and subsequently practical fertilization. It was therefore not excluded more than what could be done objectively.

### *5.1.2 The E5 predictive functions accuracy in relation to tree species and fertilizer type*

For the new predictive function $E_5$ Pettersson (1994 (a)), stated that "*the differences in the parameter estimation was found to be extremely marginal and of no practical significance*". However, in the present study the predictive accuracy was found to be much lower for spruce than for pine stands fertilized with AN and did not predict a significant part of the variation in response in spruce plots were urea was utilized for both $E_5$ predictive functions. In the field data used in the present study there was nothing to suggest that measurement errors or potential systematic errors should be any greater in spruce-dominated stands than in pine-dominated stands. The same experimental design and method for calculating the response has been used on approximately the same amount of experimental plots for the two tree species'.

However previous studies have shown that there are differences between the tree species' response to the addition of N. In general the growth response to N fertilization in conifer forest limited by N is a result of the promoted formation of new needles and increased amount of chlorophyll in the needles thus increasing the photosynthetic capacity (Tamm 1991). Spruce trees have a greater number of needle generations than pine trees and thus a slower response to the addition of N is expected. During the work with the old $E_5$ functions Rosvall (1980) found pine-dominated stands to have on average a 17 % higher response than the spruce-dominated stands after the first five years. However, the duration of the response was found to be longer in spruce stands than pine stands, thus the total response was approximately the same for both tree species' (Rosvall 1980). The same response patterns were found during the work with the new functions (Pettersson 1994 (a); Pettersson 1994(b)), and in a study of response in spruce and pine stands in Finland (Kukkola & Saramäki 1983). The differences in response between the two tree species was accounted for in the both the Swedish predictive functions evaluated and did not provide any further explanation as to why both predictive functions overestimate the response in spruce-dominated stands in the present study. Unfortunately the potential effect of a longer duration could not be assessed in the present study due to the lack of sufficient data on the total response in spruce-dominated stands.

### *5.1.3 Comparison of the two functions*

The predicted growth response based on the Norwegian experimental plots were on average 5 % higher for the new $E_5$ functions produced by Pettersson (1994 (a)) than the $E_5$ function produced by Rosvall (1980). This is in contrast to the findings of Pettersson (1994 (a)) who based on the site class factors from the Swedish experimental plots found the new $E_5$ functions to be on average 5 % lower than the old function and varying between geographical regions in Sweden (**Table 9)**.

In order to better to understand why the new functions predicted a higher response then the old functions in the present study, the influence of each individual variable was studied by locking all but one variable at the time.

**Table 9:** Percentage deviation of the predictive functions produced by Pettersson (1994(a)) compared with Rosvall (1980) (taken from Pettersson (1994 (a)).

| Comparison of the two Swedish functions | | | | | | |
|---|---|---|---|---|---|---|
| | **Northern Sweden** | | **Central Sweden** | | **Southern Sweden** | |
| | *NO* | *%* | *NO* | *%* | *NO* | *%* |
| Pine | 423 | -7 | 213 | -13 | 130 | -10 |
| Spruce | 46 | -4 | 64 | -14 | 85 | -13 |

The predictive functions produced by Pettersson (1994 (a)) do not predict a systematically lower response independent of dose, location and site class factors. The following explanations were found:

- The $E_5$ functions produced by Rosvall (1980) predicted a greater response than the new functions in stands with high site indices, combined with a high current annual increment. However a large part of the Norwegian experimental sites included in the analysis were situated on low to moderate site indices with a low to moderate annual increment. Here the predicted response was higher for the $E_5$ functions of Pettersson (1994 (a)).
- None of the Norwegian experimental sites were situated on latitudes defined as southern Sweden (< 58 $^o$ N) in the functions. Here were the differences between the functions of Pettersson (1994 (a)) and Rosvall (1980) were larger than for the northern parts (> 61 $^o$ N; **Table 9)**. A large part of the plots included in the present analysis were situated at latitudes above 61 $^o$ N where Pettersson (1994 (a)), found the response to be only marginally greater in the old functions.
- Many of the Norwegian experiments were performed in old stands with the average age at the initiation of the experiment being 91 (SD= 20,48) years in breast height. The $E_5$ function of Rosvall (1980) include the variable age at breast height whereas the variable age is absent in the $E_5$ function of (Pettersson 1994 (a)).Here the variable age is accounted for by the strong correlation between site index, current annual increment and stand age. The practical effect of the differences between the two functions was a greater predicted response in old stands for the $E_5$ function of Pettersson (1994 (a)), than when $E_5$ function of Rosvall (1980) was applied.

### *5.1.4 Response relative to dose after five years.*

In the Norwegian fertilization experiments the average observed response for the first five years coincided well with the predicted response for N doses up to 150 kg N ha $^{-1}$ for both tree species' an both functions. Nevertheless the new and old predictive functions overestimated the response at N doses over 150 kg ha$^{-1}$ for both tree species'. As observed by Pettersson (1994 (a)) and found in the present study the old functions predict a higher response at high doses of N than the in new functions (**Table 7**). In Pine stands in Norway it has previously been observed an increasing response with N doses up to 250 kg N ha$^{-1}$ (Haveraaen 1972). The present analysis of response after the first five years relative to dose revealed an increase in response to fertilizer up until 200 kg N ha$^{-1}$ and a slightly lower response observed in the relatively few plots fertilized with over 200 kg N ha$^{-1}$. For Spruce stands the response cumulated at 150 kg N ha$^{-1}$ with a lower response at higher doses. Therefore much of the $E_5$ predictive functions overestimation can be attributed to the prediction of response at high doses of N.

### *5.1.5 Total response and duration*

The function predicting the total response is based on and highly dependent on the predicted response the first five years. In the evaluation of the function estimates were performed with the total response for two different purposes. The predicted total response being based on the predicted response for both $E_5$ functions was performed in order to study how much of the variation in response could be explained from the initiation until the stand no longer responded to fertilizer. Here the unexplained variation in the $E_5$ functions influenced the accuracy of the total response functions (**Fig. 6**). Nevertheless the prediction of total response explained almost as much of the variation as E5 functions. This might, however have been partly attributed the removal of the "extreme values" plots without response and plots with an enduring response at the time of revision. In order to study the discrete performance of the total response function estimates were made based on the observed response for the first five years. The result revealed that a large part of the variation in response could be explained by the function (**Fig. 7**). However the observed total response was in average 20 % lower than the predicted. The results revealed that the largest percentile overestimation occurred from the fifth year and onwards. The weaker observed than predicted response in the years following the five firs years could be attributed differences in duration, whereas the expected duration has been found to be 6-8 years in the Norwegian field data used here and 7-10 years in the Swedish field data used to produce the function (Pettersson 1994(b); Sture 1984). However, since the methods used for determining the duration intervals was not made explicit in the literature I found it difficult to make a quantitative comparison.

The Norwegian field data included in the evaluation of the functions total response and duration were not believed to be without some bias. In addition to reducing the “noise” The plots that were discarded due to an enduring or negative response might have affected the average response. In the present study the average observed total response of the discarded plots and the plots included in the analysis did not differ significantly at the time of revision. The discarded plots had an average total response of 8,03 $m^3$ o.b. $ha^{-1}$ (SD = 9,44), whereas the remaining plots included in the analysis had an average observed response of 7,71 $m^3$ o.b. $ha^{-1}$ $total^{-1}$ (SD= 5,19). The small differences indicated that the exclusion did not have a great impact on the results. However the extent of the continuing response in the stands with response at the time of revision was not observed and could potentially account for parts of the lower observed than predicted response.

## 5.2 Influence of other factors than the ones included in the functions

Results from the Norwegian fertilization plots did not include variables for further analysis of other site specific factors, and are not treated in the present study. However, it has previously been of great interest to try to find other factors that could explain more of the variation in the response. The unexplained variation in early Norwegian predictive functions were partly assumed to be attributed climate and soil conditions (Brantseg et al. 1970). Later Rosvall (1980) more specifically addressed the need for more knowledge on the influence of weather conditions during and shortly after the application of fertilizer and site-class factors explaining the N composition prior to fertilization. During the work with the new predictive functions (Pettersson 1994 (a)) analyzed the data from the control plots adjacent to the to the experimental sites used to produce the predictive functions with emphasis site-class factors as soil texture, water class, soil profile and the thickness of and carbon / N ratio in the humus layer. For the site class factors only the carbon / N ratio proved to explain more of the variation in response. However the effect was so small and difficult to apply in practical use of the functions that it not included in the new functions (Pettersson 1994 (a)). For the influence of weather only a slight positive correlation between the response to urea and moderate precipitation during and after the application was found, whereas no relationship positive or negative was found between heavy precipitation and response to fertilizer (Pettersson 1994 (a)). In the early Norwegian experiments experiment many different fertilizer types were used as a part of establishing the best suitable fertilizer type. In the functions estimating tree growth all ammonium nitrate fertilizers are treated as one. In the present study no significant differences in response was found between different fertilizer types used.

## 5.3 Economic return

The results from the analysis of the observed response revealed that a dose of 150 kg N $ha^{-1}$ would give the highest IRR in all alternatives. For the predicted response the highest IRR was found at 250 kg N $ha^{-1}$.

From the national economic point of view the IRR of the Norwegian plots was 2, 9 % p.a , at 250 kg N $ha^{-1}$ which is less than 3,5- 4 % p.a. return advocated in national economic analysis (Finansdepartementet 2005). This is however only valid for the economic benefit and cost prerequisites made.

From a business point of view the IRR from 150 kg N $ha^{-1}$ in the Norwegian plots varied between 7,1 % and 9,7 % p.a, which was considerably lower than the estimates from the Swedish functions. The observed IRR was also in the lower bound of previous estimates in Norway which has been found to vary between 8-15 % (Haveraaen 1972; Svendsrud 1998).

The costs connected with application and fertilizer cost was believed to be relatively stable even though it might vary with fertilizer type and application method. However the use of a fixed net timber price was a course simplification of reality. The net income per $m^3$ is thought to vary with timber quality, dimensions, demand and logging costs. In a previous study where individual tree growth and diameter development was calculated for three stands at different locations in Sweden the dimensional effect was found to account for between 26 - 41 % of the total financial benefit of fertilizing (Jacobson & Pettersson 2010). This could imply that forest owners can maximize the economic return by selecting stands were a large proportion of the trees can grow into a better paid quality as a result of the additional diameter increment from fertilization.

In the present study a relatively high IRR was achieved already at 100 kg N $ha^{-1}$ for the observed response, if the cost of fertilizer would increase it could prove to be more profitable to fertilize with 100 kg N $ha^{-1}$ than higher doses.

The profitability of intensive fertilization regimes has also previously been assessed. In Holmen Skog in northern Sweden the potential IRR of three different forest fertilization regimes was evaluated. The treatments consisted of one single application of 150 kg close to maturity and two and tree recurring applications at 24 – 27, 16 – 18 and 8 – 9 years before harvest. The single shot application of fertilizer 8 - 9 years before planned harvest had the highest IRR for both spruce (13,8 %) and pine stands (11 %) almost two folds the other fertilization regimes. The fertilization effect was estimated to 16 $m^3$ o.b. $ha^{-1}$ for pine and 18 $m^3$ o.b. $ha^{-1}$ for spruce stands (Simonsen et al. 2010). This is similar to the predicted growth increase in pine stands predicted for 150 kg N $ha^{-1}$ in the present study (**Table 9**), with the observed IRR being similar to the business alternative B in the present study (**Fig. 9B**).

Jacobson and Pettersson (2010) also examined the IRR from both single shot and recurrent application of fertilizer. The highest IRR was found for a single shot applications of 150 kg N (16 % p.a ) the results indicated that the effect of a second and potentially third fertilization was expected to be lower than the initial fertilization (Jacobson & Pettersson 2010). Thus the marginal cost per $m^3$ obtained could be expected to be higher with recurrent applications.

## 5.4 Environmental impact of practical fertilization

Much of the research performed on the environmental impacts have been performed on sites fertilized with total dose of N far greater than commercially utilized. Some of these results show that nitrogen can have significant impacts on the plant community on the forest floor. However results from fertilization experiments in different parts of Sweden comparable to current commercial fertilization regimes, including one to four repeated doses of 150 kg N $ha^{-1}$, showed no effect on the number of vascular plants species' number or alteration of the vegetation type. However, epigenic lichens are sensitive to changes in the N pool and a short term decrease is to be expected. The degree of susceptibility was found to vary between species' and with total dose (Kellner 1993; Nohlgren & Nohrstedt 1995).

Intensive fertilization has been reported to reduce the amount of mycorrhiza fruit bodies (Wiklund et al. 1995). Tendencies of reduced amounts of mycorrhiza on tree roots has been observed during a single shot application of 150 kg N $ha^{-1}$ (Eriksson et al. 1984). For single shot application of fertilization this effect has been observed to level off after 2-3 years except from high doses (600 kg N $ha^{-1}$) which is believed to last for several years (Arnebrant 1991).

In relation to leaching of nutrients the general assumption based on the Norwegian research is that the forest ecosystem has a large capacity to restrain the N in the soil and tree biomass (Kjønaas et al. 1998).

### 5.5 Adaptation to practical use

In commercial forest fertilization the fertilizer will always be somewhat unevenly distributed. The uneven distribution has proved to give a reduced response compared with fertilization experiments (Aregger & Pettersson 1986; Freij & Frohm 1989). In the Norwegian research experiments the fertilizer was applied as even as possible to ensure precise results. Thus it is expected that the response to fertilizer in practical terms is somewhat lower. In a study of growth response in Sweden, where the fertilizer was applied as it would be in practical fertilization, Pettersson (1991) found the response to be on average 10 % lower than predicted by the functions produced by (Pettersson 1994 (a)) The predictive functions with correction have been reduced by 10 % for practical use. For the practical use of the two Swedish predictive functions a potential overestimation as observed in the present study can easily be corrected by reducing the constant in the function accordingly.

### 5.6 Suggestions for future research

Currently the most commonly utilized fertilizer type in commercial forest fertilizations in Norway is Opti-KAS™ 27-0-0 SKOG, an ammonium-nitrate mix consisting of 27% N with an addition of 0,2 % boron. The boron is added in order to prevent boron-deficiency when the productivity is increased. In order to assess the predictive functions accuracy it would be of great interest with a study of the effect of practical commercial N fertilization in stands in Norway with the AN fertilizer currently utilized.

## 6. Conclusion

For pine stands both the evaluated Swedish $E_5$ functions predict a significant part of the variation observed in Norwegian field experiments. For spruce, only a week correlation was found for the spruce-dominated plots fertilized with AN, and no significant correlation for the stands fertilized with urea. The $E_5$ predictive functions produced by Pettersson (1994 (a)) explain an overall larger part of the variation in response to N fertilizer in the Norwegian fertilization experiments than the function produced by Rosvall (1980). In order not to overestimate the response to N fertilizer at sites with high productivity and at the same time explain as much of the variation as possible, the function $E_5$ produced by (Pettersson 1994 (a)) seems to fit best to Norwegian fertilization experiments, and can in my opinion be used in pine-dominated stands fertilized with AN and urea at doses ranging from 50 to 150 kg N $ha^{-1}$. The total response function should according to the results in the present study be reduced by approximately 20 %. Whereas the function predicting the duration did not predict a significant part of the variation in response and in my opinion it is of little practical value. Based on the results in the present study the function should be applied with caution or not at all as the results here indicate a very low predictive value.

The present study show that the highest economic return can be achieved with an N dose of 150 kg N $ha^{-1}$ applied 8-10 years before planned harvest. For the forest owner an internal rate of return between 7,1 % and 9,7 % should be competitive with most of the other investments in forestry, many with an investment horizon far greater than 8-10 years. However without the tax benefit of the Norwegian forest fund scheme fertilization pine stands was found to be only marginally profitable and less than advocated in national economic analysis. Nitrogen fertilization at conceivable commercial rates of one to three repeated doses of 150 kg N $ha^{-1}$ might have minor implications for the plant community on the forest floor, epigenic lichens and the microbial activity, however the effect is thought to be temporal with a relatively short recovery time.

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