Effects of Site Preparation on Soil Properties and on Growth, Damage and Nitrogen Uptake in Planted Seedlings

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Abstract

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In this thesis, the effects on seedling growth and damage of some site preparation methods have been compared. Moreover, the effects of intensive site preparations, e.g. deep soil cultivation, on seedling growth and damage have also been evaluated. The effect of various site preparation methods on nitrogen mineralisation and seedling nitrogen uptake and the effect of high nitrogen uptake on seedling growth have also been studied.

In general, findings in this thesis support the hypothesis that seedling growth and survival are increased by site preparation. Soil inversion with the humus layer covered by mineral soil provided high seedling growth and survival. Soil scarification methods with the humus retained in the planting spot had high mineralisation rates. This thesis also showed that intensive site preparation methods like deep soil cultivation have to be used on sites that are rich in vegetation or frost-prone in order to secure high seedling growth and survival. Deep soil cultivation also provides an even environment for seedlings and hence an even stand structure. High seedling nitrogen uptake was positive to seedling growth for newly planted Norway spruce seedlings, and both nitrogen mineralisation and root growth were shown to be important processes to seedling nitrogen uptake. Site preparation was generally positive to seedling nitrogen uptake, and root growth was positively affected by soil scarification.

The results on nitrogen and carbon loss after intensive site preparation were contradictory, showing both an increased risk of nitrogen leaching and that no increased loss had occurred ten years after soil cultivation.

Key words: carbon loss, damage, mineralisation, nitrogen loss, root growth, seedling nitrogen uptake, site preparation, soil cultivation, soil scarification.

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Appendix

Papers I-V

The present thesis is based on the following Papers, which will be referred to by their Roman numerals.

I Nordborg, F. and Welander, T. Growth responses of rooted cuttings from five clones of Picea abies (L.) Karst. after a short drought period. *Scandinavian Journal of Forestry Research:* Accepted manuscript.

II Örlander, G., Nordborg, F., and Gemmel, P. The effect of complete deep soil cultivation on initial stand development. *Studia Forestalia Suecia*: Accepted manuscript.

III Nordborg, F., Nilsson, U., and Örlander, G. Effects of different soil treatments on growth and net nitrogen uptake of newly planted *Picea abies* (L.) Karst. seedlings (Manuscript)

IV Nordborg, F., Nilsson, U., Gemmel, P. and Örlander, G. High- and low-intensive site preparation: a comparative study of total nitrogen and carbon stocks in three conifer plantations, ten years after treatment (Manuscript)

V Nordborg, F. and Nilsson, U. Growth, damage and net nitrogen uptake in *Picea abies* (L.) Karst. seedlings, effects of site preparation and fertilisation (Manuscript)

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In study I, both authors were responsible for design and measurements. Nordborg was responsible for data processing. In study II, Örlander and Gemmel were responsible for the design, establishment and maintenance of the experiment. Nordborg was responsible for the data processing. In study III, Nilsson and Örlander were responsible for design and establishment of the experiment. Nordborg and Nilsson were responsible for measurements and data processing. In study IV, Örlander and Gemmel were responsible for the establishment of the experiment. Nordborg was responsible for the design of the study and Nordborg and Nilsson was responsible for data processing. In study V, both authors were equally responsible for establishment, measurement and data processing. In all studies except study II, Nordborg was main author and responsible for writing the papers and for literature search. In study II, Örlander was main author.

Introduction

Background

In Sweden, there is currently a discussion regarding whether it is possible to increase both wood production and non-timber values in the forest. Studies have shown that diversified forest management will be the most efficient way to reach these goals (McNeely 1994, Hanski 2000). In order to be able to decrease the harvest intensity and manage the forest towards non-timber values in some landscape sections, forestry has shown an interest in increasing forest growth and reducing the rotation length in other landscape sections (Vollbrecht 1996). Intensive forest management with high production rates and short rotation length will increase the demands for rapid and successful plantation establishment. Therefore, the interest in more intensive site preparation methods may increase. In Sweden, the effects of site preparation on seedling growth and survival have been studied for more than a century and a majority of this work has been done on conifers. However, the effects of intensive site preparation like deep soil cultivation in comparison to less intensive and intermittent methods are still missing for Swedish conditions. Moreover, there is a lack of studies on the effects of various site preparation methods on nitrogen mineralisation and seedling nitrogen uptake and the effect of high nitrogen uptake on seedling growth.

In Sweden, site preparation has been an integrated part of stand establishment for the last decades in order to increase survival and early growth in planted seedlings. In this thesis, "site preparation" is defined as all silvicultural treatments used to change the environment with the intention of increasing seedling survival and seedling growth during the establishment phase. The term "site preparation" includes soil scarification, field vegetation control with herbicides or steam, and prescribed burning. "Soil scarification" includes "site preparation" methods where the organic layer is removed and the mineral soil surface exposed, or alternatively the organic layer and the mineral soil are mixed mechanically (Zachrisson et al. 1997). Moreover, in this thesis "soil cultivation" is defined as a soil scarification method that buries the organic layer below a mineral soil cover. The most frequently used site preparation methods in Sweden are different types of soil scarification like disc trenching, mounding and patch scarification. Field vegetation control with herbicides is seldom used in forestry, but is used regularly during afforestation of farmland. Soil cultivation techniques like deep soil cultivation and soil inversion in patches (inverting) is still only performed in experiments and not yet used in forestry. Since the risk of vole damage may be high and the competition for nutrients and water is hard from the abundant field vegetation on these sites (Bärring 1967, Bäcke et al. 1986), it has been hypothesised that the intensity of site preparation has to increase with higher fertility of the site. Site preparation/soil scarification can be intensified by treating a higher proportion of the regeneration area, but also by increasing the depth of the soil treatment. The methods used in Swedish forestry today are low-intensive to moderately intensive. In this thesis, deep soil cultivation to a depth of more than 40 cm in 50% or more of the regeneration area is defined as "intensive site preparation".

Plantation establishment is a delicate balance between expected production, costs and environmental considerations. When a forest plantation is established through planting, seedlings and planting labour are normally the greatest expenses. By using more intensive site preparation methods, the mortality of planted seedling is decreased. Hence, fewer seedlings must be planted in order to achieve the required density in the future stand. Intensive site preparation methods have been shown efficient (Thomson & Neustein 1973, Neckelmann 1995), but the risk of nutrient leaching and carbon loss might increase with higher soil scarification intensity (Wilsson and Pyatt 1984, Johnson 1992, Örlander et al. 1996a), and the regeneration success must also be financially justifiable. The financial aspect of site preparation is left out of the thesis. Moreover, conifer plantations, and especially Norway spruce, have been of main interest in the thesis, and therefore a majority of the literature cited in the text is on conifers.

Site preparation and seedling damage

High mortality during the regeneration phase decreases stem density. This generally results in lower wood quality and may result in lower production in the stand (Pettersson 1992, Klang 2000). In Sweden, pine weevil (*Hylobius abietis*) causes the worst damage in young plantations, but frost, voles and browsing by roe deer and moose are also serious damaging agents.

In southern Sweden, conifer seedlings planted the first three years following clear-cutting will usually be severely damaged by pine weevil (Örlander & Nilsson 1999). Today an insecticide (permethrine) is used to protect conifer seedlings from pine weevil damage in fresh clearcuts, but the use in forestry will probably be prohibited in a near future. A four-year fallow period may be used to avoid damage by pine weevil, but then competition from field vegetation may be a problem instead (Örlander & Nilsson 1999, Nilsson & Örlander 1999). When a well-stocked Norway spruce stand in southern Sweden is clear-cut, the ground will usually be almost free of competing field vegetation during the first year after cutting and then field vegetation becomes abundant (Olsson & Staaf 1995, Bergquist et al. 1999, Nilsson & Örlander 1999). An abundant field vegetation cover at the site may also increase seedling damage by voles (Bärring 1967).

Site preparation methods that create a vegetation-free surface of bare mineral soil have been shown to effectively reduce damage by pine weevil and frost (Örlander & Nilsson 1999, Neckelmann 1995). The proportion of the soil surface that has to expose the mineral soil differs based on site and damaging agent. In order to decrease pine weevil damage, a patch with a radius of 10 to 20 cm around each seedling is efficient (Nordlander et al. 2000), but to avoid frost damage a higher proportion of the mineral soil has to be exposed if the site is frost-prone (Langvall 2000). To avoid voles the site has to be free from field vegetation but the mineral soil does not have to be exposed. However, a high proportion of the regeneration area has to be free from field vegetation (Bärring 1967). As mentioned above, site preparation directly reduces damage and mortality in a plantation by reducing the amount and degree of damage on newly planted seedlings. Moreover, high initial growth as a result of site preparation indirectly reduces damage, since the impact of a certain damage is smaller on a large seedling than a small seedling (Örlander & Nilsson 1999).

Site preparation and initial seedling growth

High initial seedling growth is the result of high water and nutrient availability, a fair microclimate and little severe damage. The aim of site preparation is to improve one or more of these factors. Hallsby (1994b) has shown that seedling growth is higher in soil scarification treatments where the litter and humus layer is retained or mixed with the mineral soil compared to planting in pure mineral soil. However, by exposing bare mineral soil in the surface, both damage of Pine weevil and frost is reduced compared to treatments with the organic layer intact on the soil surface or mixed with mineral soil (Nordlander et al. 2000, Langvall 2000). Moreover, damage from voles and the colonisation rate of field vegetation may also be reduced. By inverting the soil profile, i.e. by burying the organic layers in a mineral soil cover, damage may be reduced and seedling growth increased. Örlander et al. (1998) showed that soil inversion in patches (inverting) increased seedling growth compared to ploughing, mounding, disc trenching or untreated soil. Moreover, Neckelmann (1995) showed that soil inversion of the entire plot surface (deep soil cultivation) increased seedling growth compared to tilt ploughing and harrowing in clearcuts. Field vegetation control with herbicides is regularly used for farmland afforestation, and several studies have shown increased growth after field vegetation removal (Bärring 1967, Margolis & Brand 1990, Nilsson et al. 1996, Norberg 2001). However, since the competition mainly is for resources below ground, mowing is not sufficient (Nilsson et al. 1996). Although all site preparation methods mentioned above have been proven efficient, there is additional need for studies that compare the methods.

It may be difficult to establish seedlings on fertile sites since the field vegetation on such sites is dense. The field vegetation competes with the seedlings for resources such as water, light and nutrients (Nambiar & Sands 1993, Malik & Timmer 1996, Imo & Timmer 1999). Moreover, the field vegetation provides protection to damaging agents (e.g. voles). Deep soil cultivation will decrease the field vegetation and mineral soil with little nutrients may also delay the recolonisation rate of the field vegetation. However, soil profile inversion in patches has also shown promising results on initial growth (Örlander et al. 1998), and may be a less intensive alternative to deep soil cultivation, although experiments have not yet been carried out on fertile sites with rich vegetation in Sweden.

Site preparation and nitrogen uptake

Nitrogen is the limiting plant nutrient in most forest ecosystem in Sweden (Tamm 1991). Despite the abundance of nitrogen on a clear-felled site (Högbom et al. 2001) nitrogen availability is low, something which limits the growth of newly planted seedlings (Munson & Bernier 1993). Seedling nitrogen uptake has been shown to be higher after site preparation compared to untreated ground (Nilsson & Örlander 1999). By planting various mixtures of mineral soil and organic matter, the seedling nitrogen uptake becomes higher than in scarification methods that remove the soil organic matter (Hallsby 1994a). Moreover, seedling growth during the second growing season is positively correlated to seedling net uptake of nitrogen during the first growing season after planting (Bärring 1967, Nilsson & Örlander 1999). There is little available nitrogen for the seedlings after clear-felling as a result of competition from field vegetation (Nilsson et al. 1996) or due to non-optimal conditions for decomposition of the soil organic matter (Johansson 1994).

In order to achieve a high nitrogen uptake during the first growing season in the field, site preparations have to provide high nitrogen availability. High nitrogen availability is achieved by good conditions for root growth and nitrogen mineralisation. Root growth gives the seedling access to a larger soil volume and thereby increases the amount of available nitrogen and water (Burdett et al. 1984, Kozlowski 1987, Burdett 1990, Brissette & Chambers 1992). Moreover, root growth improves the root/soil contact for newly planted seedlings. Root growth in conifers declines in a dry environment (Coutts 1982, Rook et al. 1977). This may in turn affect future water and nutrient uptake and thereby also growth negatively (Burdett et al. 1984, Burdett 1990). Moreover, shoots are seldom in balance with the root system at the time of planting, since the root system is not intact after removal from the nursery, and since there are less available nutrients and water in a clearcut than in the nursery. Consequently, early root growth may also balance the shoot-to-root ratio after the seedlings have been transplanted (Grossnickle & Heikurinen 1989).

Root growth is enhanced by soil scarification due to lower soil density, higher soil temperatures and improved soil moisture conditions (Ross & Malcolm 1982, Örlander et al. 1990, Örlander et al. 1998). Soil scarification is also shown to increase the decomposition of soil organic matter (Johansson 1994) as a result of increased soil temperature and improved soil moisture conditions when the humus layer is buried by or mixed with mineral soil (Örlander et al. 1990, Fleming et al. 1994). However, if the humus layer is removed by soil scarification and the seedlings are planted in mineral soil, the nitrogen available to the seedlings may be reduced (Munson & Timmer 1995, Nesdoly & Van Rees 1998, Nohrstedt 2000).

The field vegetation has been shown to compete with tree seedlings for the available water and nitrogen (Nambiar & Sands 1993, Fleming et al. 1994, Staples et al. 1999). This can be a severe problem, particularly to the development of newly planted seedlings (Nilsson & Örlander 1995, McMillin & Wagner 1995). Soil scarification reduces the abundance of competing field vegetation (Örlander et al. 1990, Staples et al. 1999). Moreover, seedlings growing in undisturbed soil have lower nitrogen uptake and growth than seedlings in scarified soil (Nilsson & Örlander 1999, Örlander et al. 1996b). Field vegetation control with herbicides has also been shown to increase seedling nitrogen uptake (Nilsson et al. 1996, Malik & Timmer 1996). However, it has not been conclusively shown that competition from field vegetation for nitrogen occurs in clearcuts when the availability of this nutrient is high (Nambiar & Sands 1993, Nilsson & Örlander 1999).

Since nitrogen leaching is common in clearcuts (Ring 1994, Ring 1996), a balance must be attained between high nitrogen availability to provide fast initial seedling growth, and the risk for elevated leaching, respectively. Intensive soil scarification methods have been shown to increase nitrogen and carbon loss (Wilson and Pyatt 1984, Johnson 1992, Örlander et al. 1996a), and there have been concerns that early advantageous effects of intensive soil preparation do not persist throughout the rotation period (e.g. Thomson & Neustein 1973, Lundmark 1977, Johansson 1994). In addition to the risk of decreased fertility at the site, nitrogen loss may cause problems in streams and lakes and the carbon loss may add to the problems with global warming.

The objectives of this thesis have been to study site preparation methods that provide a low level of seedling damage and mortality and high initial growth for planted seedlings. The effects of site preparation on seedling nitrogen uptake, and the relation between root growth and net nitrogen mineralisation and seedling nitrogen uptake, respectively, have been of special interest. Focus has been put on Norway spruce (*Picea abies* (L.) Karst.), but in two studies other tree species have also been studied.

The following hypotheses have been addressed in this thesis; i) Site preparation increases growth and decreases damage and mortality in planted seedlings, ii) Intensive site preparation methods have to be used on front-prone sites or sites that are rich in vegetation in order to secure high seedling growth and survival, iii) Nitrogen limits seedling growth during establishment and increased nitrogen uptake is positive to the growth of newly planted seedlings, iv) High seedling nitrogen uptake is achieved in site preparations with high soil nitrogen mineralisation and high initial root growth, v) Intensive site preparations increase nitrogen and carbon loss during the establishment phase.

Material and methods

Five studies were carried out to answer the hypotheses stated in this thesis. One of these studies was a laboratory experiment performed in a climate chamber (I) and four were field experiments (II-V). Field experiments have been the main tool in this thesis since focus has been put on site preparations and their effects, but the special topic in study I was best answered in a laboratory experiment. All experiments have been planted with Norway spruce (*Picea abies* (L.) Karst., but several tree species were included in the analysis in the ten-year-old experiment in studies II and IV. The studies were mainly performed in southern Sweden, but the experiment used in studies II and IV had sites in northern Sweden also (Fig. 1). The overall hypotheses in the thesis are answered by the results from the five studies together, although the hypotheses in each study and the overall hypotheses did not always match exactly.

In studies II, III and V, site preparation effects on growth and damage were evaluated (hypothesis 1), and the effects of intensive site preparation on damage and growth were studied in studies III and V (hypothesis 2). In studies III and V, the effects of site preparation on mineralisation, root growth and seedling nitrogen uptake were studied and related to seedling growth (hypotheses 3 and 4). Since root growth was regarded as an important process in order to increase nitrogen uptake, effects of drought on root growth were examined in study I. In studies IV and V, effects of intensive site preparations on nitrogen and carbon loss were studied (hypothesis 5).

In this thesis, seedling growth expressed as biomass (I, III, IV, V), shoot or root elongation (I, II, III, V), height and diameter (II, III, V) and basal area (II), have been considered as direct seedling/tree response parameters in the site preparation treatments. In addition, physiological plant parameters such as nitrogen concentration/content (III, IV, V), tissue water content (I) and plant water potential (III) have been used as seedling/tree response parameters. Seedling damage has also been regarded as a response parameter, but since damages affect growth, it has to be considered as both a direct parameter and an indirect response parameter.

The effect of the treatments on the seedling environment has been monitored in the experiments. Nitrogen and water availability has been in focus, but also climatic parameters have been measured. Nitrogen mineralisation and the availability of inorganic nitrogen in the soil have been determined according to well-known methods, e.g. the buried-bag method and the in-situ-soil-core method (Eno 1960, Raison 1987) (III, V). The soil water potential has been monitored with gypsum blocks, which also is a standard method (III, V). The severity of the drought in experiment I could not be measured in the root environment in the aeroponics system. Instead, root water content and a comparison of response patterns with earlier studies was used to indirectly measure the severity of the drought.

The effect of the soil treatments on nitrogen and carbon loss was made using total nitrogen and carbon analyses in soil and vegetation (IV), but also through soil water sampling with ceramic suction lysimeters installed at 60-65 cm depth (V).

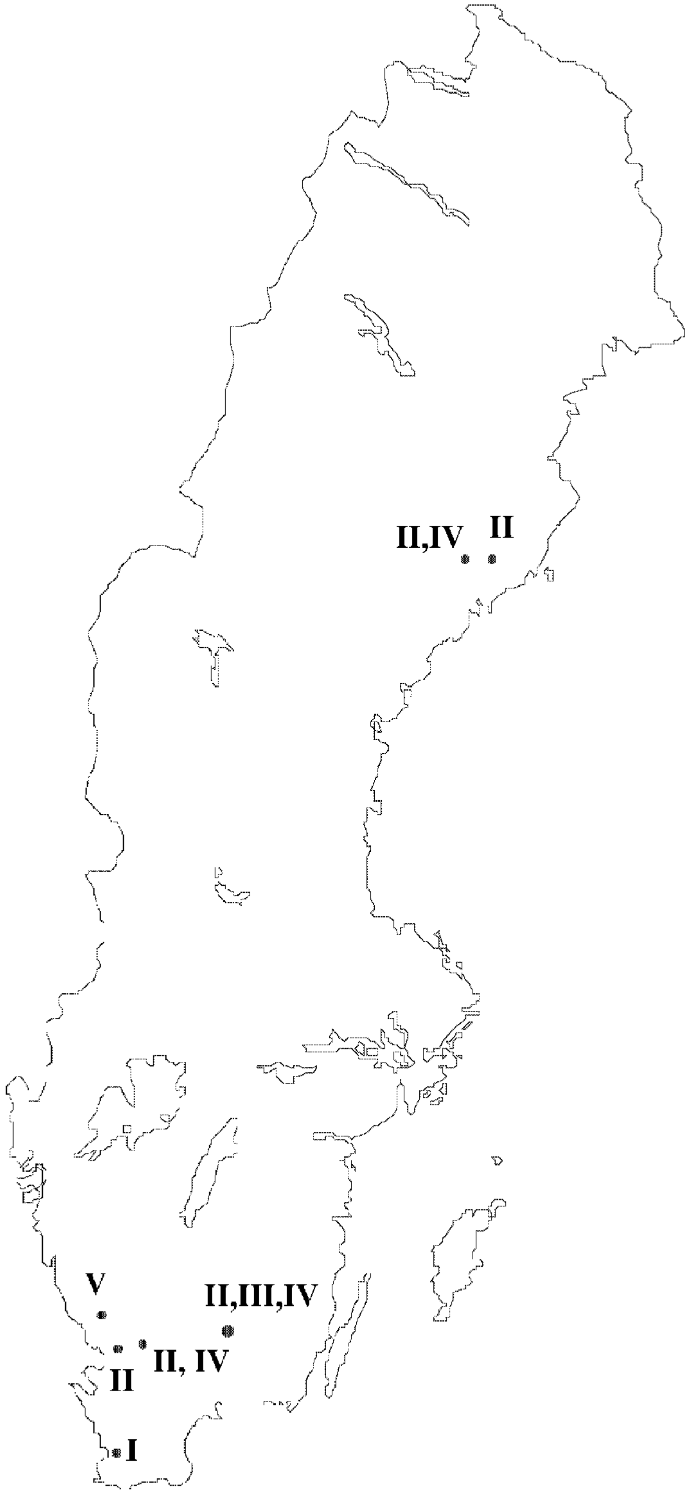

Figure 1. Geographical location of the study sites in the five papers.

Results and discussion

Effects of site preparation on growth and damage

In general, findings in this thesis support the hypothesis that seedling growth and survival are increased by site preparation. However, contrasting results were also found. Soil inversion in patches (inverting) increased seedling growth compared to the untreated control on the moderately fertile site in study III, but growth of seedlings in patch scarification with humus removal was not better than in the untreated control. Results from study II also indicated that inverting has higher initial seedling growth and less damage compared to patch scarification (Härsängen). The importance of retaining the humus layer in the planting spot after soil scarification has also been shown by Hallsby (1994a). In the north of Sweden, Örlander et al. (1998) found that soil inversion in patches (inverting) increased seedling growth compared to scarification methods with humus removal like ploughing, mounding, disc trenching and an untreated control treatment. Moreover, they found that seedling damage was lower in all site preparations compared to the control in this study. Örlander et al. (1998) suggested that the rapid seedling growth after inverting was the result of increased nutrient availability. This suggestion was supported by results from study III, where seedling growth was increased by increased nitrogen availability. It can thus be concluded that inverting effectively promotes seedling growth and survival after planting on moderately fertile sites in the boreal and boreo-nemoral zones.

This thesis showed that intensive site preparation methods have to be used on front-prone sites or sites that are rich in vegetation in order to secure high seedling growth and survival. On the fertile site with rich vegetation in study V, deep soil cultivation of the whole plot created higher seedling growth and lower damage and mortality than inverting, herbicide treatment and untreated control. In the deep soil cultivation, damage and mortality (mainly by voles) was less than 5%, whereas mortality was approx. 20%, 35% and 75% in the inverting, herbicide and control treatments, respectively. Results showed that deep soil cultivation is a more effective site preparation method than inverting and herbicide treatments on a site with rich vegetation. On fertile sites, competition for water, nutrients and light can be severe (Nilsson et al. 1996, Imo & Timmer 1999). The amount of field vegetation was strongly reduced by deep cultivation. However, fertilising increased the colonisation rate of field vegetation (V). As a result of increased competition, fertilising was negative for seedling growth in these treatments (Malik & Timmer 1996, Imo & Timmer 1999). Even ten years after deep soil cultivation, there was less field vegetation biomass than in the less intensive site preparations, but this may also depend on shadowing from the denser tree stand in deep-cultivated plots (IV, Thomson & Neustein 1973).

On frost-prone sites, deep soil cultivation decreased frost damage in conifers compared to patch scarification and herbicide treatments (II), since high quantities of bare mineral soil in the soil surface results in a higher near-ground temperature (II, Langvall 2000). In addition, increased seedling growth as a result of soil scarification means fewer years when the leading shoot is exposed to frost. On the frost-prone sites in study II, deep soil cultivation has given conifer seedlings a growth advantage corresponding to several years compared to seedlings in patch scarification. Deep cultivation of half the area in strips was just as efficient as deep soil cultivation of the whole area in order to provide high survival and high initial growth on frost-prone sites (II). This could be explained by the fact that the near-ground temperature close to the seedlings was equal in the two treatments (II).

Reduced frost and vole damage by deep soil cultivation in this thesis confirm results of earlier studies (Bärring 1967, Neckelmann 1995). Neckelmann (1995) showed that complete deep soil cultivation was equally efficient as a shelterwood in order to reduce frost damage. On frost-prone sites, deep soil cultivation can therefore be a substitute to shelterwoods when the risk for wind-throw is great. Results from vole damage showed that seedlings injured during establishment have less growth than undamaged seedlings in coming years (V).

Complete deep soil cultivation was relatively more effective on coarse than finely textured soils in study II, but results from study V showed that deep soil cultivation could be effective on finely textured soils also. However, the effect of soil texture type may be of minor importance compared to other effects such as damage and the type of control treatment. Sites with coarsely textured soil, such as Härsängen and Norrekvarn in study II, were exposed to summer frost. Hence, the positive result on growth and survival in deep-cultivated plots may have been a result of reduced frost damage and not an effect of the soil type. However, at Degerön in study II, the positive effect on seedling growth could not be explained by a reduction in damage. The lack of effect between treatments on finely textured sites in that experiment may also be explained by damage. Moreover, deep soil cultivation was compared to repeated herbicide treatments at Sperlingsholm in study II. This may also be considered an intensive site preparation and that could explain the lack of increased growth of deep soil cultivation on that site.

Long-term studies on the effect of site preparation are rare, which is why the experiments in study II were established. Usually, site preparations such as mounding or a herbicide treatment only result in an advance which corresponds to 1 to 2 years of growth (Nilsson & Örlander 1999, Nilsson & Allen in prep.). However, after deep soil cultivation on sandy and/or frost-prone sites, the advance may correspond to as much as 2-6 years and, on one site (Degerön), the trees in deep cultivated plots were still growing faster ten years after planting (II). The stands in study II are still young, and it is too early to draw any conclusions about the sustainable growth rates. However, in a site preparation experiment in Scotland that was studied for thirty years, growth was improved after complete deep cultivation during the first ten years following treatment compared to less intensive cultivation techniques (Thomson & Neustein, 1973). An analysis of the stand after thirty years showed that a) the current growth was about the same for all treatments, b) the difference in volume production achieved after ten years still remained, and c) benefits from deep cultivation may still be present (Wilson & Pyatt, 1984).

In study II, deep cultivation resulted in a more even stand structure. The lower coefficient of variation for height in deep-cultivated plots was probably a reflection of a more uniform environment, a lower degree of competition and less damage during the establishment period for seedlings planted in deep-cultivated plots than in control plots (cf. Weiner & Thomas 1986, Nilsson & Allen in prep.). The variability in stands of equal age generally increases with age/size and a low variability in tree size may postpone the onset of self-thinning (Weiner & Thomas 1986, Nilsson & Allen in prep.).

Effects of site preparation on seedling nitrogen uptake

Seedling growth in newly planted Norway spruce seedlings was positively correlated to seedling nitrogen uptake (III, V). Seedling biomass increase during the first season was the highest in site preparations with the highest net nitrogen uptake. High nitrogen uptake in Norway spruce seedlings early in the growing season resulted in increased growth during the first season (III, V), and this growth was mainly allocated to the roots. However, when the Norway spruce seedlings were taking up nitrogen late in the growing season (between August and November) the nitrogen was stored and used for growth during the next growing season (III). In study V, most of the seedling nitrogen uptake occurred between July and September, but the growth occurred over the whole growing season (May to September). In Norway spruce seedlings, high seedling nitrogen uptake during the first growing season and high seedling N concentration after the first growing season resulted in high growth the following season (III, V, Bärring 1967, Nilsson & Örlander 1999). However, superior growth for seedlings in soil-cultivated treatments in studies III and V during the second and third growing seasons was probably also a result of good conditions in these years and not only during the first growing season. Millard & Proe (1993) showed for *Picea sitchensis* that the conditions during current year also affect seedlings that are rich in nitrogen, although initial growth during the growing season is primarily determined by conditions in the previous season. Moreover, it has been shown that seedlings that are rich in nutrients are less sensitive to competition from field vegetation than others (Malik & Timmer 1996).

The site preparations with the highest nitrogen uptake almost doubled their seedling nitrogen content during the first growing season, while the untreated control plots had a negligible nitrogen uptake (III, V). The site preparations with the highest seedling nitrogen uptake were complete deep soil cultivation (V) and inverting (III, V), which both had the organic layer buried below a mineral soil cover through inversion. Hallsby (1994b) also showed that soil scarification with the humus layer mixed with the mineral soil promoted seedling nitrogen uptake and seedling growth compared to pure mineral soil. Seedlings in patch scarification with the organic layer removed did not have a significantly higher nitrogen uptake than undisturbed ground (III), but plots with herbicide treatment had a significantly higher seedling N content than the control throughout the experiment (V). The herbicide treatment has earlier been shown to increase seedling nitrogen uptake and growth (Malik & Timmer 1996).

Fertilisation increased the seedling nitrogen uptake but the seedling growth was not always increased. In study III, fertilisation of the patch scarification after planting resulted in a high seedling nitrogen uptake and growth during the first growing season, but the inverting had higher nitrogen uptake during the second growing season as a result of mineralisation in the buried humus layer. Due to increased competition from field vegetation, fertilising in herbicide or control treatments did not increase seedling nitrogen uptake (V, Malik & Timmer 1996, Imo & Timmer 1999). Moreover, in study V, fertilising increased the seedling nitrogen uptake and the seedling nitrogen concentration in soil-cultivated treatments during the first growing season. However, growth was not positively affected by increased nitrogen uptake. It could be that another factor limited growth.

Effects of site preparation on nitrogen mineralisation

The net mineralisation rates found in this thesis did not fully explain the nitrogen uptake in Norway spruce seedlings. The seedling net nitrogen uptake was positively correlated to net mineralisation in study III, but in study V, correlation was negative. High net mineralisation was provided in the inverting, where the organic layer remained in the planting spot. By contrast, soil scarification where the organic layer was removed had low mineralisation rates (III). In study V, the highest mineralisation rates were found in the untreated control and in the herbicide treatment, where the seedling nitrogen uptake was the lowest. However, in study V, the organic layer was buried deeper than in study III, and the mineralisation studies were performed above (down to 30 cm depth) most of the buried organic layer in inverted treatments and treatments with deep soil cultivation. Munson & Timmer (1991) did not find any correlation between mineralisable N and seedling growth in a study on *Picea mariana*. However, soil testing in bulk soil does not reflect the amount of nutrients that are actually available to the seedlings (Smethurst 2000). Moreover, testing of bulk soil does not show the conditions in the rhizosphere, where microorganisms and root exudates change the soil conditions (cf. Marschner 1995). Since we only measured inorganic N and organic N is shown to be available for seedlings (Näsholm et al. 1998), this is also a possible source of error. Soil measurements do not take the nutrient uptake capacity by the seedling roots into account. In both studies III and V, root systems were small where the nitrogen uptake was small. This indicates the importance of the volume of soil exploited by the seedlings for nitrogen uptake.

Effects of site preparation and root growth

In Norway spruce seedlings, the seedling net nitrogen uptake was correlated to increased root growth (III, V). Root growth is shown to be decisive for newly planted seedlings in order to reach water and nutrients in the soil (Brisette & Chambers 1992, Munson & Bernier 1993). Moreover, root growth increases the possibility of reaching soil patches that are rich in nutrients (III, Ross & Malcolm 1982). Furthermore, the root/soil contact is improved by root growth (Burdett 1990). Root growth could be increased through site preparation, and the root growth was the highest in the soil cultivation treatments (inverting and deep soil cultivation) and in the fertilised soil scarification treatments (III, V). High root growth has been found in soil scarification where the humus layer is mixed or buried (Grossnickle & Heikurinen 1989, Hallsby 1994b). The increased rooting depth in deep soil-cultivated plots in study IV was probably partly a result of increased nutrient availability in the subsoil compared to the patch scarification. Soil cultivation and soil scarification also resulted in lower soil densities (IV, V) and lower field vegetation amounts (III, V). Root growth was the lowest in untreated control plots and herbicide-treated plots in both study III and V, and was probably a result of high soil densities (Hildebrand 1983), low soil temperatures (Örlander et al. 1998) and competition with field vegetation (Örlander et al. 1990, Staples et al. 1999). In addition, chemical interference with field vegetation and impaired root/soil contact may explain poor seedling root growth (Jarvis 1964, Grossnickle & Heikurinen 1989).

Contrary to mineralisation, root growth was correlated to nitrogen uptake in both study III and V. However, nitrogen uptake was not always followed by increased root growth, in fact in most treatments the processes were parallel. It is therefore difficult to show if root growth results in increased nitrogen uptake or if nitrogen uptake results in increased root growth. Two examples from study III showed that both processes occurred. Increased nitrogen uptake as a result of fertilising early in the first growing season resulted in subsequent increased root growth. By contrast, the high seedling net uptake of nitrogen during the first growing season in the inverting treatment occurred after the roots had reached the buried humus layer, where the nitrogen was more abundant than in the mineral soil (III). When nitrogen uptake, shoot and root growth were all parallel, more factors than nitrogen uptake probably controlled seedling growth.

Drought can reduce both root and shoot growth (I, Rook et al. 1977, Coutts 1982). However, during the experimental periods in studies III and V only minor drought events occurred. The soil water potentials were, however, the lowest in the soil cultivation treatments, where the root growth was the greatest. In study I, a drought in Norway spruce rooted cuttings at the time of shoot growth reduced root growth during the drought event, but the root growth had recovered completely after seventeen days. By contrast, the shoot growth was not affected at the time of drought, but at the end of the growing season the current-year shoots were shorter than in the treatment without drought. This effect may be explained by a decrease in capacity for water and nutrient uptake by the smaller root system in the drought treatment compared to the control (I, Burdett et al. 1984, Brisette & Chambers 1992).

Effects of intensive site preparation on nitrogen and carbon loss

Results from study IV did not support the hypothesis that the loss of C and N from the soil/ecosystem increases with increased intensity of the disturbance. This result is in contrast to a number of earlier studies, which have shown that the stocks of both N and C decreased after intensive scarification (Wilsson and Pyatt 1984, Johnson 1992, Örlander et al. 1996a, De Wit and Kvindesland 1999). One explanation to the contradictory results may be that the soil organic matter in study IV is buried deeper and thereby in a colder and less aerated environment (Ross & Malcolm 1982) than in other studies. This might result in lower mineralisation rates (Lomander et al. 1998). Moreover, Carlyle (1993) found that decreased decomposition rates after deep cultivation could be a result of interaction between organic residues and inorganic colloids in sandy soils. The soil organic matter becomes physically stabilised as a result of this interaction. Another explanation could be that the loss of N and C occur during the entire rotation and not as enhanced rates during the establishment phase. The methodology used in study IV might then be insufficient to detect the small differences after the first ten years of rotation.

The risk for nitrogen loss was hypothesised to be higher in deep soil cultivation than in untreated soil or herbicide treatment in study V. Elevated nitrogen concentrations in the soil water in deep cultivated plots occurred during the autumn and winter when the soil water flow was high (V). By contrast, the nitrogen concentration in the soil water was high in the herbicide treatment and untreated soil during spring and summer when the soil water flow was low (V). There was no difference in nitrogen concentration in the soil water between the untreated plot and the herbicide treatment, and probably no difference in soil water flow either. This was probably due to the insignificant difference in field vegetation biomass. In the inverting, only 16% of the soil surface was disturbed and therefore leaching was probably less than in the deep soil cultivation treatment. However, the increased nitrogen concentration in soil water in deep soil cultivation was not repeated during the third growing season. This may be a result of nitrogen retention in the field vegetation (Högbom et al. 2001). In other studies where nitrogen loss has been estimated with suction lysimeters, low intensive site preparation (i.e. disc trenching) has not increased leaching (Ring 1996, Örlander et al. 1997). Since both the results on nitrogen and carbon loss in this thesis and in the literature are in contradiction and since the number of studies is scarce, deep soil cultivation should be used with caution.

Conclusions

The results from this thesis showed that soil scarification methods like patch soil inversion increased seedling growth and survival compared to untreated ground, herbicide treatment and patch scarification.

On frost-prone sites or sites that are rich in vegetation, deep soil cultivation of the entire regeneration area was shown to have higher seedling growth and survival than inverting, herbicide treatment, patch scarification and untreated ground. Deep soil cultivation of half of the regeneration area in strips was equally efficient as complete deep soil cultivation on frost-prone sites. Site preparation techniques that increase growth also prevent damage.

High seedling nitrogen uptake promoted high seedling growth in Norway spruce seedlings. Site preparations with the humus layer buried below mineral soil, like inverting or deep soil cultivation, increased the seedling nitrogen uptake in Norway spruce compared to other site preparation treatments in the studies. Moreover, seedling N uptake was correlated to root growth but was not shown to be conclusively correlated to mineralisation.

Intensive site preparation methods could not be shown to increase nitrogen and carbon loss, but there are few studies and further research is needed. Meanwhile, intensive site preparations should be used with caution and maybe on a small scale. Moreover, deep soil cultivation should be avoided if frost heaving or erosion may be expected or if archaeological remnants occur in the area. It is then better to use intermittent soil scarification methods, mulching, herbicide or steam treatment of the field vegetation (II, Goulet 1995, Moffat 1988, Neary & Michael 1996, Norberg 2001).

Current knowledge on the establishment of Norway spruce seedlings is large, but there are still many areas that need to be investigated further. There is still not enough information about processes for nutrient uptake in newly planted seedlings and the effects of different site preparations. Results on long-term effects of site preparation on both growth and yield, stand structure and site productivity are scarce. The effects of stand structure on future growth and yield is also an area where knowledge should be increased. An increasing number of available site preparation methods together with a decreasing amount of foresters in practical forestry make a decision support system useful. This system could help the forester choose a method and intensity for the site preparation in order to fulfil both the demands on successful plantation establishment and low nutrient and carbon loss.

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