# Effects of Silvicultural Treatments in Young Scots pine-dominateted Stands on the Potential for Early Biofuel Harvests

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Doctoral Thesis
Swedish University of Agricultural Sciences
Umeå 2011

Acta Universitatis Agriculturae Sueciae
2011:79

Cover: Sketch by Kristina Ahnlund Ulvcrona

ISSN 1652-6880
ISBN 978-91-576-7623-8

Tryck: Arkitektkopia, 2011

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## Abstract

The overall objective of the work underlying this thesis was to increase knowledge regarding growth of young Scots pine (*Pinus sylvestris* L.) - dominated mixed forests in northern Sweden and the potential for combining early biofuel harvest in such stands while leaving crop trees for future harvests. For this purpose, several studies were made. Biomass functions for the fractions stem (including bark), branches, foliage and whole trees were created for Scots pine, Norway spruce (*Picea abies* (L. Karst.), downy birch (*Betula pubescens* Ehrh.) and silver birch (*Betula pendula* Roth), based on measurements of the sampled trees in six young and dense stands (I). Growth and yield was studied for 8-11 years at four experimental sites (stand ages 17-20 years at start) in which density treatments (pre-commercial thinning, PCT, to 3 000 stems ha$^{-1}$ and no-thinning; control, C) and fertilization treatments (N fertilization at 100 kg ha$^{-1}$ every 6th year or annually: F1 and F2, respectively) had been applied alone and in two combinations (C+F1, C+F2 and PCT+F1). During the observation period total biomass yield was 58 - 79% higher (up to in total 100 ton ha$^{-1}$ DW) in the dense, unthinned stands (>11 000 stems ha$^{-1}$) than in the PCT stands. Fertilizing every year did not give significantly higher biomass production than the two fertilization applications. The 500 - 2 700 largest trees ha$^{-1}$ showed significantly higher values of measured size parameters following treatment C+F2 compared to the unthinned control (C), but not to the PCT treatment, indicating that stand density only had minor effects on growth of the largest trees (II). When allocation patterns were analysed after six years, the only significant between-treatment differences found for Scots pine trees of various size classes were among the smallest trees (with a diameter at breast height, DBH, <5 cm). These trees had slenderer stems (lower DBH/height ratios) and lower relative proportions of branches and foliage in the dense, unthinned stands than in the PCT stands (III). By studies in older PCT-trials it was found that branch diameter decreased with both increasing stand density and increasing height at the time of PCT, and the living crown (crown length/tree height) ratio decreased with increases in height at thinning and density (IV). In addition, mortality rates after PCT were low (consistently <5%) for trees in stands of all investigated densities and heights, even in stands with >9 000 stems ha$^{-1}$. Further, the trees that died (and hence were most severely affected by competition) were the smallest trees (DBH<5 cm), and timing of PCT had only marginal effects on the risk of mortality (V).

The main conclusion from the results is that substantial amounts of biofuel can be harvested from pine-dominated young stands at appropriate times, if conventional PCT is omitted, while still retaining appropriate numbers of crop trees for subsequent main harvests.

*Key words:* Allocation patterns, *Betula* spp., biomass functions, branch characteristics, mortality, *Picea abies* (L. Karst), *Pinus sylvestris* (L.), production, young dense mixed stands

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## Svensk sammanfattning

Det övergripande målet med arbetet har varit att öka kunskapen om hur tillväxt av biomassa och stamved i unga talldominerade (*Pinus sylvestris* L.) blandskogar påverkas av stamtäthet och näringstillförsel och om tidig skörd av bioenergi kan kombineras med avverkning även av konventionella sortiment i senare beståndsskeden. Fem studier har gjorts, baserade på äldre befintliga och nya fältförsök i norra Sverige. Biomassafunktioner baserade på mätningar på provträd från sex olika bestånd har tagits fram för fraktionerna stam (inklusive bark), grenar, barr och blad samt för hela trädet för tall, gran (*Picea abies* (L. Karst.) och björk (*Betula* sp.) (I). Tillväxt och produktion följdes i fyra fältförsök under 8–11 år (II). Bestånden var 17–20 år vid försökets början, de behandlingar som ingick var beståndstäthet (antingen röjt till 3 000 stammar per hektar, PCT, eller oröjd kontroll, C, med ca 13 000 st/ha) samt gödsling (kvävegödsel (N) motsvarande 100 kg N per hektar vart 6:e år med början år 1997 (behandling F1), eller årlig gödsling (F2). Gödslingen kombinerades med beståndstätheten i följande kombinationer; C, C+F1, C+F2, PCT samt PCT+F1. Totalproduktion av biomassa var 58–79% högre (motsvarande upp till totalt 100 ton torrvikt per hektar) i den täta oröjda och intensivgödslade skogen jämfört med de röjda behandlingarna. Gödsling varje år resulterade inte i signifikant högre totalproduktion jämfört med att gödsla vart 6:e år. Förklaringen antas vara den ökade konkurrensen om ljus i de täta bestånden, det extra kvävet kunde inte utnyttjas till barr- och bladtillväxt eftersom ljuset i stället blev den begränsande faktorn. De 500 till 2 700 största träden i de oröjda försöksleden resulterade i signifikant högre värden inom försöksled C+F2 jämfört med träden i behandling C, men inte jämfört med träd från de röjda behandlingarna. Detta ger en indikation av att beståndstäthet endast hade marginell effekt på tillväxten för de största träden. När allokeringsmönster (hur andelen grenar, barr och stam förhåller sig till varandra) hos tall analyserades sex år efter det att fältförsöken etablerats, var det bara för de minsta träden (med brösthöjdsdiameter < 5 cm) som det fanns signifikanta skillnaden mellan försöksled (III). De minsta träden i de täta behandlingarna var slankare (kvoten mellan diameter och höjd var lägre) och de hade även mindre andel grenar och barr jämfört med träd från röjda behandlingar. Analyser gjordes även av grenar hos tall i äldre röjningsförsök (IV). Det visade sig att grendiametern var mindre hos träd som röjts till fler stammar per hektar, och när röjningen gjorts när beståndet var högre. Andel levande krona (grönkronans längd i förhållande till trädets höjd) minskade också vid högre röjningshöjd och högre stamtäthet. Avgångar i ungskogar analyserade även (V) och generellt visade det sig att endast < 5 % av träden dött inom det studerade materialet, oavsett röjningshöjd eller antal stammar per hektar, även vid stamtätheter på > 9 000 stammar per hektar. De träd som dött var de minsta träden i bestånden med en diameter i brösthöjd på < 5 cm, och tidpunkten för röjning hade bara marginell effekt på risken för avgång. En övergripande slutsats av arbetet är att det är möjligt att tidigt skörda betydande mängder biomassa/bioenergi från unga och täta blandbestånd och samtidigt ha kvar lämpligt många utvecklingsbara träd per ha för framtida avverkningar.

*Nyckelord*: Allokeringsmönster, biomassafunktioner, björk (*Betula* sp.), gran (*Picea abies* (L. Karst.), grenkaraktärer, mortalitet, *Pinus sylvestris* L., produktion, täta unga blandskogar

*Rerum omnium magister usus*
*Erfarenheten är läromästare i allt*

# Contents

# List of Publications

This PhD thesis is based on studies described in the following five papers, which are referred to hereafter by the corresponding Roman numerals.

I. Ulvcrona, K. A., Karlsson, A., Nilsson, U. & Lundmark, T. Biomass functions for young and dense Scots pine (*Pinus sylvestris* L.) dominated mixed forests in northern Sweden. *Manuscript*

II. Ulvcrona, K. A., Bergsten U., Nilsson, U. & Lundmark, T. Biomass production in young dense Scots pine stands allowing biofuel harvest and crop trees retention. *Manuscript*

III. Ulvcrona, K. A., Ulvcrona, T., Nilsson, U. & Lundmark, T. Stand density and fertilization effects on aboveground allocation patterns and stem form of Scots pine in northern Sweden. *Manuscript*

IV. Ulvcrona, K. A., Claesson, S., Sahlén, K. & Lundmark, T. 2007. The effects of timing of pre-commercial thinning and stand density on stem form and branch characteristics of *Pinus sylvestris*. *Forestry* 80(3): 323-335.

V. Ulvcrona, K. A., Kiljunen, N., Nilsson, U. and Ulvcrona, T. 2011. Tree mortality in *Pinus sylvestris* stands in Sweden after pre-commercial thinning at different densities and thinning heights. *Scandinavian Journal of Forest Research* 26(4): 319-328.

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# 1. Introduction

## 1.1 Increased need for biomass to substitute fossil fuels and reduce greenhouse gas emissions

Targets for reducing greenhouse gas (GHGs) emissions in the United Nations framework convention on climate change and the Kyoto protocol (Anon., 1997) have substantially affected national and regional goals for energy use. Notably, the European Commission for climate action, and the European climate change program, have issued a "20-20-20" goal**,** meaning that in EU countries, by the year 2020: emissions of greenhouse gases should decrease by 20%, at least 20% of the energy should be renewable, and energy efficiency should increase by 20% (Anon., 2009a; Anon., 2009b). Further, the report from the Swedish Commission for Oil Dependence presented in 2006 stated that by 2020 Sweden should produce at least 40% more biofuel than in 2005 (Anon., 2006), since such fuel can partly replace the use of fossil fuels (Chum & Overend, 2001), and hence reduce greenhouse gas emissions (Schneider & McCarl, 2003; Solomon & Luzadis, 2009; Zhang *et al.*, 2009). This has raised interest in increasing the production and use of forest biomass. Today by-products from sawmills and the pulp and paper industry are used for bioenergy (Nordfjell *et al.*, 2008). The use of biofuels in Sweden has already increased substantially, from close to 10% of the total energy supply in the 1980s (Anon., 2008a) to 20% in 2008 (Anon., 2010a). Since branches and tree tops already are used to a large extent as biofuel from thinnings and final cuttings there is further need for forest biofuel.

In Sweden, young forests with <15 m heights cover about 18% of the forest area and could potentially yield 5 million ton DW harvests annually (Nordfjell *et al.*, 2008). Young forests are therefore major potential sources of biofuel**,** which should be exploited to help meet globally increasing needs for raw material for biofuel production (Grebner *et al.*, 2009; Heikkilä *et al.*, 2009; Larsson *et al.*, 2009; Wilkerson & Perlack, 2009).

## 1.2 Boreal forests – Large areas with potential for supplying forest raw material and biofuel

The taiga or boreal forest forms a huge belt across North America and Eurasia south of the Acrtic tundra (Begon *et al.*, 1996). Boreal forest covers about 29% of all forest land, and accounts for about 73% of the coniferous forest of the world (Kuusela, 1990). About 55% of the land area in Sweden is regarded as productive forest land (Anon., 2010), most of which is boreal forest. The dominant tree genera found in the boreal forest are evergreen conifers, including spruce (*Picea*), pine (*Pinus*), fir (*Abies*) and larch (*Larix*). Broadleaves present are birch (*Betula*), aspen (*Populus*), alder (*Alnus*), mountain ash (*Sorbus*) and willow (*Salix*); all species adapted to a short growing season (Farjon, 2010). The climate in the boreal forest has a mean temperature exceeding 10 °C for between one and four months, but frequently wide annual temperature variations (Walter, 1985). The boreal forest can be divided into maritime, continental and high-continental sub-zones, of which the continental zone is most extensive (Kuusela, 1990). Annual precipitation ranges from 400 – 1 000 mm, and mainly falls at sub-zero temperatures as snow, thus snow conditions must be taken into consideration when planning new silvicultural regimes. The climate is classified as humid, as the evapotranspiration does not generally exceed the precipitation (Havranek & Tranquillini, 1995). Lakes, bogs and marshes are common in the boreal forest (Raven *et al.,* 1992) and in Sweden about 4.5 million hectares (11% of Swedish land area) is defined as bogs and marshland (Anon., 2010a). The boreal forest zone was covered by ice during the last continental glaciation, and glacial fluvial sands, gravels, moraine loams and clays are now the major soil fractions. Sands and gravels, poor in nutrients, are covered by podzolized soils with a top layer of partly decomposed litter and raw acid humus (Kuusela, 1990). The work presented in this thesis focused on sites in the boreal forest of northern Sweden, but similar conditions with dense young coniferous forests also prevail in other Nordic countries in Europe, Russia and parts of North America.

# 2. Growth and management of young forests

## 2.1 Leaf Area Index (LAI)

Several studies have shown that growth rates of forest stands are proportional to the amount of intercepted sunlight (Madgwick & Olson, 1974; Kellomaki *et al.*, 1979; Linder, 1985; West, 2006), and several authors consider the importance of the relation between amount of foliage and biomass production (Tirén, 1927; Teskey *et al.*, 1995), and leaf area index **(**LAI) to be the best indicator of this variable (Kozlowski *et al.*, 1991; Duursma *et al.*, 2003; Montes *et al.*, 2007). Wood production has been found to be linearly correlated to LAI in young loblolly pine stands, but after canopy closure only needles in the upper part of the crown are photosynthetically active (Vose & Allen, 1988). Similar findings of low photosynthesis rates in the lower parts of the canopy have been found by several other authors (Kira *et al.*, 1969; Woodman, 1971a; Ceulemans & Saugier, 1991; Hari *et al.*, 1991). Stand growth rates peak at a specific stand density, which represent the upper limit of productivity for the specific site and environmental conditions (Will *et al.*, 2001). Total production is significantly higher in dense stands (Pettersson, 1992a; Johansson, 1993; Pettersson, 1993a;) and total production of biomass is also influenced by site conditions; growth is relatively slow in poor sites (Hägglund & Lundmark, 1977; Harcombe, 1987).

## 2.2 Nutrition

Water and nutrient availability influence the total production of foliage in a stand, and hence the amount of radiation that can be intercepted (Mooney, 1972; Linder, 1987; Gower *et al.*, 2001). Hence, fertilization with nitrogen (generally the limiting nutrient) has been shown to increase the production of needles in coniferous forests (Tamm, 1991). Further, fertilization also increases the photosynthetic activity per unit area of needles, due to the consequent increases in their nitrogen and chlorophyll contents (Linder & Troeng, 1980).

A proper nutrient balance is essential for optimum growth of a plant. The required nutrients can be divided into major elements (nitrogen, phosphorus, calcium, potassium, iron, sulfur and magnesium) and trace elements (boron, copper, manganese, molybdenum, chlorine and zinc) (Dickison, 2000; Mengel & Kirkby, 2001). Due to the requirements of metabolic mechanisms and activities of both plant enzymes and microorganisms for carbon and nitrogen, carbon uptake is dependent on nitrogen availability and vice versa (Pate *et al.*, 1979; Oaks, 1995; Whitehead *et al.*, 2001; Yamaya & Oaks, 2004; Osler & Sommerkorn, 2007). Nitrogen is the fourth most common element in plant tissues, and an essential component of chlorophyll and enzymes involved in photosynthesis, other enzymes and proteins, DNA and many metabolites, therefore nitrogen is a key element for plants (Tamm, 1991; Mengel & Kirkby, 2001; Oijen & Levy, 2004; Gruber & Galloway, 2008; Pallardy, 2008). Inorganic nitrogen is usually taken up by higher plant roots in the form of nitrate $(NO_3^-)$ and ammonium $(NH_4^+)$ ions. Uptake of nitrogen in organic form (glycine) has also been observed, in both field and laboratory studies; up to 42% of the nitrogen absorbed by Scots pine and Norway spruce trees was taken up in organic form in a study by Näsholm *et al.,* (1998).

Forest growth in boreal areas is strongly limited by nutrient availability (Linder, 1987; Tamm, 1991; Högberg *et al.*, 2006a). Forest production and nutrition have, thus, been intensively studied, and in many field experiments fertilization has been shown to increase forest production (Romell & Malmström, 1945; Tamm, 1985; Helmisaari & Helmisaari, 1992; Saarsalmi & Mälkönen, 2001; Nilsen, 2001; Nohrstedt, 2001; Jacobson & Pettersson, 2010). In addition, a balanced nutrient status enhances plants' pests resistance (Saarsalmi & Mälkönen, 2001), and fertilization can increase the size and number of needles (Tamm, 1991; Bergh *et al.*, 1999) as well as reduce needle mortality (Bergh *et al.*, 1999). However, nitrogen (ammonium) fertilizer is produced by the Haber-Bosch process, which is energy demanding (Hägg, 1989) and quite costly. Furthermore, potential environmental problems, such as eutrophication of terrestrial and aquatic systems, acidification and stratospheric ozone losses (Galloway *et al.*, 2003), must be taken into account when considering fertilization. In addition, repeated or intense fertilization may adversely affect wood properties, resulting (for instance) in lower wood density, smaller fibres and thinner cell walls in Scots pine trees (Roturier, 2004; Jaakkola *et al.*, 2006). Proportions of sapwood may also increase following fertilization and thinning (Mörling & Valinger, 1999). Therefore, effects of fertilization must be well understood and it must be applied with care.

## 2.3 Stand structure in young forests

In stands established by planting, the variations in heights and diameters are small (Fahlvik, 2005). The goal is often to generate, and maintain, a stand dominated by a single species; in Swedish forestry the conifers Scots pine and Norway spruce are the dominant species planted (Anon., 2010a). However, broadleaved species, e.g. silver birch (*Betula pendula* Roth) and downy birch (*Betula pubescens* Ehrh.), often regenerate naturally in the same regeneration areas (Karlsson, 2001). To obtain a conifer stand that is more or less uniform and even-aged with trees of approximately the same height, one or several pre-commercial thinning (PCT) operations are generally applied (see below) to reduce densities of trees of other species as well as natural generated pines/spruces, and competition between trees (Fahlvik, 2005).

In contrast, a naturally established stand, e.g. following seeding from seed trees, is more often heterogeneous and often results in a mixed forest, which may have wide height and diameter distributions as a result of plants establishing over several years (Lyly & Saksa, 1982; Fahlvik, 2005; Miina & Saksa, 2008). Variations in competition from weeds and broad-leaves in the establishment phase, together with variations in soil properties, also contribute to within-stand variation (Saksa, 1992; Kuuluvainen *et al.*, 1993; George *et al.*, 1997). Naturally established stands also often have clustered spatial distributions of plants as a result of variations in site variables, such as soil moisture and nutrient availability (Kozlowski *et al.*, 1991; Fahlvik, 2005). Nevertheless, heterogeneous stands may have a final structure similar to that of planted monocultures, especially if appropriate PCT and thinning operations, with selection for high quality stems, are applied (Fahlvik, 2005).

The success of natural regeneration and subsequent stand structure are dependent not only on site conditions, but also on the amount and quality of seeds produced (Hagner, 1962; Karlsson, 2000a; Karlsson, 2001; Wennstrom *et al.*, 2002). Seed production is not regular and for many forest tree species varies widely between years (Kozlowski *et al.*, 1991). Further, the amounts of seeds produced differ among species, for example birches can generally produce large numbers of seeds and have efficient seed dispersal mechanisms (Hagner, 1962; Karlsson, 2001). Hence, cone production is generally lower in northern Sweden than in southern Sweden, and at higher altitudes (Hagner, 1958).

Use of mixed heterogeneous forest stands (with, for example, birch shelter over spruce) may also help to increase production and decrease the risks for frost damage (Mård, 1996; Bergquist, 1998; Johansson, 2001). However, as shown by Pretzsch (2009), results may differ substantially. Some studies have found minor differences in production between monocultures and mixed stands (Jonsson, 1962; Pukkala *et al.*, 1994; Linden & Agestam, 2003; Agestam *et al.*, 2005). Some have found above ground production to be highest in pure stands (Kelty, 1992), but others have found it to be highest in mixed stands (Assmann, 1970; Pukkala *et al.*, 1994; Mård, 1996; Frivold & Kolström, 1999; Linden & Agestam, 2003).The differences in results can be explained by the overall effects of diverse factors (such as tree species, stand and site characteristics and climate factors) that affect (negatively or positively) productivity (Pretzsch, 2009). It has been shown that birch has somewhat deeper root system compared to spruce (Sirén, 1955) and may have the possibility to take up nutrients from deeper horizonts (Fisher, 1990). Brandtberg *et al.* (2000) found higher base content in the forest floor of mixed stands of spruce and birch, and further that the difference may occur without difference in rooting depth.The spatial and temporal stratification of roots or foliage may also reduce competition for limiting resources such as light and nutrients in mixed stands since different species use different niches (Kelty, 1992). Examples of such reductions in competition include variations in utilization (and transmittance) of light, based on crown features, by different tree species (Terborgh, 1985; Canham *et al.*, 1994).Variations in the vertical distribution of root systems may also result in increased resource availability, and hence reduce below-ground competition, providing illustrative support for ecological niche theory (McKay & Malcolm, 1988). There are also differences in volume increment changes during rotation periods for different species. For conditions relevant for this thesis it has been concluded that birch has a higher increment than spruce until the age of about 35-50 years, but thereafter spruce trees have higher volume increment (Mård, 1997; Frivold & Kolström, 1999).

## 2.4 Conventional silviculture of young stands

In the 1950's, when the clear-felling system and planting was substantially extended in Sweden (Anon., 2002; Bäckström, 1984), PCT became a standard operation in silvicultural management (Anon., 2002). During 1950-1970 chemical treatment with herbicides to kill deciduous trees was introduced in addition to manual (axes, knives) and motor-manual (brush saw) operations (Fahlvik, 2005; Ligné *et al.*, 2005a). The herbicides against deciduous trees were generally forbidden by the law in 1983 (Björk, 1994). Since almost all other forestry treatments have been rationalised and mechanised, but PCT is still carried out with a motor-manual brush saw in the same way as during the last 50 years, the relative cost of PCT has steadily increased (Glöde & Bergkvist, 2003; Ligné *et al.*, 2005b). PCT can be characterized by the way removed stems are selected. Overall, a major difference is between selective and geometric (schematic) thinning, selective thinning being based on the positions and properties of the individual trees while in geometric thinning trees are cut in a specific pattern, e.g. rows or corridors (Bergström, 2009; Johansson & Gullberg, 2002). However, PCT is not always carried out, partly because it is considered expensive; the operation has direct costs but provides no immediate revenues (Fällman, 2005). Regimes including PCT at several steps will, of course, be even more expensive. Thus, although PCT is justified by calculations showing that it will pay back by the time of the first commercial thinning, many forest owners still omit it (cf. Fällman, 2005). However, due to the high costs associated with PCT, together with the problems arising from omitting it (dense stands and increasing height), and difficulties in attracting personnel for doing motor manual and hard work, new techniques for PCT or whole tree thinning have started to emerge (Ligné *et al.*, 2005b; Bergström, 2009; Bergström *et al.*, 2007).

In the 1970s, PCT was applied in about 200 000 hectares of young forest in Sweden each year. It was regulated by the Swedish Forestry Act of 1979, and consequently in the 1980s the area subjected to PCT increased to about 300 000 hectare year$^{-1}$ (Anon., 2004). However, in 1994 the Forestry Act was changed (Anon., 1995) and PCT was no longer regulated. In the late 1990's the area annually subjected to PCT had fallen again, to 201 000 hectares (Anon., 2000a), although it subsequently rose again, to close to 370 000 ha in 2008 (Anon., 2009c).

PCT has the following aims. Firstly, to avoid strong competition between stems in the stand, and hence increase the growth of individual trees (Anon., 2000b; Albrektson *et al.*, 2008). Secondly, to increase quality, by releasing the best quality trees, for later commercial thinning and finally clear-cutting (Björkman, 1877; Wahlgren, 1914; Anon., 1968; Anon., 2000b). Thirdly, to select tree species, e.g. keeping the most productive species for the specific site, in mixed stands (Jäghagen & Sandström, 1994; Anon., 2000b; Albrektson *et al.*, 2008). Fourthly, to create stable stands, avoiding damage to the main stems caused by whipping (Saksa & Miina, 2007), moose (Härkönen *et al.*, 2008) and snow pressure (Valinger *et al.*, 1994; Nykänen *et al.*, 1997; Päätalo *et al.*, 1999). The number of stems left in conifer-dominated stands after PCT in Sweden varies, between around 1 400-3 400 stems ha$^{-1}$, depending on site quality and tree species (Anon., 2000b).

Responses of trees to PCT depend on stand densities, and stands' growth rates also depend on their age (Pettersson, 1992b) and thinning intensity (Braastad & Tveite, 2000). Generally, PCT is applied to young stands, when the mean height exceeds 1.3 m (usually as a single operation when the stand is 2-3 m tall in Scots pine and Norway spruce stands) (Anon., 2000b; Fahlvik, 2005). However, in very dense regenerations it may be necessary to carry out a first PCT (plant cleaning) operation when the seedlings are small, approximately 0.5 m tall. Such cleaning is often used to release planted or naturally regenerated conifer seedlings from strong competition by numerous naturally regenerated broadleaves and conifers (Andersson, 1993; Anon., 2000b; Albrektson *et al.*, 2008). Since the broadleaved trees often continue to compete with the conifer seedlings through sprouting (Ligne *et al.*, 2005a), additional PCT operations are often required (Andersson, 1984; Andersson, 1993).

Browsing by moose (*Alces alces*) on Scots pine is another serious damage in young forests in Sweden (Lavsund, 1989). Since moose most frequently browse trees up to approx. 4 m tall, forest managers often wait until the stand reaches "moose-safe height", an arithmetic mean height of 4-5 meters (Anon., 2000b), before they apply PCT. Thus, variations in site quality, tree species and the risk for damage, caused for instance by browsing moose may all affect the PCT regimes chosen by forest owners.

## 2.5 Stand structure and timing of pre-commercial thinning

Stand structure is influenced (in addition to site characteristics) by events from early stand development onwards (Lutz & Halpern, 2006; Jäghagen, 1997; Nilsson & Albrektson, 1994), notably the timing of PCT may affect diverse tree characteristics, such as stem form, the living crown ratio and diameter at breast height, DBH (Pettersson, 1993b). Options applied in plantation forestry, such as thinning methods, spacing and species, will therefore affect the stand characteristics (Nilsson & Gemmel, 1993). Notably, the stand density and timing of PCT affect the saw timber quality more for Scots pine (Pettersson, 1996; Agestam *et al.*, 1998; Huuskonen & Hynynen, 2006; ) than Norway spruce (Nilsson & Gemmel, 1993; Pettersson, 1993).

Although the overall aim of PCT is to obtain high quality material, several studies indicate that stem quality is higher following later (at a higher tree height) PCT (Salminen & Varmola, 1990; Ruha *et al.*, 1997; Varmola & Salminen, 2004; Fahlvik *et al.*, 2005). Good stem form, i.e. small taper (the DBH/height ratio), is associated with high stem densities (Jäghagen, 1997; Agestam *et al.*, 1998), and high stand density is also related to high branch mortality and hence high live crown heights and low living crown ratios (Larson, 1963; Johansson, 1992; Mäkinen, 1996; Fahlvik *et al.*, 2005). Further, the quality of wood is strongly dependent on knot characteristics of the stem (Nylinder, 1959; Salminen & Varmola, 1993;), and there is a connection between the quality of sawn timber and the largest branch in the lowest part of the stem (Persson, 1976; Persson, 1977; Persson *et al.*, 1995). Hence, knot and branch characteristics are fundamental aspects of the Swedish system for grading sawn timber (Anon., 1999; Anon., 2008b and they are strongly affected by silvicultural practices. By keeping stands dense, higher quality stems could be produced (Persson, 1976; Persson, 1977; Persson *et al.*, 1995). However, there is also a risk in dense stands that the preferred species and crop trees of best potential quality may be severely adversely affected by competition or other damaging agents (cf. Karlsson *et al.,* 2002). There are also indications that artificial pruning may be necessary for high quality timber production, as delayed thinning limits possibilities for reducing the knottiness of the stems (Mäkinen, 1999).

## 2.6 Stand structure and competition

When stem densities become sufficiently high to induce competition for resources, mortality due to suppression will occur (Heding, 1969; Ford & Diggle, 1981; Kobe *et al.*, 1995; Kobe & Coates, 1997; Jäghagen, 1997; Lutz & Halpern, 2006). Kobe and Coates (1997) define suppression as "survival under low growth rates", i.e. a state in which growth is inhibited as a consequence of competition (for light) (Kobe & Coates, 1997; Satoo & Madgwick, 1982). During these circumstances with light being limiting, low or even negative rates of photosynthesis can be observed. The consumption of organic matter by respiration is then larger than the production by photosynthesis (Satoo & Madgwick, 1982). One essential aspect of competition is its dependence on the size of individual trees in relation to neighbouring trees; a small tree close to a big tree will be more severely affected by competition between them than the big tree (Goff & West, 1975; Ford & Diggle, 1981; Weiner & Thomas, 1986; Kobe *et al.*, 1995; Jäghagen, 1997; Pretzsch, 2009). It is often noted that competition between trees starts at the time of canopy closure (Cannell *et al.*, 1984; Messier *et al.*, 1989; Eichhorn, 2010), although competition may also occur earlier (Ford & Diggle, 1981; Peet & Christensen, 1987).

The shading from neighbouring trees in a dense stand restricts amounts of available light in the lower part of the canopy, resulting in reductions in the living crown ratio (Larson, 1963; Vanninen, 2004) and (hence) photosynthesis (Woodman, 1971b; Harcombe, 1987; Grossnickle, 2000). Furthermore, death rates are higher among shaded individuals, regardless of age (Harcombe, 1987), although shade-tolerant species can survive even in low light conditions, while less shade-tolerant species cannot survive long periods of suppression, i.e. low growth rates (Kobe & Coates, 1997; Pretzsch, 2009). Hence, Nilsson and Gemmel (1993) found that competition for light starts earlier for Scots pine (due to relatively rapid crown growth) than for Norway spruce. Further, Erefur *et al.* (2008) found that light requirements could not be moderated by improving nutrient supplies when seedlings of Scots pine and Norway spruce were grown under shelter (150 and 500 stems $ha^{-1}$) for four years.

Natural mortality as an effect of competition, or self-thinning, is a process caused by increasing size of neighbouring trees, aging and decreasing tolerance of light deficiency, and is an example of natural selection in forest stands (Westoby, 1984; Zeide, 2010). The self-thinning rule (cf. Westoby 1984) states that this imposes a "density-dependent upper boundary of stand biomass for even-aged pure plant stands in a given environment" (Bi *et al.*, 2000). In addition, large trees accumulate more biomass than suppressed trees (Jäghagen, 1997); the increments of suppressed trees progressively decline and the differences in size between suppressed and larger trees progressively increase. In commercial forestry, this pattern is most likely to appear in stands with large differences in tree size, for example naturally regenerated stands with significant differences in height among the trees originating from the spread in times of establishment, or stands with in-growth, where the in-growth population is likely to suffer from competition in later stages (Weiner & Thomas, 1986).

# 3. New possibilities for new silvicultural regimes for young stands

The goal to reduce use of fossil fuel and thus greenhouse gas (GHGs) emissions, and consequently increases in demands for renewable energy, has led to new ideas for improving production and use of bioenergy. The Swedish Forestry Act of 1994 dropped the obligation to undertake PCT, and the area of young, dense stands in Swedish forests increased (Anon., 2000a). In recent years, there have been increasing demands to increase biomass production in the forests to provide material for bioenergy (Grebner *et al.*, 2009; Heikkilä *et al.*, 2009). These demands have also prompted the development of new regimes for the silvicultural management of young forests that provide possibilities for biomass harvests, which may even generate a direct income. For such energy harvests, the utility of thinning in rows or corridors has been tested (Bergström, 2009). These new silvicultural possibilities and potential regimes for young stands have raised needs for further knowledge about total biomass production during early stages (and methods to estimate production), aboveground allocation patterns in different stands, the development of stands and analysis of risks connected with dense stand silviculture and biofuel harvests.

## 3.1 Biomass functions

Biofuels from the forest consist of logging residues, stumps, wood with no industrial use and industrial by-products, and short-rotation products (Anon., 2000a). The production of wood biomass as a third marketable forest product, besides timber and pulpwood, requires new silvicultural regimes. Therefore, there is a need for biomass functions adjusted for forests with high stand density. Additionally, biomass functions are used for estimating sizes of specific fractions in evaluations of carbon budgets and ecosystem productivity in forest stands (Monserud *et al.*, 2006; Litton *et al.*, 2007; Case and Hall, 2008). Numerous equations have been developed for various tree species, and there are functions for estimating both whole tree biomass and diverse components, both above- and below-ground (Madgwick & Kreh, 1980; Albrektson *et al.*, 1984; Marklund, 1988; Johansson, 1999; Bond-Lamberty *et al.*, 2002; Zianis *et al.*, 2005; Muukkonen & Mäkipää, 2006). However, these biomass equations are not based on, and therefore not adapted for, young, dense boreal forests that are suitable for forest fuel harvests.

The use of stand tables and regressions are the most common procedure for estimation of biomass and volume in forest stands (Baskerville, 1972). Reviews of regression equations for estimating biomass show that most use diameter at breast height (DBH), tree height, or a combination of these variables (Young, 1976; Hitchcock & McDonnell, 1979). Satoo and Madgwick (1982) discuss the utility of different variables for estimating biomass, and conclude that DBH and tree height are suitable variables for estimating both stem and total tree biomass. In addition, they note that DBH is not sufficient, as a single variable, to predict the biomass of the canopy. Tadaki (1966) reached the same conclusion, and that regression constants for crown components are affected by growth stage, stand density and site conditions.

## 3.2 Damage risks and analysis

There are several risks, for both abiotic and biotic damage, connected with treatments (or no treatment) of young forests. For example, leaving stands unmanaged until they are ready for commercial thinning increases risks for damage by snow pressure (Valinger *et al.*, 1994). Various stand and tree characteristics influence the risk of such damage, e.g. tree taper, tree species and stand density (Persson, 1972; Lohmander & Helles, 1987; Peltola *et al.*, 1997; Nykänen *et al.*, 1997; Päätalo *et al.*, 1999). PCT increases the possibility for the remaining main stems to increase diameter growth and become more stable and resistant to snow pressure (Nykänen *et al.*, 1997; Päätalo *et al.*, 1999). However, during the first winters following thinnings in dense stands there may still be a risk for damage from snow pressure (Valinger *et al.*, 1994).

When stand growth is estimated mortality predictions are required in addition to information on the likely growth and harvest parameters (Harcombe, 1987). Hence, algorithms for stand establishment, used to estimate and predict forest development, usually include three major variables: growth, harvest and natural mortality (Fridman & Ståhl, 2001).

The problem is that mortality is variable, and thus difficult to predict (Lee, 1971; Monserud & Sterba, 1999), especially for suppressed trees, which are especially sensitive to competition for light and thus have high rates of mortality (Heding, 1969; Goff & West, 1975; Ford & Diggle, 1981; Kobe *et al.*, 1995; Jäghagen, 1997; Kobe & Coates, 1997; Lutz & Halpern, 2006; Ulvcrona *et al.*, 2010).

All trees are dependent on the availability of light, nutrients and water, and the competition for these resources depend on the individual tree in relation to other close standing trees in the stand (Pretzsch, 2009). Furthermore, ecological and climatic aspects such as altitude, different terrestrial biomes, soil characteristics, length of growing season, temperature sum and precipitation all effect the particular stand and thereby the possibilities for growth (Kozlowski, 1991). For the forest owner's point of view, it is important to consider different characteristics of each stand, when it comes to decisions regarding stand development. From different aspects, such as tree species and diameter distribution, stand density and site index, different long time until the stand should be harvested for bioenergy will come into the question.

# 4. Objectives

The overall objectives of the work underlying this thesis were to evaluate the possibilities for increasing biomass production for bioenergy harvests while leaving trees of high potential timber quality in young, dense Scots pine-dominated mixed stands in northern Sweden. Specific goals were to:

- Construct biomass functions based on data acquired from sampled trees in dense and sparse Scots pine-dominated mixed stands in northern Sweden (I). The main objective for these biomass functions was to estimate biomass production (II).
- Estimate the total biomass production for Scots pine, Norway spruce and birch, based on the constructed functions, when different treatments are applied, including: no-thinning with no fertilization, fertilization every six years, or every year**;** and PCT (to 3 000 stems ha$^{-1}$) with no fertilization or fertilization every six years (II).
- Analyse density and fertilization treatment-related differences in allocation patterns, i.e. differences in stem form, allocation to branches and needles (III).
- Analyse effects of PCT at different tree heights and stand densities on branch characteristics, stem form, living crown ratios and DBH for Scots pine (IV).
- Analyse density-related effects of competition and mortality risks for Scots pine (V).

# 5. Material and Methods

## 5.1 Study areas

### Sites

For the first study, biomass sampling was carried out in six young, Scots pine-dominated stands on mineral soils in northern Sweden (Figure 1, Paper I) where the altitude varied between 20 m a.s.l. – 220 m a.s.l, and site index (dominant height at 100 years of age) for Scots pine varied between 18-24 m according to definitions made by Hägglund & Lundmark (1977). The length of the growing season, defined as number of days when the daily mean temperature exceeded 5 °C was 120-180 days. The mean annual precipitation during the period from establishment of the studied stands (in 1997) to the final measurements (in 2008) considered here was 700-800 mm (Degerön, Kulbäcksliden and Renfors, data from Gagnet not available) (Anon. 2010b), compared to 700-800 mm for the climatic reference period (1961-1990) for the actual sites (Anon., 2011). For further details, see Table 1, Paper I.

For the second study, total biomass production was estimated at four sites used in a field experiment in northern Sweden - Degerön, Kulbäcksliden and Renfors close to Vindeln, Västerbotten - and Gagnet, close to Sollefteå, Ångermanland. Biomass was sampled at the sites before the field experiment was established, in 1997 at all sites except Gagnet (1998) (Figure 1, Paper 1). The altitude at these sites varied from 125 m a.s.l. (Gagnet) to 195 m a.s.l. (Renfors) and the site index, $H_{100}$, was estimated using site factors according to definitions made by Hägglund & Lundmark (1977) to be between 18 m (Renfors) and 24 m (Gagnet). All sites were on mineral soil, and the soil texture varied between sandy loam (Degerön) and loamy sand (Kulbäcksliden and Renfors) according to definitions made by Hägglund & Lundmark (1987). The field vegetation at the sites was dominated by bilberry (*Vaccinium myrtillus* L.) according to definitions made by Hägglund & Lundmark (1977), see Table 1, Paper II, for further details. All stands were naturally regenerated, mixed and Scots pine-dominated. Other tree species present were Norway spruce, Birch (*Betula pendula* Roth and *B. pubescens* Ehrh.), hereafter named birch. Further, scattered willow (*Salix* ssp.), mountain ash (*Sorbus aucuparia* L.), aspen (*Populus tremula*) and grey alder (*Alnus incana* L.) were found.

The tree species distribution at the time of establishment of the field experiment was about 59-99% for Scots pine, 2-13% for Norway spruce and 1-39% for deciduous spieces, based on basal area in the dense stands. In the PCT-treatments the tree species distribution was 84% Scots pine, 5% Norway spruce and 11% birch. The diameter distribution was not normally distributed for the dense stands (Figure 1). The third study was carried out in the sites Degerön, Kulbäcksliden and Renfors described in study I and II above. The fourth study was carried out at two sites: Norrliden (latitude 64° 21' N) and Stugun (63° 17' N), both located in northern Sweden. Both sites were included in "Group 2" of an experimental series, established by the late Professor Dr. S-O Andersson and described below (Karlsson & Ulvcrona, 2010), intended to assess effects of the timing of selective PCT. The Norrliden site was naturally regenerated using Scots pine seed trees after final felling in 1956, while the Stugun site was regenerated by direct Scots pine seeding after prescribed burning in 1958.

The fifth study was based on analyses of 9 924 Scots pine trees from, in total, 94 plots at 26 experimental sites, spanning latitudes 57° 56' N - 65 ° 9' N in Sweden (Figure 1, Paper V). All of these plots were included in "Group 1" of the experimental series established by S-O Andersson during 1953-1972, intended to assess effects of selective PCT, or "Group 2" (intended to assess effects of its timing, as mentioned above) (Karlsson & Ulvcrona, 2010).

### Field experiment sites in Vindeln and Gagnet

In study II, five 900 $m^2$ experimental plots were used, each measuring 45 × 20 m or 30 × 30 m (except for one plot, treatment C, in Gagnet that measured 20 x 20 m) depending on stand characteristics, with 5-m buffer zones, at each of the sites (blocks) listed above (Degerön, Kulbäcksliden, Renfors and Gagnet). Two plots (and the respective buffer zones) at each site had been subjected to PCT, to leave 3 000 trees $ha^{-1}$, while the others were left unthinned (control, C). At each site, one of the PCT plots (designated PCT+F1) and one of the C plots (designated C+F1) were fertilized from 1997 (Degerön, Kulbäcksliden and Renfors), 1998 (Gagnet), 2003 (Degerön, Kulbäcksliden and Renfors) or 2004 (Gagnet) onwards. F1 and F2 refer to N fertilization at 100 kg $ha^{-1}$ every 6th year and annually, respectively, from the establishment of the field experiment, using Skog-AN + Superba Mikromix in 1997-2001, and Skog-CAN granula (Yara International ASA) thereafter (Table 2, Paper II). Fences to protect the sites from moose were erected in 1998 at Degerön and Kulbäcksliden. Sprouts (<1.3 m) have been cleaned in the PCT-treatments since the establishment of the field experiment.

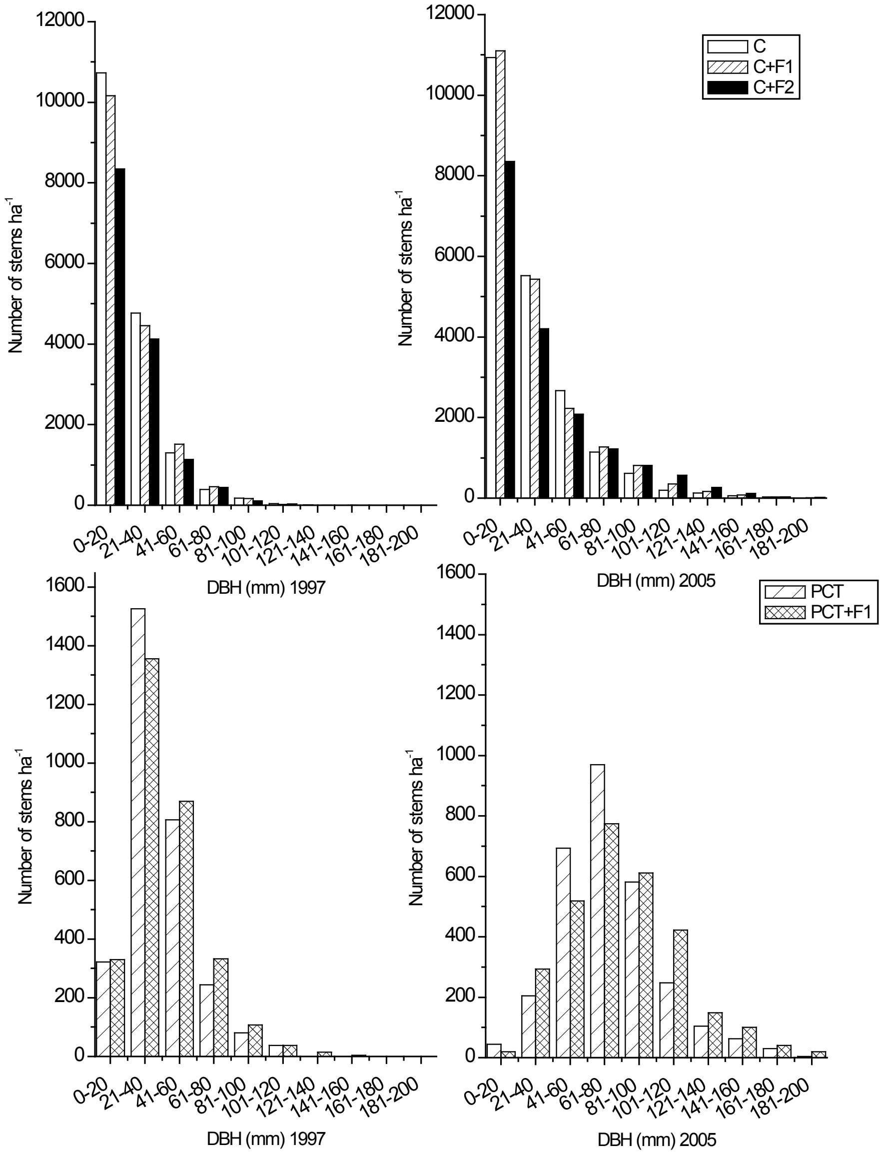

*Figure 1.* DBH (mm) distribution and number of stems ha$^{-1}$ at the establishment of the experiment in 1997 to the left, and after eight years in year 2005 to the right. Sites included are Degerön, Kulbäcksliden and Renfors. The dense treatments C, C+F1 and C+F1 in the upper part of the figure, and the PCT and PCT+F1 treatments in the lower part of the figure. Abbreviations as in Table 1.

The stands at Renfors and Kulbäcksliden were established in 1977, while those at Gagnet and Degerön were established in 1979 and 1980, respectively, so the stands were 17-20 years old when the experiments were established in 1997 (Degerön, Kulbäcksliden and Renfors) and 1998 (Gagnet). The arithmetic mean DBH in the dense stands was somewhat lower in Degerön in 1997 (16-19 mm) than in Renfors and Kulbäcksliden (21-26 mm) and Gagnet (36-41 mm). No significant differences were found in dominant height (4.3 m-7.2 m), but it was greatest at Gagnet. The number of stems in the unthinned stands varied from 8 600 (Renfors) to 24 867 (Degerön). For further details, see Table 3 in Paper II.

## 5.2 Biomass sampling and biomass functions

For study I, trees were sampled for biomass analyses on three occasions in total, 1997/1998 (Claesson *et al.*, 2001), 2003/2004 and finally in spring 2010. On the first occasion, in 1997-1998, trees from all six sites were sampled and analysed (Claesson *et al.*, 2001), but on the following two occasions only trees from the plots established close to Vindeln and described above (for study II) were sampled. For study III, allocation patterns of Scots pine were analysed six years after establishment of the field experiment using the trees sampled for biomass analysis (study II) in 2003-2004**.**

On each occasion a number of trees were sampled, aiming to select trees representing their respective stands, with the same DBH distribution as the stands, ignoring damaged trees. The DBH, height and crown length of all trees were measured, and their crowns were divided into four strata of equal length. A sample branch was collected from each stratum, and six discs along the stem were collected (Figure 2, Paper I). For the smallest trees, the BH disc overlapped with the 30% disc; as such, only five discs were cut from these trees. Discs and branches were weighed in the field to obtain their fresh weights, placed in air-tight plastic bags and stored in a freezer (-20 °C) until they were dried in a ventilated oven at 85 °C for 48 h (branches and foliage). The discs were dried for ≥48 h to constant dry weight (DW). When drying discs after the second sampling (2003/2004), an increase in DW between consecutive weighing occasions were observed, although the discs were always weighed immediately after they were taken from the oven. The reason for this was the migration of water from larger to smaller discs, even though a ventilated oven was used. Therefore, small discs and large discs were separated before drying thereafter.

Biomass functions were constructed for the fraction stem including bark, branches including bark, foliage, and dead branches. Additionally functions for the whole tree including all fractions mentioned above were constructed.

The biomass functions were constructed based on regression models (study I). A number of different variables were evaluated and accepted variables were significant at $p \leq 0.05$. All variables were transformed with the natural logarithm to obtain constant variance. To avoid multicollinearity, each variable was used only once in each regression (Tamhane & Dunlop, 2000). When retransforming the results, correction for logarithmic bias was calculated according to Finney (1941). For the selected functions, analysis of residuals was made as the difference between estimated DW (g) and calculated DW (g) for sample trees as the mean value (g) per DBH –class (cm).

## 5.3 Tree and stand measurements (I-III)

DBH was measured from one direction of the tree at the height of 1.3 m. After establishment, all field inventories for study II were done in autumn (September and October) after the growing season. The first inventory (1997) was done using callipers and a dot list, while Haglöf® Mantax Digitech® callipers (Haglöf Sweden AB, Långsele) were used for the second inventory. Height measurements were acquired using a height pole in 1997 and a digital hypsometer (Vertex®; Haglöf Sweden AB, Långsele) thereafter.

To ensure that all trees measured in the stand were only measured once in each inventory, measurement tapes were used to create ca. 5 m corridors through the plots. When a tree was measured, the stem was marked. The DBH of all trees >1.3 m tall in the net-plot, including sprouts of birch and aspen, was measured. The height of a number of sample trees in each plot (40-80) was also recorded (the nine largest trees of each species, and a number representing actual DBH-classes). Using height and DBH data acquired from these trees, all trees in the respective plots were assigned individual heights for each treatment and species using equations presented by Näslund (1936), see further study (II) equation 5.

Damaged trees were registered, but seriously damaged trees were not selected for height measurements. Standing dead trees were also recorded.

Biomass production (study II) was estimated using biomass functions from study I. Total and annual production of biomass and stem volume were estimated for both an early period and a later period. Annual growth during each period was estimated as the increase in size parameters, for all trees (including trees that were dead at the end of each period) and living trees from the beginning of each analysed period; the increases were then divided by the number of vegetation seasons between inventories.

Size parameters of the 500 (corresponding to a typical number of stems per ha at final cut), 1500 (corresponding to a typical number of stems per ha after a conventional first thinning following after PCT) and 2 700 largest trees per ha (corresponding to the density in the PCT-plot with the highest mortality since the start of the experiment) at the end of the experimental period were compared between treatments for the sites Degerön, Kulbäcksliden and Gagnet. In addition, sizes of 2 700 trees per ha, marked as trees that could be left after a selective first thinning, were compared between-treatments and to the sizes of the 2 700 largest trees per ha. Only healthy trees with no damage were selected for this analysis. Analysis of variance was then applied to evaluate the effects of the treatments with sites as blocks (random effects). For all statistical tests, $p \leq 0.05$ was considered to be significant.

### Foliage analyses

To detect potential nutrient imbalances due to fertilization (study I, II and III), samples of foliage (shoots from current year+1, C+1) from three Scots pine and three Norway spruce trees representing each treatment and site were collected for analysis, in February, from the third branch of the top shoot on the south side of the crown using secateurs on a pole. The needles were dried in a ventilated oven (85 °C), and samples of needles from each tree were weighed using a laboratory balance (0.005 g). Pooled samples of equal weight representing each combination of species, treatment and site were then formed, and their elemental contents were analysed at the Swedish University of Agricultural Sciences, Umeå, using an Elan 6100 ICP/MS-DRC instrument and a 2400CHN Element Analyzer (both supplied by PerkinElmer, Norwalk, Connecticut, USA).

## 5.4 Old PCT-experiments (IV-V)

In total, field experiments were established in more than 150 stands all over Sweden in the S-O Andersson series. Most of the stands are Scots pine and Norway spruce stands, for further details, see Karlsson & Ulvcrona (2010). Data acquired from measurements of trees in plots established in field experiments by late Professor Dr. S-O Andersson in 1950's to 1980's were used for two of the studies (IV and V). In study IV branch characteristics were analysed in two Scots pine stands of Group 2 (intended to assess effects of the timing of selective PCT), while in Study V mortality was analysed in Scots pine stands of both Groups 1 (intended to assess effects of selective PCT) and 2 (Karlsson & Ulvcrona, 2010).

Selective PCT experimental plots (Group 1) were divided into subgroups a, and b. Sub-group 1a was established during 1953-1961 at 28 sites in Sweden, 24 with pure Scots pine stands to which no thinning, or selective PCT to 1 500, 2 500, 3 000, 4 000, 5 000 or 6 000 stems ha$^{-1}$ was applied. Sub-group 1b were established during 1970-1985 with no-thinning or PCT to 600, 1 000, 1 400, 1 800, 2 500 and 3 200 stems ha$^{-1}$. The PCT timing was also varied, by applying it at heights ranging from 0.5 m to 7.5 m. In total 16 sites with Scots pine, and 10 sites with Norway spruce experiments were included in group 1b (Karlsson & Ulvcrona, 2010).

The main objective of the Group 2, timing of selective PCT, experiments was to study the combined effects of the number of stems after PCT and the timing of PCT. Four timings **(**defined as the mean height of the remaining stems**)** were chosen: <1.5 m or 1.5-2.0 m (T1), 2.0-3.5 m (T2), 3.5-5.5 m (T3) and 5.5-7.5 m (T4). The number of stems ha$^{-1}$ after PCT was 1 000, 1 800 and 2 500 at fertile sites (site index >26 m), and 600, 1 000 and 1 800 stems ha$^{-1}$ on poorer sites (Karlsson & Ulvcrona, 2010).

## 5.5 Branch characteristics (IV)

Branch characteristics were analysed in study IV, in which 5 067 branches in 1 041 whorls of the 90 trees were measured in stands pre-commercially thinned to 600, 1 000 and 1 800 stems ha$^{-1}$ and at heights of 1.5, 3, 5 and 7 m. Branch diameters were measured, perpendicular to the branch axis, using an electronic slide calliper (with ± 0.03 mm accuracy); living branches over bark and dead branches under bark.

## 5.6 Mortality (V)

Individual mortality were analysed in study V, in which 9 924 Scots pine trees from 26 PCT-experiments comprising a total of 94 plots were analysed. Experiments from groups 1 (spacing experiments) and 2 (timing of PCT experiments) of the dataset were used (Karlsson & Ulvcrona, 2010) and selection of plots was made on the basis of whether data on the number of stems before PCT was available. The field experiments analysed were established between 1953 and 1972 in Sweden (57°-66° N) and evaluated about 8-23 years after PCT. A majority of the stands examined were established by natural regeneration and a few stands were established by direct seeding, planting, or prescribed burning followed by natural regeneration The PCT-treatment factors included stand density and height at the time of PCT. The stand densities varied between 600 stems ha$^{-1}$ and >9 000 stems ha$^{-1}$ before PCT. The height at the time of PCT varied between 1 m and 8 m.

Not all DBH-classes were represented at all sites with respect to mortality at different heights at PCT, stem density before PCT and stem density after PCT. Therefore the variable "site" was not included in the model. Mortality in this study refers to the proportion of dead trees out of the total number of stems after PCT. Mortality was calculated as the mean value for each class and site and thereafter analysed with variance analyses (study V).

# 6. Results and Discussion

## 6.1 Biomass functions (I, II)

Biomass functions for estimating the dry weight (DW) of the above-ground parts of whole trees (including stem, dead and alive branches and foliage) and the fractions stem including bark, alive branches and foliage were derived using data acquired from the sample trees. No significant correlation between the DW of the dead branches fraction and DBH was observed. Therefore, no biomass function for this fraction was constructed. A number of variables and combinations of variables were tested, and the most suitable for estimating all fractions was found to be *ln DBH * ln Tree Height*. DBH and tree height have also been found by other authors to be suitable for estimating biomass (Young, 1976; Hitchcock & McDonnell, 1979; Sato o & Madgwick, 1982). The variable *ln (DBH * crown length)* was found to be suitable for estimating the DW of the branches and foliage fractions. Similar results, with improvements in regressions for predicting crown parameters by adding the living crown ratio, have also been previously reported for pine and spruce (Marklund, 1988), shortleaf pine (*Pinus echinata*) (Loomis *et al.*, 1966), Virginia pine (*Pinus virginiana*) and radiata pine (*P. radiata*) (Madgwick, 1979; Madgwick & Kreh, 1980).

All these variables (DBH, tree height and crown length) are easy to measure, and thus advantageous for estimating DW biomass. Analyses of the residuals (the estimated weight - true weight) indicated low values for all species, treatments and fractions (Study I, Figure 3-6). The biomass functions were then used to estimate the total biomass (DW) for the stands examined in study II.

## 6.2 Biomass production (II)

About 14-17 $m^3$ $ha^{-1}$ of the stem volume and 10-12 ton $ha^{-1}$ total biomass (50%), and about 15 400 or 80% of the number of stems, where cut and left in the forest during the PCT-operation at the time of establishment of the experiment (Figure 2). The no-thinning treatment resulted in about 58%-78% higher yield than the PCT-treatments, in accordance with previous studies (Pettersson, 1993a) (Figure 3 and Table 1). These results are based on the living trees at the end of the experimental period. If the stems left in the forest at PCT was included in the analyses the total yield was 68.4 ton $ha^{-1}$ (PCT) and 73.7 ton $ha^{-1}$ (PCT+F1). In addition, for the 1 500 largest trees per ha, the C+F2 treatment yielded the highest values for all measured parameters and the C treatment the lowest values (Figure 4). The same pattern was found for the 500 largest trees per hectare, with the exception with highest value for branches in treatment PCT+F1. Significant differences between these two treatments were found for total biomass, biomass of the stem, branches, foliage, basal area and arithmetic mean diameter. No significant between-treatment differences were found for stem volume and arithmetic height. Results from study II show that the C+F2 treatment resulted in 79% higher yield compared to PCT 3 000 stems $ha^{-1}$, and 129% higher yield than PCT to 1 500 stems $ha^{-1}$ (Figure 5). These results indicate the potential for increasing biomass production by solely leaving a higher number of stems after PCT, or harvesting biofuel at a dominant height of about 8-10 m. For biomass production per diameter class from the time for establishment of the experiment and eight years later, see Figure 6. Figure is based on results from the sites of Degerön, Kulbäcksliden and Renfors. Also when analysing the 2 700 largest trees, corresponding to the PCT-treatments (some of the originally 3 000 stems were dead in the end of the experimental period), the same result was found with no significant difference for stem biomass or arithmetic mean height. The lowest values were again found for treatment C, and the highest for treatment C-F2, with significant differences between these treatments for total biomass, biomass of the stem, branches, foliage and basal area. The C+F1 treatment also resulted in significantly higher foliage biomass than treatment C, and the C+F2 treatment significantly higher values than the two PCT-treatments. The annual growth was higher during the first period, both for treatment C and C+F2. The decrease during the later period was however larger in treatment C (25%), compared to C+F2 (1.7%). This might explain the differences observed for the 2 700 largest trees in the end of the experimental period, whereas in study III, significant differences were only observed for the smallest trees (Table 1).

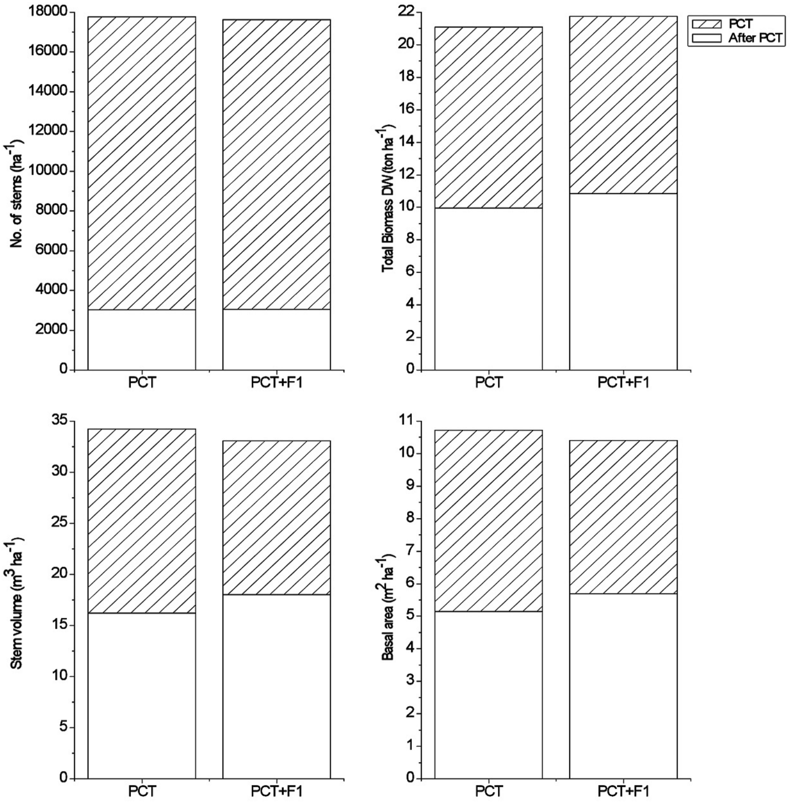

*Figure 2*. Number of stems upper left, total biomass DW (ton ha$^{-1}$), upper right, stem volume (m$^3$ ha$^{-1}$) lower left and basal area (m$^2$ ha$^{-1}$) lower before and after PCT treatment. Abbreviations as in Table 1.

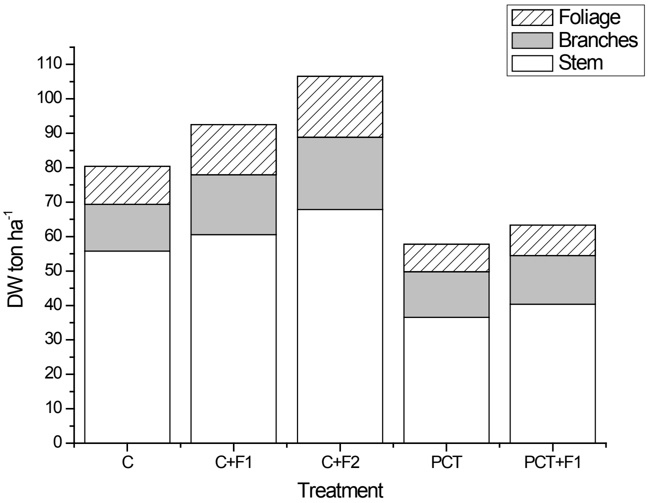

*Figure 3*. Study II. Biomass of different fractions at the end of the experimental period from the sites Degerön, Kulbäcksliden and Gagnet and different treatments. Abbreviations as in Table 1.

*Table 1.* Study II. Annual growth and yield of total biomass, stem volume and basal area for each period defined as early period (1997-2002/2003, all sites included), later period (2002/2003-2008, all sites included, Renfors with data from 2005) and full period (1997-2008, all sites included, Renfors with data from 2005) and for each inventory, and the difference in yield between start to end. F-C is the difference between the fertilized treatment and the control (C and PCT, respectively). The additive yield by F is kg, m$^3$ and m$^2$, respectively per kg N added during the experimental period. Comparisons are made by treatment[a] and period or time. Means with different letters are different at the 0.05 level of significance according to Tukey´s multiple comparison test

| *Treatment* | *Annual growth* | | | *Yield* | | | *Effect of Fertilizer* | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Early* | *Later* | *Full* | *Start* | *End early* | *End late/exp.* | *Difference in yield: End - start* | *F - C* | *Additive yield by F* |
| Biomass ton ha$^{-1}$ | | | | | | | | | |
| C | $6.2^{ab}$ | $4.6^{b}$ | $5.2^{bc}$ | $26.2^{a}$ | $57.2^{a}$ | $79.4^{ab}$ | $53.2^{b}$ | - | - |
| C+F1 | $6.7^{a}$ | $6.5^{ab}$ | $6.4^{ab}$ | $27.0^{a}$ | $60.5^{a}$ | $92.3^{a}$ | $65.3^{ab}$ | 12.1 | 60.5 |
| C+F2 | $8.0^{a}$ | $7.9^{a}$ | $7.5^{a}$ | $23.8^{a}$ | $63.5^{a}$ | $100.4^{a}$ | $76.9^{a}$ | 23.7 | 21.6 |
| PCT | $4.0^{c}$ | $5.3^{ab}$ | $4.5^{c}$ | $9.8^{b}$ | $29.5^{b}$ | $56.0^{c}$ | $46.3^{b}$ | - | - |
| PCT+F1 | $4.6^{bc}$ | $6.0^{ab}$ | $5.1^{bc}$ | $10.5^{b}$ | $33.2^{b}$ | $62.9^{b}$ | $52.4^{b}$ | 6.1 | 30.5 |
| Stem vol. m$^3$ ha$^{-1}$ | | | | | | | | | |
| C | $10.7^{ab}$ | 8.0 | $9.0^{bc}$ | $41.0^{a}$ | $94.4^{ab}$ | $142.6^{abc}$ | $92.3^{bc}$ | - | - |
| C+F1 | $12.0^{a}$ | 10.1 | $10.7^{ab}$ | $42.8^{a}$ | $102.8^{a}$ | $158.4^{ab}$ | $108.7^{ab}$ | 16.4 | 0.08 |
| C+F2 | $13.8^{a}$ | 12.4 | $12.2^{a}$ | $37.3^{a}$ | $105.8^{a}$ | $177.8^{a}$ | $125.8^{a}$ | 33.5 | 0.03 |
| PCT | $6.3^{c}$ | 8.3 | $7.1^{c}$ | $15.7^{b}$ | $46.7^{c}$ | $98.1^{d}$ | $73.3^{c}$ | - | - |
| PCT+F1 | $7.4^{bc}$ | 9.3 | $8.2^{bc}$ | $17.0.^{b}$ | $54.2^{b}$ | $104.5^{c}$ | $83.8^{bc}$ | 10.5 | 0.04 |
| Basal area m$^2$ ha$^{-1}$ | | | | | | | | | |
| C | $2.0^{bc}$ | 1.3 | $1.6^{b}$ | $13.1^{a}$ | $23.2^{a}$ | $29.2^{a}$ | $16.1^{b}$ | - | - |
| C+F1 | $2.2^{b}$ | 1.5 | $1.8^{ab}$ | $13.2^{a}$ | $24.4^{a}$ | $31.5^{a}$ | $18.3^{ab}$ | 2.2 | 0.01 |
| C+F2 | $2.9^{a}$ | 1.7 | $2.2^{a}$ | $11.7^{a}$ | $26.1^{a}$ | $34.4^{a}$ | $22.8^{a}$ | 6.7 | 0.01 |
| PCT | $1.4^{d}$ | 1.3 | $1.3^{b}$ | $5.1^{b}$ | $11.9^{b}$ | $18.5^{b}$ | $13.4^{b}$ | - | - |
| PCT+F1 | $1.5^{cd}$ | 1.5 | $1.4^{b}$ | $5.7^{b}$ | $13.3^{b}$ | $20.5^{b}$ | $14.8^{b}$ | 1.4 | 0.01 |

---

[a]

C = dense stand with no fertilization

C+F1 = dense stand and fertilization 100 kg N ha$^{-1}$ 1997 and 2003 (Degerön, Renfors, Kulbäcksliden) and 1998 and 2004 (Gagnet)

C+F2 = dense stand with 100 kg N ha$^{-1}$ year$^{-1}$

PCT = pre-commercial thinning 3 000 stems ha$^{-1}$

PCT+F1 = pre-commercial thinning and fertilization 100 kg N ha$^{-1}$ 1997 and 2003 (Degerön, Renfors, Kulbäcksliden) and 1998 and 2004 (Gagnet).

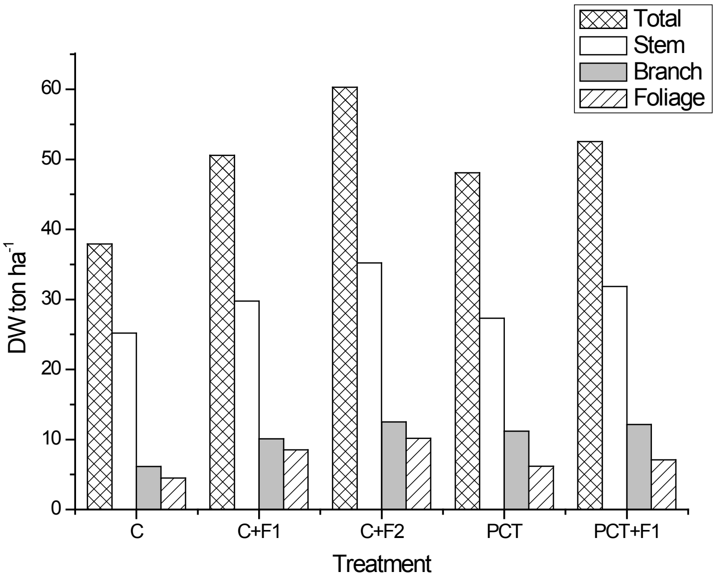

*Figure 4.* Study II. Total biomass, and the different fractions stem, branch and foliage of the 1 500 largest trees $ha^{-1}$ for each treatment. Sites included are Degerön, Kulbäcksliden and Gagnet, and results are from the end of the experimental period. Abbreviations as in Table 1.

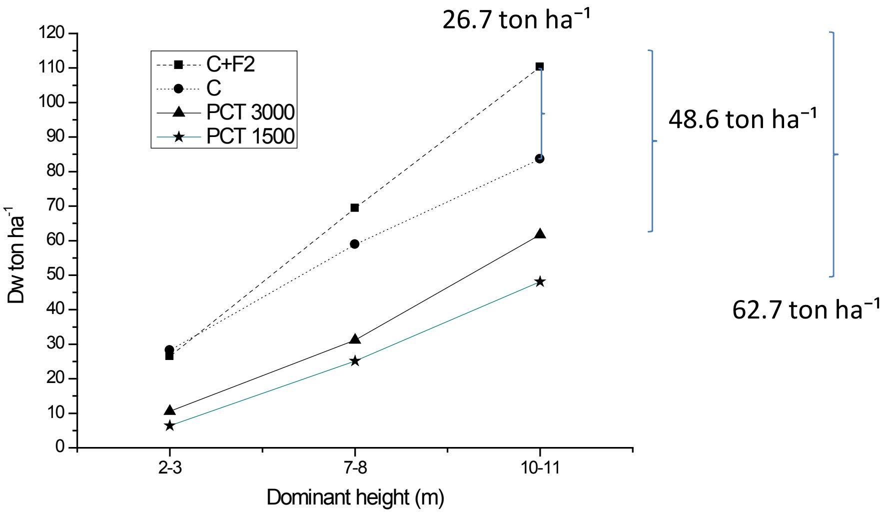

*Figure 5.* Study II. Biomass production in the dense, fertilized stands (C+F2), the dense control stands (C) and stands subjected to two levels of PCT (1 500 and 3 000 stems $ha^{-1}$) without any fertilizer. Data for PCT to 1500 stems $ha^{-1}$ were recalculated from data for the 1500 largest stems $ha^{-1}$ in the PCT 3000 stands. Sites included were Degerön, Kulbäcksliden and Gagnet. Abbreviations as in Table 1.

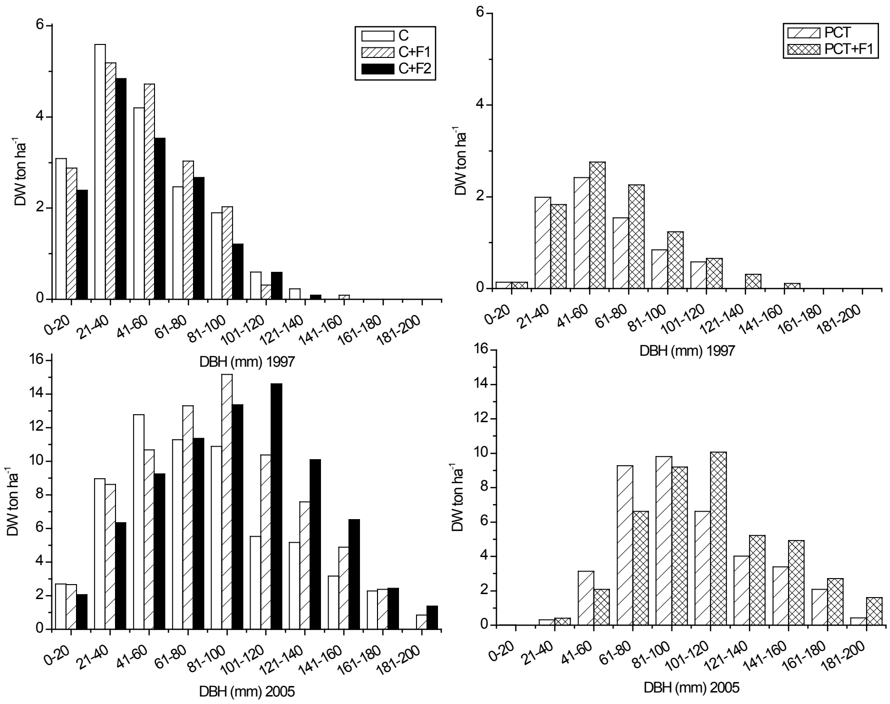

*Figure 6.* Total biomass DW ton ha$^{-1}$ per DBH (mm) class at the establishment of the experiment in 1997 to the left, and after eight years in year 2005 to the right. Sites included are Degerön, Kulbäcksliden and Renfors. The dense treatments C, C+F1 and C+F1 in the upper part of the figure, and the PCT and PCT+F1 treatments in the lower part of the figure. Abbreviations as in Table 1.

A comparison for the difference between the 2 700 largest trees and 2 700 selected trees remaining after biofuel harvest was also done. Significant differences were only found for branches and foliage. For branches, the PCT+F1 treatment resulted in the highest value, and the C+F1 treatment the second highest (significantly higher, in both cases, than treatment C). For foliage, the only significant difference was between treatments C and C+F2. These results indicate that the largest trees continued to grow even in the dense stand, and that combining bioenergy harvests with leaving stems in the stand for future thinnings is feasible. These results correspond with previous findings (Watkinson *et al.*, 1983; Weiner & Thomas, 1986).

The fertilizer given two times during the experimental period resulted in more biomass, higher basal area and higher volume per kg N added than the annual fertilization treatment (Table 1), although the intensive fertilization resulted in (insignificantly) higher production, possibly because maximum LAI had already been reached in the stands, hence further fertilization could not increase LAI any further (Ceulemans & Saugier, 1991).

It seems likely that the selected fertilization level of 100 kg N ha$^{-1}$ year$^{-1}$ was not optimal for these Scots pine-dominated stands. Similar results have been found by other authors (Tamm, 1985; Jacobson & Nohrstedt, 1993; Aber *et al.*, 1995;Tamm *et al.*, 1999; Högberg *et al.*, 2006b), possibly due to reductions in foliar Mg:N and Ca:Al ratios resulting from increases in anion mobility followed by increased cation leaching losses (Aber *et al.*, 1995). Another possible explanation is associated with the negative influence on myccorrhizae and consequent reductions in the ability of the tree roots to take up nutrients (Jacobson & Nohrstedt, 1993). However, mycorrhizae were not analyzed in the studies this thesis is based upon, so effects of fertilization treatments in young, dense mixed forests in this respect remain to be investigated.

Repeated additions of N have also been found to cause no serious nutrient deficiencies and (non-significant) increases in growth by Jacobson & Pettersson (2001). However, Aber *et al.* (1995) found reductions in tree growth and increased tree mortality with increasing nitrogen additions. Further, they reportedly caused decreased Mg:N and Ca:Al ratios in the foliage, which might be one explanation for the decreased tree growth (Aber *et al.*, 1995). Results from other field studies indicate that intensive fertilization can significantly increase increments of Norway spruce (Tamm, 1985; Stockfors *et al.*, 1997; Bergh *et al.*, 1999; 2005).

Clearly, when adding nutrients it is important to detect any deficiencies in foliage (Linder, 1995). Therefore foliage was analysed during the experiments considered here. Needle samples have been collected and analysed since 1999. In 2005, increased levels of nitrogen were found in needles from fertilized trees, but the difference in this respect between treatments C and C+F2 was only close to significant ($p$=0.056) for Scots pine. For Norway spruce significant differences were detected between treatments C+F2 and C ($p$=0.016), PCT ($p$=0.049) and PCT+F1 ($p$=0.026). For Norway spruce significant differences between the C+F2 and PCT+F1 were also found for foliage boron contents ($p$=0.012) (Table 2).

*Table 2*. Study I, II, III, Nutrient levels in needle samples of Scots pine and Norway spruce trees collected in February 1999 and 2005 for each treatment[a] (except for P and B; results for samples from 2002). Target values summarized from Brække (1994). Numbers in bold font within these target values

| Treatments | Nutrient | Target value | Scots pine | | Norway spruce | |
|---|---|---|---|---|---|---|
| | mg $g^{-1}$ | mg $g^{-1}$ | 1999 | 2005 | 1999 | 2005 |
| C | N | 15-25 | 12.80 | 11.73 | 14.43 | 11.53 |
| C+F1 | | | 12.37 | 12.80 | 10.97 | 13.13 |
| C+F2 | | | 13.03 | **16.47** | 13.07 | **18.57** |
| PCT | | | 12.70 | 13.10 | 13.13 | 12.90 |
| PCT+F1 | | | 12.80 | 11.93 | 13.37 | 12.10 |
| C | P | >1.5-2.0 | 1.32 | 1.41 | **2.05** | **2.26** |
| C+F1 | | | 1.35 | **1.51** | **2.08** | **1.73** |
| C+F2 | | | 1.37 | 1.39 | **1.99** | **1.72** |
| PCT | | | 1.39 | 1.40 | **2.00** | **1.71** |
| PCT+F1 | | | 1.45 | 1.40 | **1.77** | **1.58** |
| C | K | >6-8 | 4.82 | 2.66 | **6.77** | 3.26 |
| C+F1 | | | 4.47 | 4.31 | **6.21** | 4.74 |
| C+F2 | | | 4.85 | 3.89 | **6.30** | 3.26 |
| PCT | | | 4.66 | 3.79 | **6.46** | 2.95 |
| PCT+F1 | | | 5.31 | 3.14 | 5.64 | 3.59 |
| C | Ca | >3-4 | 2.96 | **4.45** | **6.62** | **4.36** |
| C+F1 | | | **3.49** | **5.40** | **4.74** | **6.05** |
| C+F2 | | | **3.10** | **3.98** | **5.59** | **3.12** |
| PCT | | | **3.49** | **4.09** | **4.56** | **3.50** |
| PCT+F1 | | | 3.34 | 4.21 | 5.21 | 4.78 |
| C | Mg | >0.7-1.1 | **0.95** | **0.83** | **0.86** | 0.66 |
| C+F1 | | | **0.91** | **0.72** | **0.79** | 0.69 |
| C+F2 | | | **0.85** | **0.72** | **0.92** | 0.51 |
| PCT | | | **0.87** | **0.89** | **0.94** | 0.63 |
| PCT+F1 | | | 0.85 | 0.83 | 0.98 | 0.76 |
| C | S | >1.9-2.2 | 0.83 | **2.92** | 1.03 | **3.38** |
| C+F1 | | | 0.89 | **2.08** | 0.89 | **3.09** |
| C+F2 | | | 0.89 | **2.35** | 0.91 | **3.17** |
| PCT | | | 0.92 | **2.07** | 0.87 | **3.09** |
| PCT+F1 | | | 0.88 | **2.89** | 0.87 | **2.88** |
| C | B | 0.008-0.025 | 0.003 | 0.003 | 0.007 | 0.005 |
| C+F1 | | | 0.007 | 0.007 | 0.006 | **0.009** |
| C+F2 | | | **0.010** | **0.010** | **0.010** | **0.010** |
| PCT | | | 0.005 | 0.005 | 0.007 | 0.003 |
| PCT+F1 | | | **0.010** | **0.010** | 0.007 | **0.009** |

[a] Abbreviations as in Table 1.

The findings of higher DW total biomass in the dense, unthinned stands are also supported by other studies. By doing a pre-commercial thinning leaving 1 000, 1 600 or 2 200 stems per hectare at dominant heights of 3, 6 and 9 m respectively, a remarkable loss of merchantable wood production was detected 23-25 years later in the 1 000 stems per hectare treatment for Scots pine (Varmola & Salminen, 2004). The growing stock can thus be decreased by heavy thinnings, and leaving too few stems per hectare may result in losses of merchantable yields at stand level (Huuskonen & Hynynen, 2006). Differences in density may also lead to differences in increments, with higher annual growth during the first period in the dense stand, compared to the PCT-treatments. The difference was smaller during the later period, possible as an effect of increased competition in the dense stand, and also increased foliage in the PCT-treatments.

Similar results was also found by others, for instance, Nilsson and Albrektson (1994) recorded higher increments in stands with 40 000 stems per ha than in stands with 10 000 stems per ha to ages up to 10 years. However, in the following six years, increment was higher in the stands with 10 000 stems per hectare (Nilsson & Albrektson, 1994), obviously because competition increased more strongly in the denser stands. Similar results have been reported by Agestam *et al.* (1998), in a comparison of stands with stem densities of 1 600 and 6 400 stems per hectare. The relative growth of height and diameter is often found to be lower in a denser stand, even for larger trees (Nilsson, 1994). Early, intensive PCT (resulting in wide spacing) reportedly induces the strongest diameter increment responses (Pettersson, 1993b; Huuskonen & Hynynen, 2006), while higher densities after PCT result in higher total yields but smaller mean diameters (Pettersson, 1993a). An increase in volume production was also found up to 14-16 m in dominant height for densities varying from 500 - 4 000 stems after PCT. For stand densities >4 000, the increase by stem density was significantly less pronounced (Pettersson, 1996).

## 6.3 Allocation patterns (III)

In study III, only the smallest Scots pine trees in the stand were found to be significantly affected by the stand density or fertilizing treatments in terms of: the DBH/height ratio; stem weight/total weight ratio; weights of branches, foliage and dead branches (relative to total weight); and crown length/tree height ratio (Figures 7). These results are also supported by previous studies, in which more biomass was found to be allocated to stem wood in suppressed trees and trees in dense stands (Nilsson & Albrektson, 1993; Mäkinen & Vanninen, 1999). Nilsson and Gemmel (1993) also found that increased competition increased the allocation to stem growth and decreased allocation to needles in young Norway spruce and Scots pine trees.

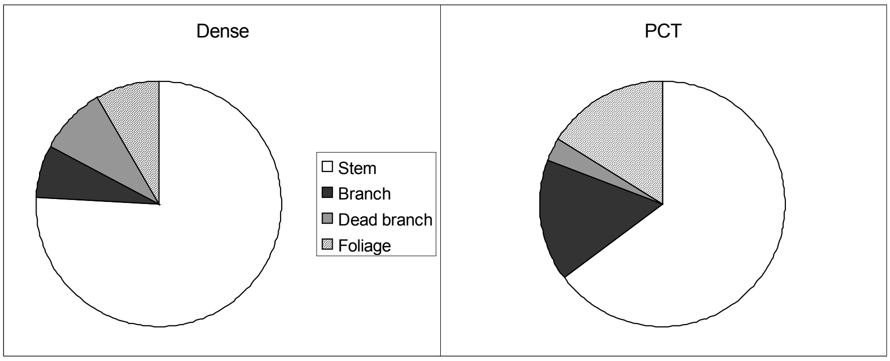

*Figure* 7. Study III. Above-ground allocation patterns presented as percentages of each fraction relative to total weight for Scots pine trees DBH <50 mm in the dense stands (to the left) and in the PCT-stand (to the right) after biomass sampling in 2003/2004 (spring) in the sites Degerön, Kulbäcksliden and Renfors.

Allocation patterns can also be changed by changing abiotic factors, such as irrigation and fertilization. Irrigation has the potential to increase biomass distribution to fine roots and decrease biomass to foliage relative to other plant parts. Fertilization has the potential to increase biomass allocation to coarse roots, tap roots and branches, with accompanying reductions in allocation to fine roots and foliage (King *et al.*, 1999).

### 6.4 Time of pre-commercial thinning and branch characteristics (IV)

Both DBH and the living crown to height ratio decreased with increasing stand density, and the height/DBH ratio increased with increasing stand density for Scots pine trees in stands in which PCT to 600, 1 000 and 1 800 stems ha$^{-1}$, at various tree heights (1.5, 3, 5 and 7 m), had been applied. The same results were generally also found for increased height at PCT. Branch diameter decreased with increases in stand density, and decreased with increases in height at the time of PCT (Figure 8). These results correspond with previous findings that increases in stand densities and reductions in crown length are associated with more cylindrical trees (Larson, 1963). More pronounced taper was also recorded 5-10 years after thinning from below (removing 65% of basal area at a stand height of 12-15 m) than in trees from unthinned stands by Karlsson (2000b).

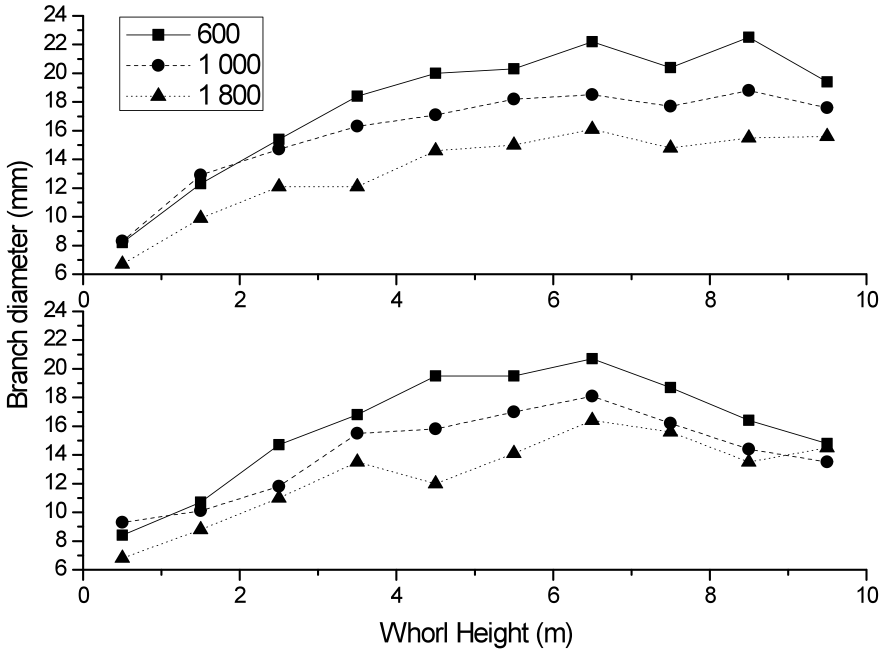

*Figure 8*. Study V. Branch diameter (mm) at different whorl heights (m), and stand densities 600, 1 000 and 1 800 stems ha$^{-1}$ from Norrliden, above, and Stugun, below.

For Scots pine, high stand densities result in both slower branch development and decreased DBH increments (Huuskonen & Hynynen, 2006). Branch diameter in the lower part of the stem has also been found to decrease with increasing stand density (Persson, 1976; Persson, 1977; Salminen & Varmola, 1993; Karlsson *et al.*, 2002; West, 2006), and increases in height at PCT (Fahlvik *et al.*, 2005).

Agestam *et al.* (1998) found that trees in naturally generated Scots pine stands had higher quality than those in planted stands, in accordance with other findings that planted Scots pine trees usually become more branchy than naturally generated trees (Salminen & Varmola, 1993), and dense spacing results in higher quality (Persson, 1977; Uusvaara, 1991; Persson *et al.*, 1995). These findings might be due to high densities resulting in adequate competition in the seedling and sapling stages. Uusvaara (1991) also provides an explanation regarding the development of branches, being affected not only by spacing, but also the homogeneity of the stand. Increases in branch diameter have also been associated with increases in site fertility and decreases in stand density (Fryk, 1984; Lämsä *et al.*, 1990; Uusvaara, 1991; Mäkinen, 1996; Mäkinen & Colin, 1999).

## 6.5 Risk of mortality (V)

When one or more resources required by a population falls below a critical level, density-dependent intra-specific competition occurs (Ford & Diggle, 1981; Peet & Christensen, 1987; Zeide, 2010) accompanied by increased mortality risks. However, overall mortality for the time period in the Scots pine trees examined here was found to be low, <5% even in the stand with >9 000 stems ha$^{-1}$ and the smallest trees in the stand died. Similar findings, of highest mortality among small trees, have been previously reported by Pettersson (1992b), Monserud and Sterba (1999) and Ulvcrona *et al.,* (2010), and (in a study of forest structure and associated changes up to 38 years after a clear-cut in Oregon, USA) by Lutz and Halpern (2006). Higher total mortality was also found 15 years after planting in the stands with 40 000 stems per ha than in those with 10 000 stems per ha examined by Nilsson & Albrektson (1994). Similar results have also been found by He and Duncan (2000).

The results regarding the DBH distribution among dead trees correspond well with other studies, which have concluded that much less xylem is produced in suppressed trees than in dominant trees, leading to increasing differences between the smallest and larger trees in the stand (Kozlowski & Peterson, 1962). Weiner and Thomas (1986) postulated that mortality is related to the relative size of a particular tree in the stand, rather than the absolute size. However, in an analysis of DBH-related mortality of Norway spruce in mixed stands with a large sample size ($n$=26 699), a U-shaped distribution was obtained, with about 7% mortality for trees with DBH < 5 cm, declining to less than 2% for DBH-classes up to 70 cm, but increasing again to ca. 5% for trees with DBH >70 cm (Monserud & Sterba, 1999). When the larger trees were further analysed, 15 out of 21 dead trees were found to be older than 140 years, and for the remaining six trees the mortality rate was below 2%, equal to that of trees of with DBH of 35-65 cm. These findings correspond well with several other studies (Goff & West, 1975; Buchman *et al.*, 1983; Harcombe, 1987; Ulvcrona *et al.*, 2010).

Trees receiving more light have been found to have more efficient needles (Vanninen, 2004), and the characteristic drought tolerance of Scots pine needles could be acquired at the expense of shade tolerance in the species (Hansen *et al.*, 2002). When crowns become shaded, their competitive capacity for water and nutrients will decrease. The following inhibition of photosynthesis reduces the supply of carbohydrates, and thus cambial and root growth, leading to decreased absorption of water and nutrients (Kozlowski *et al.*, 1991). Therefore, suppressed trees will have reduced growth rates and a higher risk of mortality (Waring, 1987; Kenkel, 1988; Kozlowski *et al.*, 1991; Kobe *et al.*, 1995; Pretzsch, 2009). The cambium will also produce xylem for a shorter time in a suppressed tree compared to a dominant tree (Kozlowski & Peterson, 1962). These findings can also be connected to the findings from study II, that annual growth was lower in the dense stands during the later period than in the first period, while annual growth in the PCT-treated stands increased during the later period due to the increase in foliage biomass.

Further, Pettersson (1992) found differences in mortality between Scots pine and Norway spruce. For Scots pine, higher mortality was found in the densest stands considered, while for Norway spruce no clear differences in mortality were detected among stands with densities ranging from 2 500 to 6 000 stems ha$^{-1}$ (Pettersson, 1992b).

# 7. Conclusion and management implications

## 7.1 Major findings

The results indicate that total biomass yields could be substantially increased by omitting conventional PCT. The total biomass (stem including bark, branches dead and alive and foliage) yield at the end of experiment was 59% - 78% higher in the dense stands (up to in total ~ 100 DW ton ha$^{-1}$) than in the sparse PCT stands, and fertilization further increased total biomass production. However, annual fertilization was not the most cost-effective option for these Scots pine-dominated stands, since it did not raise yields more than adding fertilizer twice during the experimental period.

The highest annual increment was found in the dense stands during the early period, as an effect of stand density. During the later period, increased competition for light in the dense stands resulted in lower increments, but increases in foliage in the PCT-plots resulted in higher increments than in the early period. These observations provide indications of the relationships between leaf area index, light conditions and increments in the stands. To optimize the management of dense stands it is thus important for biofuel to be harvested before competition for resources (light) becomes too severe. Further studies should reveal appropriate time windows.

A further result was that the size distribution (arithmetic mean height and DBH, and the fractions total biomass, stem biomass and volume, biomass of branches and foliage) of the 500-2 700 largest trees did not differ between the dense and PCT stands, indicating that the larger trees in the dense stands were not affected during the experimental period by competition from the small trees, but fertilizer resulted in the largest trees becoming larger.

Regarding the estimation of total biomass in the stand, biomass functions based on sample trees from dense stands provided better estimates of total biomass than biomass functions based on sample trees from stands treated with pre-commercial thinning (Marklund, 1988). Further, since the residuals (true weights-estimated weights) were small, the constructed biomass functions should be robust for these species.

Regarding above ground allocation patterns, no significant between-treatment differences were found for Scots pine trees DBH >50 mm, and it was concluded that these trees were not affected by stand density or fertilization to the same extent as trees DBH <50 mm, for which some significant treatment-related differences were found. The smallest trees from the dense stands were significantly taller at the same DBH, had higher stem weight/total weight ratios, fewer branches (both alive and dead), less foliage and shorter crowns.

The results from the study of branch characteristics indicate that late PCT and increases in stand density reduce branch diameters, suggesting that the number of stems left after PCT affect tree size and shape more strongly than its timing. It was further concluded that the smallest trees in the stands are most strongly affected by competition and mortality. Overall, mortality was low in the studied stands and there were sufficient living, healthy trees in them to ensure adequate growth and stem numbers up to first thinning.

Based on these results it seems possible to apply a substantial biofuel harvest in dense young stands at a tree height of ca. 8-10 m. After such a harvest the goal could be to continue to manage the stands appropriately for later timber and pulp wood harvests.

## 7.2 Needs for further research

After harvesting in dense stands there might be a risk of damage by wind and snow, thus further research regarding damage after bioenergy harvests in young dense stands is required. The stands analysed in studies I, II and III were thinned in 2009, at a dominant height of 9 m and the results regarding damage over longer time periods due to snow and wind have not yet been analysed.

Further, economic aspects have not been considered in the parts of the project this thesis is based upon, but need to be addressed thoroughly, especially in relation to the timing of harvest. Issues related to harvesting technology also need to be addressed. Research and interest regarding biofuel harvest in dense forests have increased and new types of harvesting equipment have been developed for this type of harvesting in young dense forests (Bergström, 2009), but their utility and optional applications require further analysis.

The results reported here are based on analyses of Scots pine-dominated mixed forests on stands with site index 18-24 in northern Sweden, and further research is needed to identify the optimum stand density for stands with different site index, and the optimum combination of harvest, thinning and fertilization programs. Finally, effects of other combinations of tree species and stand densities need to be further analysed.

# Acknowledgements

Detta är inte resultatet av en persons arbete….!
Så många har gjort så mycket för att detta nu går i tryck! Jag vill rikta ett STORT TACK till alla som på olika sätt bidragit till detta, utan alla er hade det inte blivit vad det nu faktiskt är! Så….

…till Tomas Lundmark som drog igång projektet, och sedan hållit det vid liv! Under åren har vi även hunnit med både fisketurer och andra utflykter. Din entusiasm är verkligen smittande, heders för det! Till Kenneth Sahlén som stått ut med alla funderingar om än det ena än det andra genom åren. Martin Strand som bidragit med den växtfysiologiska biten, jag hoppas att det kan bli mer av den i framtiden! Urban Nilsson, ska han beskrivas med en mening så måste det bli hans citat ”Det här blir jättebra!” Med en positiv inställning blir allt så mycket bättre! Jag håller verkligen med! Urban Bergsten som med outtröttlig energi angriper texter. Ingen kan som Urban klura ut en figur som på ett finurligt sätt ska illustrera något! Sist men verkligen inte minst i raden av handledare, Anders Karlsson som även gett röjningen en plats inom projektet. Med en otrolig förmåga att dela sin tid även till korrekturläsning och handledning av detta projekt på ett alltid lika entusiastiskt sätt, jag är djupt tacksam!

Jag hoppas verkligen att vi även i fortsättningen kommer att diskutera skogliga frågeställningar på flygplatser på väg mot något, vid middagsbordet efter en inspirerande dag, och i skogen där verkligheten bor!

Jag vill även rikta Ett STORT TACK till….

… Svante Claesson som började inom detta ungskogsprojekt och gjort mycket arbete innan jag kom in. Förutom utlagda försök fanns redan data, biomassaprovtagningar, grenmätningar och en hög med referenslitteratur! Ingen har dock varit i ungskogen lika mycket som Ida Manfredsson. Jag vet inte hur många timmar vi har varit ute och klavat, tagit barrprover, pumpat lysimetrar, tagit vattenprover, mätt provträd, tagit biomassa, mätt grenar... Genom åren har vi dessutom hunnit varit ute ett antal dagar på andra försök och vi har även åkt tåg i både Marocko och Frankrike. Jag har lärt mig mycket av Ida genom åren, det allra första hon lärde mig var ”glöm inte att skriva dagbok, du kan aldrig skriva för mycket”. Jag har haft mycket nytta av den lärdomen!

Det är många andra som också varit med och kämpat med klave i täta ungskogar, åkt skidor med fara för liv och hälsa när man tar barrprover i tät skog och det är skarsnö, oförtröttligt kämpat på i biomassabranschen, mätt grendiametrar i -15 grader fast fingrarna håller på att trilla av, suttit och pillrat barr fast ryggar och nackar är trötta för länge sedan.... Tack för allt ni gjort inom detta projekt; Emma, Ulla, Irina, Andréas, Gunnar, Hasse, Samuel, Thomas H., Stina A. och Stina B .

Ett särskilt TACK till Ulla Nylander som med sin layouterfarenhet högst troligt förhindrade ett antal sömnlösa nätter när alla dessa bokstäver skulle anpassas till givna ramar och uppgjorda mallar! Du är verkligen helt *magisk*! Förutom det är du en riktig klippa och en sann pärla och jag ser fram mot många kommande Midsomrar och Nyårsaftnar!

Det finns några på parken som inte varit *lika* involverade inom projektet som andra, men som ändå bidragit till tillvaron i form av lunchpromenaderna med hundarna, kantarellutflykterna, alla diskussioner vid fikat, videokvällarna, fisketurer, utflykter, biobesök, middagar, alla pratstunder i skogen. KRAM till er alla som förgyllt tillvaron under dessa år!

...Och Sören Holm, som hållit kurser och *ändå* oförtröttligt förklarat statistiken, rett ut begrepp, svarat på frågor, kontrollerat beräkningar och metoder. Min rad av frågor tycks aldrig ta slut, och ju mer man vet om något, desto mer inser man hur lite man vet.... Till all personal på Skogisbiblioteket som genom åren burit böcker, sökt referenser, fixat kopior och fjärrlån, utan era insatser skulle detta inte heller ha varit vad det nu är!

En särskild KRAM till de klippor och pärlor som kommer med uppmuntrande ord och bara finns där när man behöver er! Jag ser fram mot kommande fikastunder, resor, orienteringar, bakdagar, spa-dagar, shopingdagar, loppisrundor. Raden av vänner är lång, men en särskild KRAM till Malin, Charlotta, Ingrid, Birgitta, Monica, Eva, Marie, Sophia, Tina, Helena....
..Och Mats för alla härliga dagar i skidbackarna och middagarna!

En särskild tanke till vänner och kollegor inom Hemvärnet, Staben och Röda Korset, det är verkligen toppen att ha en aktivitet som ger andra utmaningar! ...Och till vänner i Tväråbäcks Idrottsklubb, Intresseföreningen och alla grannar, oerhört stimulerande att genomföra alla lyckade projekt och aktiviteter tillsammans med positiva bybor. Det ger energi!

Till Mamma och Pappa, Bengt med familj och Ingrid med familj, Anneli och Börje; för uppmuntrande tillrop från kanten! Det betyder mer än ni kan ana!

Sist, men inte minst, Thomas som varit delaktig i allra högsta grad på olika sätt! En GULDSTJÄRNA till dig för allt!

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