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Productivity of Norway Spruce Compared to Scots Pine in the Interior of Northern Sweden

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Productivity of Norway spruce (*Picea abies* L. Karst.) and Scots pine (*Pinus sylvestris* L.) was studied in 12 paired plots in the interior of northern Sweden. Stands were established between 1928 and 1959; yield plots were established between 1974 and 1983 during pre-commercial thinning of the stands. Gross stem-wood production was significantly higher for Scots pine than for Norway spruce, stem-wood production by Norway spruce being 29.4% that of Scots pine. The site index for Norway spruce was lower than for Scots pine at all sites except one; the average difference in site index was 4.8 m. The simulated maximum mean annual increment (MAI_{max}) during the rotation was 19% higher than the MAI_{max} estimated with the site index for Scots pine, whereas simulated MAI_{max} and MAI_{max} estimated from the site index was about the same for Norway spruce. The simulations also indicated that MAI peaked about 50 years later for Norway spruce than for Scots pine. More small trees were included in the diameter distribution of Norway spruce than of Scots pine resulting in a lower stem-wood volume for Norway spruce when stands with the same dominant height were compared. This study shows that the difference in growth and rotation length between Scots pine and Norway spruce has implications when choosing which species to grow in the interior of northern Sweden.

Keywords current annual increment, mean annual increment, *Picea abies*, *Pinus sylvestris*, site index, yield
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1 Introduction

Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst.) are the two dominant tree species in Sweden. Scots pine contributes about 38.9% to the total volume of Swedish forests; the corresponding figure for Norway spruce is about 40.5% (Swedish National Forest Survey 2010). Despite their dominance, few comparisons of stem volume production by these two species have been published but several non-experimental studies have been made to quantify the productivity of pine and spruce on different site types in the north (Palo and Stejmar 1984, Elfving and Nyström 1996, Jonsson 1999, 2001, Ekö et al 2008).

Pine is classified as a pioneer species with fast initial growth while spruce is classified as a late successional species with slow initial growth (Engelmark and Hytteborn 1999). In natural stands, Scots pine establish after disturbance, such as fire or wind-throw, while Norway spruce is a late successional tree species that will continue to dominate undisturbed stands for long periods. In addition, Scots pine is regarded to have higher volume production on sites with low availability of nutrient and/or water than Norway spruce (Heiskanen and Mäkitalo 2002, Bergh et al. 2010). Since availability of nutrients is related to temperature, Scots pine grows in general faster than Norway spruce in northern Sweden while Norway spruce grows faster than Scots pine in southern Sweden. Because of the general difference in growth between the two tree species and because initial growth of Norway spruce has sometimes been found to be extremely slow in northern Sweden (Björkman 1953), Scots pine has been preferred when regenerating northern clearcuts. The proportion of Scots pine in relation to Norway spruce increase from 0.6 in southern Sweden (latitude 57ºN) to 1.6 in northern Sweden (latitude 66ºN). Also in Finland Scots pine and Norway spruce are the dominating tree species, making up over 80% of the stem volume. The volume proportion of Scots pine in relation to Norway spruce is 1.2 in southern Finland (south of latitude 64ºN) and 3.2 in northern Finland (north of latitude 64ºN) (METLA 2010).

There is a tendency for increased planting of Norway spruce in northern Sweden because improved seedlings material and regeneration practices have improved initial growth in Norway spruce plantations. (Örlander et al. 1990, Nilsson et al. 2010). In addition, growth of Norway spruce has been considered to be negatively influenced by prescribed burning (Elfving 1983, Kardell and Laestadius 1987), and since prescribed burning is now almost totally abandoned as a regeneration method, this is no longer a rationale for not choosing Norway spruce for regenerations. Lastly, inventories of browsing damage by the National Forest Inventory indicate that the proportion of trees with fresh browsing damage is on average around 10% (National Board of Forestry 2010), which is well above the 2% goal set by forest companies. Since moose hardly ever browse Norway spruce, it is understandable that forest managers prefer this tree species in regenerations. If this trend continues, Norway spruce stands will be much more common in north Swedish forests than they are today and it is therefore important to examine the effect this might have on the future production of stem volume and biomass.

In a study of temporary plots in adjacent stands of Norway spruce and Scots pine, Leijon (1979) estimated that Norway spruce had greater growth than Scots pine on sites where Norway spruce yielded 10–12 m^2 ha^{-1} $year^{-1}$, while production was equal where Norway spruce yielded 4–6 m^2 ha^{-1} $year^{-1}$. Ekö et al. (2008) used data from the National Forest Inventory to study the potential yields of Norway spruce, Scots pine and birch. They estimated ratios between tree-species using potential yield derived from site index values determined from a number of site properties. They found that Norway spruce was superior to Scots pine in southern Sweden while the two species were equally productive in the north. Palo and Steimar (1984) studied temporary plots in 45 neighboring plantations of Scots pine and Norway spruce aged between 25 and 35 years. Simulations of growth in these stands indicated Norway spruce to be less productive than Scots pine on most sites. It was only on the most fertile sites that Norway spruce yielded as much as Scots pine. Jonsson (1999, 2001) reported from two experiments located in northern Sweden (66ºN 520 m a.s.l.) and in central Sweden (60.5ºN, 70 m a.s.l.) with Scots pine and Norway spruce in pure and mixed stands. In the southern experiment, stem volume production at age 40 was 300 m^3 ha^{-1} for Scots pine and 113 m^3 ha^{-1} for Norway spruce. In the northern experiment, dominant height indicated site index (dominant height at age 100 years) 19 m for Scots pine and 15 m for Norway spruce. Briceno- Elizondo et al. (2006) simulated growth of Norway spruce and Scots pine in southern and northern Finland and found growth of Norway spruce to be higher than growth of Scots pine in both locations. Öyen and Tveite (1998) found that the potential yield of Scots pine was only 50% that of Norway spruce on 92 neighboring stands in western Norway.

Before 1970, no long-term experiments designed for comparing production in Norway spruce and Scots pine had been established in Sweden. However, in the early 1970:s, a large number of regeneration experiments from the 1950:s were identified for possible future tree-species comparisons. From these, the twelve most suitable experiments with respect to survival, area and site condition were chosen. Thereafter, paired permanent yield plots were established with the two tree-species.

In the present study, stem wood production of Norway spruce and Scots pine were compared during the first 50–70 years after planting in paired plots at 12 sites in the interior of northern Sweden. Specifically, we tested two hypotheses:

1) Scots pine is more productive than Norway spruce on poor sites, while Norway spruce grows better on rich sites
2) Comparisons of gross and net stem-wood production in Scots pine and Norway spruce need to include production that occurs late in the rotation because the mean annual increment peaks significantly later in Norway spruce than in Scots pine.

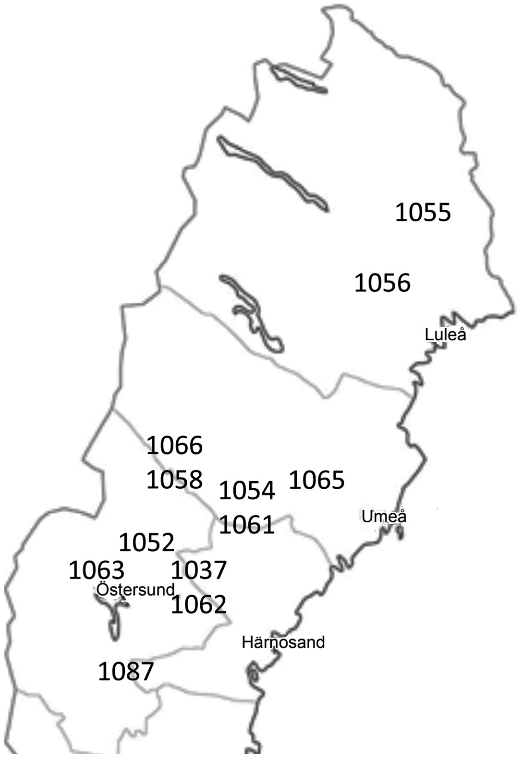

Fig. 1. Geographical locations of the experimental sites.

2 Material and Methods

Scots pine and Norway spruce yields were compared on paired plots at twelve different sites, all of which were situated between latitudes 62º43' and 66º21' and between 200 m and 470 m above sea level (Fig. 1, Table 1). Most plantations were originally regeneration experiments used to test different planting and direct-seeding methods, which used local provenances of Norway spruce and Scots pine. Before planting or direct seeding, eight of the sites were burnt in order to facilitate regeneration (Table 1). On three sites, the clearcut was not burnt before planting or direct seeding; for one site there is no record of prescribed burning. The soil-moisture class was mesic on all sites except site 1065, which was dry. At the time of planting, the ground vegetation was dominated by blueberries (*Vaccinium myrtillus*) and/or lingon berries (*Vaccinium vitis-idea*) at most sites. However, at sites 1052 and 1063 the ground vegetation was dominated by moderately nutrient-demanding herbaceous vegetation, and on site 1066 the ground vegetation was dominated by nutrient-demanding herbaceous vegetation. Temperature sum (day-degrees >5ºC) was calculated from altitude and latitude according to Odin et al (1983) and varied between 705–890 day-degrees (Table 1).

Table 1. Description of the sites at the start of the experiment.

Site	Lat	Long	Tepperature sum (Degree days)[a]	Height above sealevel (m)	Start of exp.	Prescribed burning
945/1037	63°25'	16°13'	867	350	1982	1952
1052	63°43'	15°03'	845	355	1983	No
1054	64°15'	15°15'	842	325	1980	1945
1055	66°37'	21°47'	737	290	1974	1956
1056	66°14'	20°45'	840	200	1974	1953
997/1058	64°21'	15°39'	705	470	1980	1942
1061	63°58'	16°44'	818	370	1974	1943
1062	63°25'	16°03'	782	445	1979	1950
1063	63°21'	14°14'	889	330	1980	No
1065	64°15'	15°25'	747	430	1975	1932
1066	64°23'	16°14'	713	460	1980	No
1087	62°43'	14°34'	804	465	1975	?

[a] Temperature sum Day-degrees>5°C) calculated according to Odin et al (1983)

Table 2. Description of regeneration methods and stand characteristics at the start of the experiment.

Site	Scots pine Regene-ration method [a]	Plot size (ha)	SIS[b] (m)	SIH[c] (m)	Age	Density (stems ha^{-1})	Height (m)	Basal area ($m^2 ha^{-1}$)	Norway spruce Regene-ration method[a]	Plot size (ha)	SIS[b] (m)	SIH[c] (m)	Age	Density (stems ha-1)	Height (m)	Basal area ($m^2 ha^{-1}$)
945/1037	Pl 1954	0.10	21	27.7	31	2920	11.2	32.2	Pl 1953	0.10	20	21.9	34	2460	5.6	5.2
1052	Pl 1959	0.05	23	25.8	28	2000	8.7	21.5	Pl 1959	0.06	22	21.7	28	1967	4.4	3.4
1054	Pl 1951	0.05	20	24.0	33	2023	8.9	20.0	Pl 1951	0.04	16	19.4	33	2083	4.5	3.2
1055	Pl 1959	0.07	19	24.7	18	2269	3.5	3.4	Pl 1959	0.05	15	21.6	19	2906	1.9	0.1
1056	Pl 1954	0.14	20	24.2	27	2020	4.8	8.2	Pl 1954	0.13	16	19.5	24	3109	2.5	1.3
997/1058	Pl 1944	0.10	20	25.7	39	2284	12.8	33.2	DS 1943	0.07	18	19.9	38	1875	5.0	3.4
1061	DS 1943	0.10	19	25.3	32	1500	8.9	17.0	DS 1943	0.10	18	19.3	32	2000	3.8	2.5
1062	PL 1951	0.10	19	24.6	32	1870	8.2	23.8	DS 1952	0.18	17	21.8	28	1995	4.4	4.6
1063	PL 1958	0.04	23	27.5	21	1892	6.3	11.6	PL 1958	0.07	21	25.8	23	1978	4.8	4.8
1065	DS 1943	0.14	18	22.8	33	1655	7.4	18.2	DS 1945	0.19	16	18.5	31	1934	3.2	1.4
1066	PL 1955	0.06	20	23.8	28	2037	7.8	21.6	PL 1949	0.07	21	26.3	36	2108	8.7	22.0
1087	DS 1928	0.10	20	23.6	48	1080	13.8	22.5	DS 1928	0.10	18	17.8	48	2040	6.4	8.2

[a] Pl=planting; DS=Direct seeding;
[b] Site index according to site properties
[c] Site index according to dominant height

The site indexes (dominant height at 100 years of age) were estimated in three different ways. Firstly, site index (SIH) was estimated from equations using the height of dominant trees at the last measurement (Elfving 1997, 2010). Secondly, the site index (SIS) was estimated from the site properties latitude, height above sea level, vegetation type, soil moisture class, and soil structure measured at the time of planting using functions developed by Hägglund and Lundmark (1977) and Hägglund (1979). Thirdly, a site index for Norway spruce (SICON) was estimated from the SIH of Scots pine converted with functions developed by Leijon (1979). SIH varied between 17.1 m and 25.1 m for Norway spruce, and between 19.8 m and 27.9 m for Scots pine (Table 2). The corresponding figures for SIS were 15–22 m for Norway spruce and 18–23 m for Scots pine. SIH was always higher than SIS for Scots pine. SIH was higher than SIS for Norway spruce in all except three sites. On average SIH was 3.7 m and 1.4 m higher than SIS for Scots pine and Norway spruce, respectively (Table 2). Productivity, defined as the maximum mean annual increment during the rotation (MAI_{max}) was estimated from the site index (Hägglund 1981a, b) using second-degree polynomials (Ekö et al. 2008).

Between 1974 and 1983, most of the regeneration experiments were pre-commercially thinned to about 2000 stems ha^{-1} (Table 2). The stem number varied between the Scots pine and Norway spruce plots but was, on average, 16.9% higher for Norway spruce (Table 2). When the experiment was established, square plots of variable sizes ranging from 0.044–0.14 ha, and from 0.035–0.19 ha for Scots pine and Norway spruce, respectively, were set out in the plantations. At most sites, only one plot of each tree species was established, but on sites 1056, 1062 and 1065 two plots were established for each species. However, since these were not blocked, the average values of their yields were used in the statistical analysis. Thus, the sites were considered as blocks in the statistical analysis (see below). Each plot was surrounded by a buffer zone of at least 5 m but usually in excess of 10 m.

At the beginning of the experiment, the total age of the stands varied between 18 and 48 years for Scots pine, and between 19 and 48 years for Norway spruce. On four of the sites, the total age was the same for Norway spruce and Scots pine. On the other sites, the age difference between stands of the two species was between 1 and 4 years, except for site 1066 where the Norway spruce plantation was 8 years older than the Scots pine plantation. Due to the inherent faster initial growth of Scots pine, average height and basal area was higher for Scots pine than for Norway spruce at the beginning of the experiment at all sites except site 1066 (Table 2). The mean difference in average height was 3.9 m, the difference ranging between –0.9 m and 7.8 m. Basal area was on average 14.4 m^2 ha^{-1} higher for Scots pine, the difference ranging between –0.4 and 29.8 m^2 ha^{-1}.

The diameter at breast height (DBH), (130 cm above ground), was recorded for all trees at the start of the experiment and thereafter at irregular intervals of between 5 and 10 years. The diameter was measured with calipers to the nearest mm, in two directions at 90º to each other. The position and orientation of the calipers on the stem was permanently marked to ensure that it did not vary between measurement occasions. At the same time, tree species, status (retained, missing, wind-felled) and physical damage were recorded (see Nilsson et al. (2010) for description of damage types). Additional measurements were done on sample trees. At least 15 representative sample trees were systematically selected and five sample trees were randomly selected among the 100 trees ha^{-1} with largest diameter. For the sample trees, tree height (H) and height to the living crown (HL) were recorded. In addition, the thickness of the bark was recorded in the Scots pine plantations. The height and crown-heights were measured to an accuracy of about ± 0.1–0.2 m; thickness of the bark was recorded with an accuracy of about ± 0.1 mm. Separate sample trees were selected among the 100 trees with largest diameter.

Stem-volume of sample trees were calculated with functions developed by Brandel (1990) using as independent variables diameter at breast height (DBH), height (H) and height to the first living branch (HL) for Norway spruce; and DBH, H, HL and thickness of the bark for Scots pine. Thereafter, the volumes of all callipered trees were estimated by assigning volume to their respective DBH-class, which were grouped in 2 cm intervals. The weighted volume of a sample tree within a 2 cm diameter-class was then assigned to a callipered tree within the same diameter class. The volume of sample trees within a DBH-class was weighted by DBH_{cs}/DBH_{ss}, where DBH_{cs} was the average squared diameter of callipered trees within a diameter class, and DBH_{ss} was the corresponding average diameter of all sample trees. The system for assigning volume to callipered trees is thoroughly described in Nilsson et al. (2010).

Because total age sometimes varied between the tree species within a site, the total volume production at the final measurement for tree species of the same age was estimated by adding the product of the current annual increment during the last measurement period, and the difference in age, to the total production of the younger tree species.

The dominant height (H_{dom}) for each plot was estimated on each measurement occasion by the height-curve given by Näslund (1936):

$$H = DBH^x / (a + bDBH)^x + 1.3$$

Where H = tree height (m); DBH = diameter at breast height; a and b are coefficients; and x has the value of 2 for Scots pine and 3 for Norway spruce (Pettersson 1955). Thereafter, the H_{dom} was estimated from the height function, as the height corresponding to the arithmetic mean height of the 100 trees/ha with greatest DBH.

Volume is reported as gross- and net volume production until each measurement occasion. In net volume production, the volumes of self-thinned trees, missing trees and wind-felled trees are subtracted from gross-volume production.

Diameter distributions at the same H_{dom} were compared by selecting seven sites where inventories were taken at similar measures of H_{dom} (Table 3). Thereafter, the diameter distributions of each site and tree species were divided into ten diameter-classes of similar size. Thus, the first diameter-class consisted of trees with a diameter corresponding to 0–10% of the diameter of the thickest tree; the second, diameters corresponding to 10–20% of the thickest tree; and so on. The relative frequency of trees in each diameter-class was calculated as the ratio between the number of trees in a specific diameter class and the total

Table 3. Sites and revisions selected for the analysis of diameter distribution.

Site	Scots pine		Norway spruce	
	H_{dom}	Age	H_{dom}	Age
1054	12.1	39	12.1	62
1055	12.0	41	12.0	54
1058	14.1	39	13.6	67
1062	12.1	40	13.3	58
1063	15.6	40	15.3	52
1065	11.2	43	11.9	65
1087	14.7	48	14.7	82

number of trees on the plot. Finally, the average relative frequency for all seven sites was calculated for each diameter-class and tree species.

The MAI_{max} was estimated by simulating growth with a growth model (Ekö 1985). Data from the last inventory (stem-number, basal area, site index and total age) were used as the initial state in the simulations. The simulations continued until the MAI reached its maximum value. If the basal area in the simulations went above 45 m^2 ha^{-1}, a thinning was done in order to avoid self-thinning which is not well estimated in the model. In the thinning, 10% of the basal area was removed and thinning was done among the smallest trees in the tree-list.

Statistical tests were performed with the SAS general linear model (SAS/STAT™ user´s guide 1998) using the following specific model:

$$Y_{ij} = m + A_i + B_j + e_{ij}$$

where A_i = effects of site (block) and B_j = effect of tree species. Differences between tree species were evaluated using LSD mean separation tests following analysis of variance ($p < 0.05$).

3 Results

Total net- and gross stem volume production at the last measurement were significantly larger for Scots pine than for Norway spruce ($p < 0.0001$ for both net and gross volume production) (Fig. 2). On average, total net volume production of Norway spruce was 33.2% of the total net-volume production of Scots pine. The corresponding figure

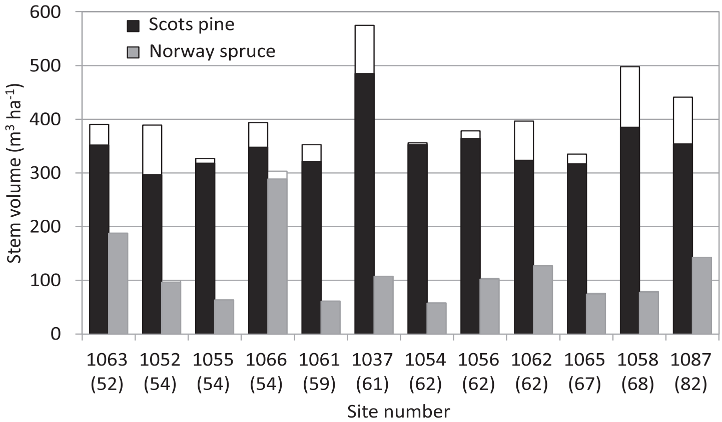

Fig. 2. Total production at the time of the last measurement for Scots pine and Norway spruce plots on twelve sites in the interior of northern Sweden. The whole bars indicate gross stem-wood production; the dark parts of the bars indicate net stem-wood production excluding self-thinning. Total age at the time of the last measurement is indicated in brackets below the site number.

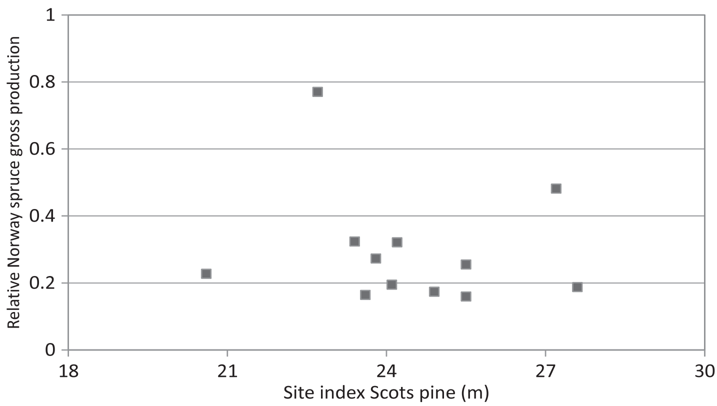

Fig. 3. Relative Norway spruce production (the ratio of gross stem-wood production at last measurement in Norway spruce and Scots pine) relative to the Scots pine site index (m).

for gross-volume production was 29.4%. Of the twelve sites, only one (1066) gave similar net- and gross stem volume production for Norway spruce and Scots pine. Mortality was low for the Norway spruce plantations; significant mortality (4.9%) was recorded at only one site (1066) (Fig. 2). In contrast, mortality was higher than 3.6% in all except one Scots pine plantation, and maximum mortality was 22.6% of total production.

There was no correlation between site index for Scots pine and relative Norway spruce gross volume production (ratio between gross volume production of Norway spruce and Scots pine) (Fig. 3). The correlation coefficient between SI of Scots pine and relative Norway spruce gross volume production was –0.14 ($p = 0.67$).

The site index (SIH) at the last measurement was, on average, 2.8 m lower for Norway spruce than for Scots pine (Fig. 4). The absolute difference in SIH between the tree species was not correlated to SIH for Scots pine. Estimated SICON for Norway spruce (conversion function using

Table 4. Site indexes (SIH) estimated with H_{dom}, maximal mean annual increment (MAI_{max}) estimated from SIH and the simulated MAI_{max} for Scots pine and Norway spruce plantations on the twelve sites, and the average values for all sites.

Site	Scots pine Site index (m)	MAI_{max} estimated from SI	Current MAI	Current age	Simul-ated MAI_{max}	Age at simulated MAI_{max}	Norway spruce Site index (m)	MAI_{max} estimated from SI	Current MAI	Current age	Simul-ated MAI_{max}	Age at simulated MAI_{max}
945/1037	27.7	7.6	9.3	58	9.6	73	21.9	5.1	1.8	61	4.8	146
1052	25.8	6.6	7.2	54	7.9	69	21.7	5.6	1.8	54	5.1	124
1054	24.0	5.8	5.7	62	6.5	87	19.4	4.4	0.9	62	3.6	167
1055	24.7	6.1	6.0	53	7.2	83	21.6	5.0	1.2	54	4.5	154
1056	24.2	5.9	6.1	62	6.7	82	19.5	4.5	1.6	59	4.6	164
997/1058	25.7	6.6	7.3	68	7.7	78	19.9	4.6	1.1	67	3.5	182
1061	25.3	6.4	6.0	59	6.8	79	19.3	4.4	1.0	59	3.6	189
1062	24.6	6.1	6.4	62	7.0	77	21.8	5.1	1.9	58	4.8	148
1063	27.5	7.5	7.3	50	8.4	75	25.8	7.0	3.6	52	6.4	107
1065	22.8	5.3	5.0	67	5.7	92	18.5	4.2	1.1	65	3.5	170
1066	23.8	5.7	6.5	46	7.8	71	26.3	7.2	7.0	65	7.6	90
1087	23.6	5.6	5.4	82	5.7	92	17.8	4.0	1.7	82	4.0	162
All	25.0	6.3	6.5	60	7.2	80	21.1	5.1	2.1	62	4.7	150

MAI = mean annual increment; MAI_{max} = maximum MAI during the rotation
Current MAI and age = MAI and age at last measurement

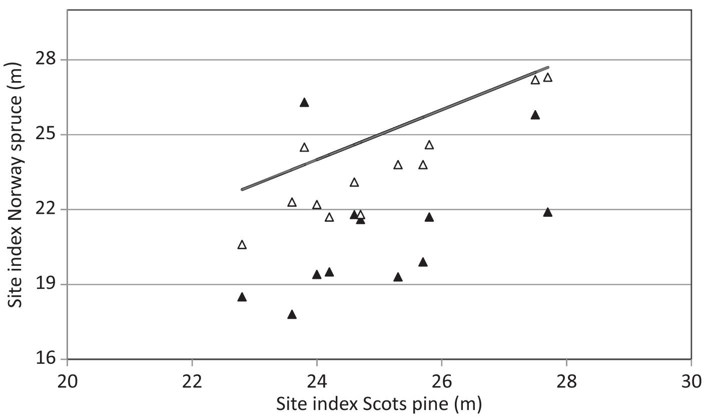

Fig. 4. The site indexes for Norway spruce estimated from the dominant height (SIH) at the last measurement (filled triangles), and by functions converting the site index for Scots pine to site index for Norway spruce (open triangles), in relation to the site index (SIH) for Scots pine (solid line).

SIH for Scots pine) was higher than SIH. On average, SIH was 2.45 m lower than SICON.

The MAI_{max} estimated from SIH was almost 23% higher for Scots pine than for Norway spruce (Table 4). MAI at the last inventory was more than three times as high for Scots pine as for Norway spruce, and simulated MAI_{max} was more than 50% higher for Scots pine. In six of the twelve sites, the MAIs at the time of the last measurement were higher than the MAI_{max} values estimated with the site index for Scots pine. For Scots pine, the simulated MAI_{max} was higher than the MAI_{max} estimated from the site index in all sites, and the average simulated MAI_{max} was 16% higher than the MAI_{max} estimated from the site index. For Norway spruce, the current MAI was never higher than the MAI_{max}, and the simulated MAI_{max} was higher than the MAI_{max} estimated from the site

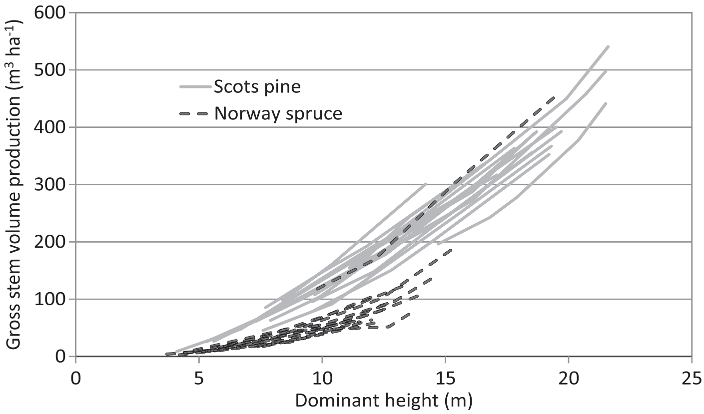

Fig. 5. Gross stem-wood production ($m^3\ ha^{-1}$) for Scots pine and Norway spruce plots, plotted against dominant height (m).

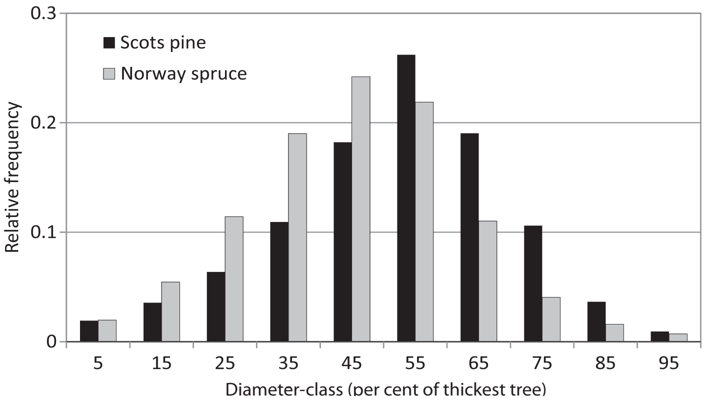

Fig. 6. Average diameter distribution of trees in seven Scots pine and Norway spruce sites. Diameters are classed as percentages of the thickest tree on the plot. Thus, the first diameter-class contains trees with a diameter smaller than 10% of the thickest tree, etc.

index for two sites (Table 4). On average, the simulated MAI_{max} was 8% lower than the MAI_{max} estimated from the site index. The average age for MAI_{max} was 82 years for Scots pine and 150 years for Norway spruce. Because of the longer rotations, the average simulated period of growth was longer for Norway spruce (88 years) than for Scots pine (20 years) (Table 4).

Total gross stem volume production at a specific H_{dom} was lower for Norway spruce than for Scots pine for all sites except one (1066) (Fig. 5). A polynomial regression function was fitted to the Scots pine and Norway spruce gross stem wood productions with H_{dom} as the independent variable. For Norway spruce, data from site 1066 were excluded since it was an obvious outlier. The regression functions indicated that total production at a H_{dom} of 5 m were 18.9 $m^3\ ha^{-1}$ and 9.5 $m^3\ ha^{-1}$ for Scots pine and Norway spruce, respectively. At a H_{dom} of 12 m the corresponding values were 164.1 $m^3\ ha^{-1}$ and 80.8 $m^3\ ha^{-1}$.

The relative frequency of trees was higher for Norway spruce in diameter-classes up to 50% of the diameter of the thickest tree (Fig. 6). In larger diameter-classes, Scots pine had the higher relative frequency. For Norway spruce, 39.2% of the trees had a diameter exceeding 50% of the thickest tree. The corresponding number for

Scots pine was 60.4%. Skewness of the Norway spruce diameter distribution was significantly higher (0.1597) than for Scots pine (–0.3184) (p = 0.0084). Skewness deviated significantly from zero both for Scots pine and Norway spruce, indicating that the Norway spruce distribution was skewed to the left while the Scots pine distribution was slightly skewed to the right.

4 Discussion

The hypothesis that the yields of Norway spruce and Scots pine are similar on sites with medium fertility, and that the yield of Norway spruce exceeds that of Scots pine on rich sites, was not supported by data from this study. On all sites except one, Scots pine had superior growth compared to Norway spruce, both in terms of the yield measured at the latest inventory, and the simulated MAI_{max}. The only site where Norway spruce and Scots pine yields were similar, differed from other sites with respect to ground vegetation, namely site 1066, which had a high growing, nutrient-demanding herbaceous vegetation, while the ground vegetation on most other sites was dominated by blueberries and lingonberries indicating a lower availability of nutrients. That Norway spruce grows better than Scots pine on fertile sites has been found in other studies (Leijon 1979, Öyen and Tveite 1998, Ekö et al. 2008). However, the present study does not confirm previous findings of Leijon (1979) and Ekö et al. (2008) with regard to yield comparisons on poor and moderately fertile sites in northern Sweden whereas results presented by Jonsson (1999, 2001) and Nyqvist (2000) were in line with the findings presented in this study.

The simulations presented in this study do support the second hypothesis that the MAI peaks significantly later for Norway spruce than for Scots pine. On average, the MAI in Norway spruce peaked 70 years later than it did for Scots pine; consequently, the yield of Norway spruce will be significantly underestimated relative to Scots pine if they are compared when the MAI for Scots pine peaks, or if yields are compared in the middle of the rotation. Because the MAI for Norway spruce increases during the final 30–40 years at a slow rate, and because the standing volume is high, the long rotations indicated in Table 4 are probably not economically motivated. Thus, in operational forestry, Norway spruce will probably be harvested long before its MAI peaks. Furthermore, the longer simulation period for Norway spruce probably resulted in less accurate estimates of MAI than for Scots pine.

The yield of Norway spruce in relation to Scots pine was much lower in this study compared to that reported in other published work (Leijon 1979, Öyen and Tveite 1998, Briceno-Elizondo et al. 2006, Ekö et al. 2008). This might be explained by several factors. Firstly, the site index for Norway spruce was lower than would have been expected if the site index for Scots pine were converted to the site index for Norway spruce. Therefore, it might be expected that the comparison of productivity using the site index, as performed by Ekö et al. (2008), would give a relatively higher productivity for Norway spruce than we found in the present study. The functions used to convert the site index for Scots pine, into the site index for Norway spruce, was developed by Leijon (1979), using temporary plots in adjacent stands. The conversion functions were estimated for the whole of Sweden and it is likely that the material available from the interior of northern Sweden was relatively small, since very few Norway spruce stands had been established in that region up until the 1980s (Elfving and Nyström 1996). It may also be difficult to assess age in natural regenerations of Norway spruce (Elfving and Nyström 1996).

The second reason for the unexpectedly high yield of Scots pine in relation to Norway spruce is that the measured Scots pine yield and the simulated MAI_{max} were higher than when MAI_{max} was estimated from the site index, while the simulated MAI_{max} of Norway spruce was marginally lower than expected from the MAI_{max} values estimated from the site index. The functions for estimating MAI_{max} from the site index were derived from the same growth model as was used in this study in the simulations of MAI_{max} (Hägglund 1981b, Ekö 1985). The different results must therefore originate from differences in starting values. The stands in this study originated from homogeneous, planted or direct-seeded regenerations, while Hägglund (1981b) used initial states from the national forest inventory, which may have included more heterogeneous stands with slower initial development.

Scots pine stands were more productive than Norway spruce stands when compared at the same H_{dom}. One reason for this is that the diameter distributions in the Norway spruce and Scots pine stands were different. In the Scots pine stands most of the trees had a diameter that exceeded 50% of the thickest tree, while in the Norway spruce stands most trees had diameters that were less than 50% of the thickest trees' diameters. The Norway spruce stands in this study also had a lower stem volume at a specific H_{dom} than did Norway spruce stands in southern Finland and in southern Sweden. Cao et al. (2006) reported an average basal area of 26.5 m^2 ha^{-1} at an average dominant height of 13.3 m for eight planted Norway spruce stands in southern Finland, Nilsson et al. (2010) found an average basal area of 33.5 m^2 ha^{-1} at Hdom of 14.3 m for 13 Norway spruce plantations in southern and central Sweden and Albaugh et al. (2009) measured 31 m^2 ha^{-1} at H_{dom} of 15 m in a Norway spruce plantation in south-central Sweden. All three examples are much higher than for most of the sites in the present study. The large difference in yield at a specific H_{dom}, both when comparing Scots pine and Norway spruce in northern Sweden, and when comparing Norway spruce in northern Sweden with southern Finland and Sweden, may partly be due to differences in seedling establishment. The establishment of Norway spruce seedlings in this study was slow, their average height being about 1.5 m at a total age of 15 years (data not shown). Faster seedling establishment might reduce the amount of variation between individual tree sizes and increase the yield at a given H_{dom}. Better seedling material and more intensive scarification methods would probably ensure faster seedling establishment (Örlander et al. 1990, Örlander et al. 1998) and it is therefore possible that the yield of Norway spruce in the present study underestimates what might be expected if modern regeneration methods were to be used.

Prescribed burning has been shown to have negative effects for Norway spruce development (Elfving 1983, Kardell and Laestadius 1987). The only site in this study where the yield of Norway spruce was similar to Scots pine was on one that was not burned. However, at least two other sites were not burnt before regeneration, and on these there was no indication of any improvement in the yield of Norway spruce relative to Scots pine. Nyqvist (2000) reported no clear effect of prescribed burning from two experiments in northern and central Sweden to compare biomass production of Norway spruce and Scots pine 16 years after planting. Data from the present study can therefore neither confirm nor reject the hypothesis that prescribed burning negatively influences Norway spruce yield. However, together with other studies, this study does indicate that prescribed burning might have a minor effect on long-term yield.

Bergh et al. (1999) studied Norway spruce production after intensive fertilization of a stand in northern Sweden. The yield of the unfertilized plots in that study was similar to the yield of several of the Norway spruce plots in this study. However, fertilization did dramatically increase stem-wood production. After eight years of annual fertilization, the current annual increments increased by more than 300% in the fertilized plots. This fertilization study indicates that the growth of Norway spruce in northern Sweden is not restricted by climatic factors, but that nutrient availability is a more important factor. We therefore hypothesize that the poor growth of Norway spruce in the present study can be partly explained by a lower availability of nutrients and that it should be possible to increase the yield of Norway spruce in this area either by fertilization, or by the appropriate manipulation of sites to make nutrients more available to the Norway spruce trees.

Ideally tree species comparisons should be done in experiments designed for this purpose with e.g. randomized block design. However, no such experiments were laid out in Sweden before 1970 and it is therefore not possible to compare long-term growth of Scots pine and Norway spruce in the interior of northern Sweden in statistically correct experiments. This study used data from an experiment where tree species comparisons was created by pre-commercial thinning in regeneration studies from the 1950:s where both Norway spruce and Scots pine were represented. Thus, the assignment of tree species to plots was not done by random. However, this shortcoming of the present study is probably of minor importance. Since comparisons were made on 12 different sites and since there is no reason to believe that Norway spruce was systematically planted on plots with lower fertility, eventual differences in fertility between plots was probably not important for the results obtained in this study.

In conclusion, this study has shown that Norway spruce in the interior northern Sweden undergoes significantly less growth than Scots pine over a wide range of sites that vary in their level of fertility. Data from this study indicate that, from a production point of view, Norway spruce should only be planted on the most fertile sites that have a high availability of nutrients and water. Alternatively, Norway spruce productivity may be enhanced by intensive fertilization. However, the stands in this study were established with old seedling material and mostly without scarification. It is possible that using modern seedling types and undertaking good scarification of sites at the time of planting may improve the yield of Norway spruce. The discrepancy between the site index estimated with H_{dom} and the site index estimated by converting the site index for Scots pine may lead to a sub-optimal choice of tree species and a possible loss of future production. Similarly, the discrepancy between the maximum MAI for Scots pine calculated with functions and simulations may lead to wrong decisions being made when choosing tree species for regenerations. It is therefore important that the validation of conversion functions and functions for estimating maximum MAI and their eventual adjustment should be prioritized in future research.

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