Potential production of Norway spruce in Sweden

Johan Bergha,*, Sune Lindera, Johan Bergströmb

aSouthern Swedish Forest Research Centre, Swedish University of Agricultural Sciences,
P.O. Box 49, SE-230 53 Alnarp, Sweden
bForest Research Institute of Sweden, Uppsala Science Park, SE-751 83 Uppsala, Sweden

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Abstract

In this paper, the potential stem wood production for Norway spruce was estimated for different regions in Sweden. This was done by using basic physiological relationships of intercepted radiation versus biomass production and knowledge of how a water deficit reduces the potential production, derived from results of field experiments on nutrient optimisation. To scale these relationships up to regional and national levels, data of incident radiation and humidity during the growing season for all of Sweden were used. The figures for potential and attainable production indicate that the temperate to boreal climate allows considerably higher production than the current production, if availability of water and nutrients is non-limiting. In northern Sweden, the attainable production is ca. 300% higher than the current production and in southern Sweden, the yield can be increased by ca. 100%. In absolute numbers, as a mean for a whole rotation period, it is possible to achieve an annual stem-wood dry mass production of 7–9 Mg ha⁻¹ in southern and central and ca. 5–6 Mg in northern Sweden. This increased production would mean that rotation periods can be shorter than they are now by 20–30 years in southern Sweden and by ca. 50–60 years in northern Sweden.

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1. Introduction

A common assumption is that the climate in the northern temperate and boreal region is too harsh and the evergreen coniferous forests too slow-growing to allow high rates of forest production. However, this is not entirely true, since photosynthesis during the growing season is as effective and the amount of assimilated carbon per day and unit leaf area are of the same order of magnitude as for fast-growing tree species at more southerly latitudes. The main differences are the length of the growing season (Bergh et al., 1998, 1999) and the nutrient constraints in the soil (Tamm, 1991).

The beginning and end of the photosynthetically active season closely corresponds to the beginning and end of the growing season, defined as the period when mean air temperature is persistently above +5 °C. Gas
exchange experiments conducted in Sweden and Finland (Pelkonen, 1980; Pelkonen and Hari, 1980; Linder and Lohammar, 1981; Troeng and Linder, 1982) showed that more than 90% of the annual carbon gain occurs during the growing season. It is, therefore not surprising that carbon gain and biomass production is strongly related to absorbed light during the photosynthetically active period. Monteith (1977) showed this relationship 25 years ago for various agricultural crops. This strong relationship has been followed up by numerous comparisons between absorbed light and forest production (Jarvis and Leverenz, 1983; Linder, 1985; Cannell, 1989; McMurtrie et al., 1994; Bergh et al., 1999).

The boreal and cold temperate forest is almost without exception limited by nutrients, primarily nitrogen (Tamm et al., 1999), but the balance between nitrogen and other nutrients can also play an important role (Tamm, 1991; Linder, 1995). Fertilisation in young forest stands greatly influences the amount of foliage produced (Linder and Axelsson, 1982; Vose and Allen, 1988; Colbert et al., 1990; Gholz et al., 1991; Albaugh et al., 1998). Increasing the leaf area has a direct effect upon the amount of incoming radiation intercepted in a stand (Linder, 1987; McMurtrie et al., 1994; Sampson and Allen, 1999). An additional effect is that fertilised stands convert more of the absorbed energy into stem wood than do unfertilised stands (Linder and Axelsson, 1982; Axelsson and Axelsson, 1986; Bergh et al., 1999).

It has also been shown that photosynthesis is 10–20% higher per unit leaf area in shoots from fertilised trees of Norway spruce (Roberntz and Stockfors, 1998; Bergh and Linder, 1999).

Young stands of Norway spruce in Sweden, to which a complete nutrient mixture is applied annually, after 12 years of fertilisation show an increase in stem wood production of more than 100% in southern Sweden and of ca. 400% in northern Sweden, compared with unfertilised control stands (Bergh et al., 1999). In these experiments, water was also supplied during summer to keep the soil water content close to field capacity. Water had no or little effect on the production in northern Sweden, but lack of water reduced the stem wood production in southern Sweden by 15–35% (Bergh et al., 1999). These experiments illustrate that potential production lies far above the actual production in Sweden. The actual mean production for a whole rotation period, in m$^3$ ha$^{-1}$ a$^{-1}$, is shown in Fig. 1.

In this paper, we have used tree physiological relationships between climate and biomass production of Norway spruce, based on results from fertilisation experiments, to predict the potential production for...
different regions in Sweden. For scaling up the relationships to regional and national level, we used climate data of incoming radiation and humidity over the whole of Sweden from SMHI (Swedish Institute of Hydrology and Meteorology), and specialised programmes for geographical information, ARC/INFO and ArcView GIS.

2. Materials and methods

2.1. Site description

The Flakaliden experiment (64°07′N, 19°27′E, 310–320 m a.s.l.) was laid out in 1986 in a Norway spruce (Picea abies (L.) Karst.) stand, planted in 1963 with 4-year-old seedlings of Norway spruce of a local provenance, after clear-felling, prescribed burning and soil scarification. According to a classification scheme, based on site properties (Hägglund and Lundmark, 1977), mean annual increment (MAI) was estimated to 3.2 m³ ha⁻¹ a⁻¹. The soil is a podzolic sandy glacial till and the site conditions are typical for the northern region of Sweden. Two nutrient optimisation treatments were included. The first treatment (IL) was a complete nutrient solution, which was injected into the irrigation water and supplied during the growing season (June to mid August). The second treatment (F) was a solid fertiliser mix, which was applied in early June each year. Controls (C) and plots with irrigation (I) were also included. The Flakaliden site has a boreal climate: monthly mean air temperature at the site varies from −8.7 °C in February to 14.4 °C in July, and snow usually covers the frozen ground from mid October to early May. Mean annual precipitation is approximately 600 mm, of which more than one-third falls as snow. For further details regarding the treatments, measurements of growth, climate and site conditions see Linder (1995) and Bergh et al. (1999).

The Asa experiment (57°08′N, 14°45′E, 225–250 m a.s.l.) is treated more extensively than the main experiment at Flakaliden, with half the number of plots. The site was planted in 1975, after clear-felling and soil scarification, with 2-year-old rooted seedlings of Norway spruce. MAI for Norway spruce was estimated as 10.8 m³ ha⁻¹ a⁻¹ (Hägglund and Lundmark, 1977). The initial production capacity for the Asa experiment is somewhat higher than the normal yield for this region. Asa has a milder climate than Flakaliden and the growing season is more than 2 months longer, 190 days compared to 120 days at Flakaliden. The higher daily rates of incident radiation at Asa, together with the longer growing season, results in 40% more total incident radiation during the growing season. In addition, the mean temperature during the growing season is higher for Asa, 11.5 °C compared to 10.2 °C at Flakaliden. Mean annual precipitation is ca. 700 mm, but is frequently low in early summer.

2.2. Estimates of leaf area and amount of absorbed radiation

The estimates of leaf area in the stands are based on biomass harvests, on three occasions at 5-year intervals, together with in situ measurements of leaf area for each plot. Annual values of leaf area were estimated from regressions derived from the biomass harvest and measurements of diameter and leaf area for all the different plots (Flower-Ellis, personal communication; Albough, personal communication; Stenberg, personal communication). The amount of incident PAR, photosynthetically active radiation (400–700 nm), during the growing season each year was calculated from measured values from Flakaliden and Asa. The amount of absorbed radiation was estimated by Lambert-Beer’s law (Monsi and Saeki, 1953) and an extinction coefficient of 0.5 was used for the stands (Stenberg et al., 1995).

3. Results

The stem volume production was more than 350% higher (Fig. 2a) for the fertilised treatments (IL and F) compared with the unfertilised treatments (I and C) at Flakaliden. There was no effect of water, since there is no difference between the irrigated (I) and control (C) treatment or between IL and F. At Asa the production of the IL-treatment was more than double that of the unfertilised treatment (Fig. 2b). In contrast to Flakaliden, the effect of water was clear and was statistically significant (Bergh et al., 1999). This effect varies from year-to-year, depending to a large extent on the humidity balance in the growing season and on soil water relations.
The response of production to the irrigated and liquid-fertilised treatment can be regarded as the potential yield under the prevailing climate conditions at Flakaliden and Asa, when nutrients and water are not limiting factors. A strong linear relationship \( R^2 = 0.978, \ p = 0.0031; **P < 0.01 \) between absorbed radiation and annual production of stem volume and dry mass (Fig. 3) could, therefore, be derived for the irrigated and liquid fertilised treatment. To estimate the amount of PAR (Fig. 6a) from incoming radiation data from SMHI, we assumed that 50% of the incoming radiation was PAR (Cannell, 1989). Differences in PAR between northern and southern Sweden are mainly a result of the considerably longer growing season in southern Sweden.

The difference between IL and F indicates the loss of potential production caused by a water deficit for closed and highly productive stands at Flakaliden and Asa. A relationship has been derived between the relative production loss \(((\text{IL} - \text{F})/\text{IL}) \times 100)\) caused by a water deficit and humidity during the growing season (Fig. 4). Data for humidity are derived from measurements of precipitation and evaporation of water made by SMHI in Vindeln (25 km from Flakaliden) and in Växjö (50 km from Asa). Water storage in the soil profile and as snow-cover at the beginning of the growing season is included in the humidity calculation. Humidity is defined as the difference between precipitation and evaporation of water. This relationship is significant \( R^2 = 0.915, \ p = 0.015; *P < 0.05 \) and useful for estimating the loss of potential production as an effect of an insufficient amount of water during the growing season.

The maximum current annual increment (CAI) of stem wood is usually achieved shortly after canopy closure and is illustrated in Fig. 5. The IL treatments at Flakaliden and Asa are probably at this stage, when the IL treatments seem to have reached a stable level of production. From yield tables of Norway spruce (Eriksson, 1976; Elfving, personal communication) and forest inventory data in Sweden, our experience is that it is necessary to multiply maximum CAI by 0.65
in order to get an approximate estimate of MAI for a whole rotation period (Fig. 5).

The strong linear relationship between stem wood production and the amount of radiation absorbed during the growing season is shown in Fig. 3. Data for the amount of incoming radiation during the growing season, in different regions in Sweden (Fig. 6a), have been used to calculate the equivalent maximum CAI in other parts of Sweden. In order to obtain the MAI for a rotation period, maximum CAI has been multiplied by 0.65. Fig. 6b illustrates the result of these calculations, which shows MAI of a Norway spruce stand per rotation period, when there is an optimal availability of nutrients and water. The production potential expressed as MAI is ca. 22–24 m³ ha⁻¹ a⁻¹ in southern Sweden, 16–20 in central Sweden and 8–14 in northern Sweden.

In northern Sweden, water availability in summer does not usually limit production, since precipitation normally exceeds evaporation and there is a good supply of soil water from the snowmelt at the beginning of the growing season. However, this is not true of southern Sweden, especially in the east (Fig. 6c), where the low availability of water in summer markedly decreases the potential production. Using the relationship in Fig. 4, together with humidity data from SMHI (Eriksson, 1985), we calculated the effect of a deficit of water on the potential production of Norway spruce. The definitive map of production shown in Fig. 6d is the result. This shows the production potential of spruce with optimum nutrient supply but with insufficient precipitation. It is apparent from Fig. 6d that the largest production is achieved in the southwest (22–24 m³ ha⁻¹ a⁻¹) and in central Sweden (16–20 m³ ha⁻¹ a⁻¹). The production potential for a solid fertiliser (Fig. 6d) in northern Sweden was no different from the potential production shown in Fig. 6b, since there is normally a surplus of water.

The length of the rotation period is closely related to the growth rate, so that enhanced growth should enable the rotation period of the stand to be shortened considerably. A stand in northern Sweden with a MAI of 3.2 m³ ha⁻¹ a⁻¹ is currently felled after ca. 130 years, whereas a stand with a MAI of 10.8 m³ ha⁻¹ a⁻¹ in southern Sweden is felled after 75–90 years. If MAI were to increase according to Fig. 6d, the rotation period could be shortened considerably. It is known that MAI during a rotation period is closely related to the length of the rotation period. Using production tables for Norway spruce in Sweden (Eriksson, 1976), in which both MAI and rotation length are available, a relationship can be derived (Fig. 7). To get the extreme production levels (MAI > 17 m³ ha⁻¹ a⁻¹) attainable in southern and central Sweden, we used data from Great Britain for Sitka spruce (Hamilton and Christie, 1971). The rotation length could be reduced by approximately

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**Fig. 4.** Relationship between humidity during the growing season and relative loss of potential production at Flakaliden (squares) and Asa (circles) during 1995–2000 ($R^2 = 0.915$, $p = 0.018$; *$P < 0.05$). Relative loss is defined here as the difference between IL- and F-treatment (($IL - F)/IL$) × 100. Data for humidity originate from measurements of precipitation and evaporation of water by SMHI in Vindeln (25 km from Flakaliden) and Växjö (50 km from Asa). Humidity is defined here as the difference between precipitation and evaporation of water.

**Fig. 5.** The course of current annual increment, CAI (solid line), and mean annual increment, MAI (dashed line), during a rotation period. For further explanations see text.
Fig. 6. (a) Amount of PAR in GJ m$^{-2}$ during the growing season ($> +5\, ^{\circ}\text{C}$). Red circles show the location of Asa and Flakaliden. (b) Potential production of stem volume in m$^3$ ha$^{-1}$ a$^{-1}$ in stands of Norway spruce with optimum nutrition and water supply. The values are the mean annual increment (MAI) for a rotation period. Red circles show the location of Asa and Flakaliden. (c) Humidity in millimetres of water during the growing season ($> +5\, ^{\circ}\text{C}$). Humidity defined here as the difference between precipitation and evaporation of water (SMHI, 1985). Red circles show the location of Asa and Flakaliden. (d) The attainable stem volume production in m$^3$ ha$^{-1}$ a$^{-1}$ in stands of Norway spruce with a solid fertiliser. The values are the mean annual increment (MAI) for a rotation period. Red circles show the location of Flakaliden and Asa.
By using basic physiological relationships and by generalising results from field experiments we have been able to estimate the potential production of stem wood for different regions in Sweden when nutrient and water are not limiting. However, it is not practically or economically feasible to fulfill the requirement for water in forestry in areas of insufficient precipitation. We took, therefore the precipitation into account in order to calculate the ‘‘attainable’’ production potential for Norway spruce. The attainable production was estimated as 16–24 m$^3$ ha$^{-1}$ a$^{-1}$ in southern and central Sweden and as 8–14 m$^3$ in northern Sweden. This can be compared with the actual production of 7–10 m$^3$ ha$^{-1}$ a$^{-1}$ in southern Sweden and 2–5 m$^3$ in the north (Fig. 1). The difference between the attainable and actual production is largest in central and northern regions, where water availability is normally sufficient and the effect of adding nutrients is large because of the relatively poor soil-nutrient availability. Water plays an important role in southern Sweden, especially in the southeast, where the low availability of water (Fig. 6c) markedly decreases the attainable production potential (compare Fig. 6b and d). However, the attainable production is ca. 100% higher than the actual production. The production potential is given in m$^3$ but for biofuel purposes and the paper and pulp industry, it is more convenient to use dry mass production. A basic wood density of ca. 0.34 (mg m$^{-3}$), derived from measurements of basic wood density at Flakaliden and Asa (Mäkinen et al., 2002; Lundgren, 2003), can be used to convert the potential and attainable production (Fig. 6b and d) to dry mass production. A dry mass production of 7–9 Mg ha$^{-1}$ a$^{-1}$ in southern and central Sweden and ca. 5–6 mg in northern Sweden can be achieved. If treetops and branches are included, these numbers will increase by a further 30–40% (Flower-Ellis, 1993, 1996). The length of the rotation period is closely related to production capacity but the rotation length also depends on silvicultural methods, especially thinning strategy. If there are no or few thinning the rotation period will be shorter. Short rotation periods will improve present value calculations and the economy considerably.

The potential production in Fig. 6b is based on a very strong relationship (Fig. 3), which is supported by several earlier studies of intercepted radiation versus biomass production, while incoming radiation is measured at 14 different locations in Sweden. These measurements are then extrapolated to a large number of locations over the whole of Sweden by using measurements of cloudiness and amount of sunshine hours during the growing season. The extrapolation might lead to estimates of incoming radiation, which are biased to some extent. Forest stands growing on steep north-facing slopes receive less radiation during the growing season. These stands are, therefore not able to intercept the same amount of radiation and achieve the same level of production. An extinction coefficient ($k$) of 0.5, which has been measured at Flakaliden (Stenberg et al., 1995), is used for both Flakaliden and Asa for all 6 years. Measurements of $k$ for the last 5 years indicate a lower $k$-value of 0.47 (Stenberg, personal communication) and this might lead to biased estimation of APAR but only to a minor extent. The photosynthetically active season begins earlier in spring than the actual growing season. Photosynthesis and the absorption of PAR prior to the beginning of the growing season, therefore gives an underestimated value for absorbed PAR, according to the relationship in Fig. 3. At the same time, however,
the photosynthetic apparatus is not fully recovered and does not operate at full capacity at the beginning of the growing season. This means that the conversion of APAR to production is overestimated (Fig. 3).

The relationship between water availability and reduction in potential production (Fig. 4) is relatively strong, but there are data (outliers) that indicate that there must be explanations, in addition to the humidity balance for the growing season. Precipitation in early summer is probably more important than that in late August and September, when the aboveground growth has ceased. This seems to be evident for 1 year at Asa, when more than half of the precipitation during the growing season occurred in September–October. If rain falls in small amounts (0–3 mm) on several occasions, most of the precipitation is intercepted and evaporated by a dense stand (Cienciala et al., 1994). This can influence the soil water availability and the relationship in Fig. 4. It is also known that sandy soils with low water-holding capacity have reduced growth potential (Moering and Ralston, 1967; Cregg et al., 1988). It is debatable whether results from only four different locations can be applied to the whole of Sweden, even though they are based on strong relationships and the best climate data available. Different soil types, soil texture, moisture conditions, soil depths, extreme weather conditions and other influencing environmental factors might increase or decrease the potential and attainable production. The estimates in Fig. 6b and d, should therefore, be used with caution.

The forest land in Sweden, accounts for more than half of the total land area. If you consider the possible restrictions to intensive forestry, such as environmental aspects, location and soil characteristics, the estimated area of land suitable for intensive forestry is reduced to 54.4–65.1% of the total forest land (Table 1). If you use the economic criterion that intensive forestry should give additional production of more than 8 m$^3$ ha$^{-1}$ a$^{-1}$ of stem-wood, as a mean for a rotation period, this area is reduced to 52–53% in central and northern Sweden and to 10.5% in southern Sweden (Table 1). On a practical scale and short-term perspective, it is unlikely that intensive forestry would constitute more than 10% of the total forest land.

5. Conclusions

The figures for potential and attainable production presented in this paper suggest that the northern temperate and boreal climate allows much higher production than that currently achieved in Sweden. Using a complete solid fertiliser mix, it is possible to increase the current production by approximately 100% in southern Sweden and by 300% in the north. Water is generally not a limiting factor for production in northern and central Sweden, but the water deficit during the growing season reduces the potential production in southern Sweden, especially in the south-eastern part. The increased production would result in considerably shortened rotation periods.

There are numerous indications of future shortages of raw wood and fibre material from forests. There is a general belief that there will be an increase in the requirement for raw material by the forest industry and that the demand for sustainable sources of energy will also increase, both nationally and internationally. At the same time, there is an expectation that the supply of forest raw materials will decline as a result of certification of forestry and the requirement by the community for multiple use and protection of forest land. The forest industry must meet these demands and consider all environmental aspects at the same time as maintaining a high level of felling and cost-effective production. One way of satisfying all the demands

<table>
<thead>
<tr>
<th>Total amount of forest land</th>
<th>Suitable area for intensive forestry</th>
<th>Area with an additional production more than 8 m$^3$ ha$^{-1}$ a$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N. Sweden (&gt;63°N)</td>
<td>108940 (100%)</td>
<td>70913 (65.1%)</td>
</tr>
<tr>
<td>C. Sweden (59–63°N)</td>
<td>64130 (100%)</td>
<td>39449 (61.5%)</td>
</tr>
<tr>
<td>S. Sweden (&lt;59°N)</td>
<td>53290 (100%)</td>
<td>28972 (54.4%)</td>
</tr>
</tbody>
</table>
made on the forest by the community would be to introduce new and more intensive systems of production, with short rotation periods, on a limited amount of the land. If intensive forestry were to be applied only to monocultures of Norway spruce or to agricultural land, no environmental values would be jeopardised. Intensive forestry could also provide opportunities to set aside more forest land for biological diversity, cultural environment and recreation and outdoor life Andersson (2002).

References


Monsi, M., Saeki, T., 1953. u


