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The effects of shelterwood density and site preparation on natural regeneration of *Fagus sylvatica* in southern Sweden

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Abstract

The natural regeneration of beech (*Fagus sylvatica*) was studied under various shelterwood densities and soil preparations in a 130-year-old beech stand in southern Sweden. Between 1990 and 1996, seedling emergence, survival, growth and damage were followed in a clear-cut and in two shelterwoods with different densities, in plots with undisturbed ground, bare mineral soil or ridges with mineral soil on top of humus. Irradiation, soil and air temperatures, soil moisture and precipitation were continuously recorded during the first three growing seasons. The seedling emergence was higher in the shelterwoods than in the clear-cut. The mortality was the highest during the first year. The seedling number was the highest on bare mineral soil and the lowest on undisturbed ground, for all cutting regimes. The increase in seedling height and dry mass was greater in the clear-cut and in the sparse shelterwood than in the dense shelterwood. Damage due to frost was more frequent in the clear-cut than in the shelterwoods. Effects of most kind of damage had only minor influence on the seedling height, whereas in seedlings experiencing frequent damage height was reduced.

Keywords: *Fagus sylvatica*; Natural regeneration; Shelterwood; Site preparation; Seedling survival; Growth; Damage

1. Introduction

Beech forests in Sweden are mainly established through natural regeneration. The most common method was introduced from Germany (Burschel et al., 1964) and Denmark (Möller, 1965) and adapted to Swedish conditions (Bjerregaard and Carbonnier, 1979). According to this method, beechnuts from one mast year are used for regeneration. Soil preparation and tree shelter are important tools to control the outcome of the method. Although this is the most common method used in Sweden, the results are not always satisfactory. To improve the method, we need more knowledge of how shelterwood density combined with soil preparation affected seedling emergence, survival and growth.

By changing the shelterwood density the light climate is greatly influenced, which may affect the performance of the seedlings and the outcome of the regeneration. Thus, germination in beechnuts is favored by increased light intensity (Savoi et al., 1988) and at high light levels; more seedlings survive during the first months after emergence (Suner and Röhrig, 1980; Oosterbaan and van Tol, 1984; Savoi et al., 1988). Increased light levels also result in more leaves, thicker leaves, more branches and higher dry weight of the shoot (Watt, 1923; Burschel and Schmaltz, 1965). Plant height normally increases up to a certain light

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level (Watt, 1923; Savoi et al., 1988), and then level out or decline when the light is increased further (Burschel and Huss, 1964).

A shelterwood reduces the risk of frost (Blennow, 1998). Two hours of exposure to −4 to −5 °C is usually sufficient to kill the root of a germinating beechnut (Watt, 1923; Brown, 1960). During bud-break, seedlings may be damaged or killed by frost, and the effect of frost is more serious if the frost event is followed by full morning light (Bourne, 1945).

The competition for water from the shelterwood may reduce germination and seedling growth. Similarly, excess of water reduces the percentage of germinating beechnuts (Brown, 1960; Levy et al., 1986; Savoi et al., 1988). However, water excess may be prevented by reducing the water table through a shelterwood, thus affecting germination and seedling growth positively.

Competition for water and nutrients from ground vegetation affect survival and seedling growth negatively but this effect may be reduced through scarification (Prévost, 1992; Madsen, 1995). When beechnuts germinate on compacted soil, the root may fail to penetrate the soil surface or the seedling may form a stunted root system in the compacted soil (Harley, 1939; Becker, 1983) and the seedlings may die from desiccation (Harley, 1939; Bourne, 1945; Brown, 1960). Through scarification, soil compaction is reduced and the seedling development hence improved.

The rate of seedling emergence can often be improved by covering the beechnuts with mineral soil. This method may prevent predation on the beechnuts (Huss and Burschel, 1972), reduce the risk of frost damage and facilitate germination due to good contact between the germinating seed and the soil (Watt, 1923; leTacon and Malphettes, 1974). However, germination is delayed or inhibited if the beechnuts are covered by a compacted soil (Watt, 1923; Bourne, 1945; Hildebrand, 1983).

Biotic factors often affect the outcome in natural regeneration of beech. Thus fungi, insects, slugs and smaller rodents may harm or kill young seedlings (Watt, 1923; Brown, 1960). The influences of some biotic factors are found to interact with light and soil water conditions. Under wet conditions, Phytophtora have been shown to reduce seedling number considerably (Savoi et al., 1988). Under low light or drought, insect attacks may be more harmful to the seedlings (Watt, 1923; Brown, 1960; leTacon and Malphettes, 1974).

Thus, much information is available on natural regeneration of beech but from different sources. This may make it difficult to assess the importance of the various factors under similar conditions. Our goal was to follow a natural regeneration of beech for several years and repeatedly measure the effects of abiotic and biotic factors on the performance of the seedlings.

Our hypotheses were: (1) beech seedling survival is favored by a shelterwood, (2) dry weight and height of the seedlings increases with decreasing shelter density, (3) site preparation increases the rate of seedling emergence, survival and growth, (4) covering the beech nuts with soil increases the rate of seedling emergence, and (5) damage to seedlings reduce survival and growth of the seedlings.

To test the hypothesis we have studied: (a) the effects of shelterwood density on number of emerged seedlings, seedling survival, growth and frost damage to the seedlings (1, 2), (b) the effects of site preparation on seedling emergence, survival and growth (3), and (c) the effects on seedling emergence of covering the beechnuts with soil (4). To explain the effects of shelterwood density, we have also recorded irradiance, air- and ground temperature and soil moister content. In addition, we have recorded frequency, range and course of damage to the seedlings (5).

2. Material and methods

The study was carried out in the Skarhult experimental forest (55°50′08″N, 13°24′28″E, 105 m a.s.l.) in southern Sweden in a 130-year-old beech stand. Site index (dominant height at 100 years total age) was approximately 28 m. This is an average value for beech forests in Sweden indicating a mean annual increment of about 6.5 m^3 ha^{-1} per year (Carbonnier, 1971). The area was flat and the soil texture was fine, which resulted in an occasional rise of the water table.

The experimental site was divided into a clear-cut, a sparse and a dense shelterwood. The cutting regimes were not replicated. The total size of the experiment was 120 × 150 m or 1.62 ha (in the shape of a parallelogram). In order to reduce the risk of wind-throw, the clear-cut was placed at one end of the experimental site, followed by the sparse and the dense shelterwood. In the sparse shelterwood, the number of stems per hectare was 54, and basal area 14.9 $m^2\ ha^{-1}$ and in the dense shelter wood corresponding figures were 106 and 22.8 $m^2\ ha^{-1}$. Each cutting regime was divided into 10 areas of 12 × 50 m. In the shelters and in the clear-cut, scarification and scarification with moulding were randomly assigned to four areas each, while two areas were left undisturbed.

Scarification was carried out in the beginning of October 1989 with a disc trencher. The disc trencher was adjusted to create a large proportion of bare mineral soil. In December 1989, the ground was manually covered with soil (moulding) using rakes. Cutting was done at the end of March 1990. The logs were transported with a skidder, which caused compaction of the ground, especially in the clear-cut (Table 1, logging damage). In May 1990, the experimental site was fenced with a wire net (approx. 2 m) to keep out large herbivores. The fence was supplemented with a rabbit net in the spring 1991.

The beechnuts that fell after scarification were collected in two litter traps (0.25 m^2) in each area (20 traps per cutting regime). The nuts were counted every second week until they stopped falling at the end of December. Prior to scarification, an average of 134 beechnuts per square meter had fallen to the ground. After scarification, another 222 beechnuts per square meter fell to the ground in the clear-cut, 268 in the sparse shelterwood and 306 in the dense shelterwood.

The number of beech seedlings was recorded 18 times (1990–1996, cf. Fig. 4) in 10 plots in a line traversing diagonally through each area (100 plots per cutting regime). Seedlings from different mast years were counted separately until 1994. Two permanent sticks defined the plot positions. During each count, the plots were delimited by a frame (0.63 × 1.07 m) oriented by the sticks. The frame was divided into 3 × 5 labelled cells (0.045 m^2), and the number of seedlings within each cell was recorded. By using the frame, it was possible to identify and follow individual seedlings during the entire experimental period. At the first inventory in May 1990, the seedbed type in each cell was classified either as mineral soil (disc trench with all humus removed), or berm (mineral soil on inverted humus) or undisturbed ground. Cells subjected to logging damage, and cells where stumps, stones etc. prevented germination, were omitted from the calculations.

Seedling damage and cause of damage were recorded at each inventory. If the leaf lamina was partly missing, this was regarded as an insect injury. If a lateral shoot or the stem had been cut off, this was referred to as attacks by mammals. Leaves with yellow or brown spots were referred to as being damaged by fungi. Shrivelled or brownish leaves were considered to have been damaged by frost. Dry seedlings or seedlings that had lost leaves without any obvious reason were referred to the category non-specified damage. Damage was recorded if the disturbance was estimated to be more than 10% of the total leaf area. Only the damage that caused the largest reduction in leaf area was recorded for each seedling, at each inventory.

At the last inventory every year, the height was recorded for the seedling situated farthest to the northeast in every cell. The height was defined as the length from the ground to the top of the longest shoot. Seedling biomass was recorded from a random sample of 30 seedlings from each of the three cutting regimes.

Table 1
Number of cells with different site preparations, or damaged by logging, or omitted from the recordings due to obstacles

	No. of cells		
	Clear-cut	Sparse shelter	Dense shelter
Mineral soil	130	171	286
Berms (mixture of mineral soil and humus)	225	510	524
No ground preparation	274	420	645
Number of cells used to calculate mean for blocks	629	1101	1455
Logging damage	854	391	20
No measurements (e.g. stone, stump, path, lost markers)	17	8	25
Total	1500	1500	1500

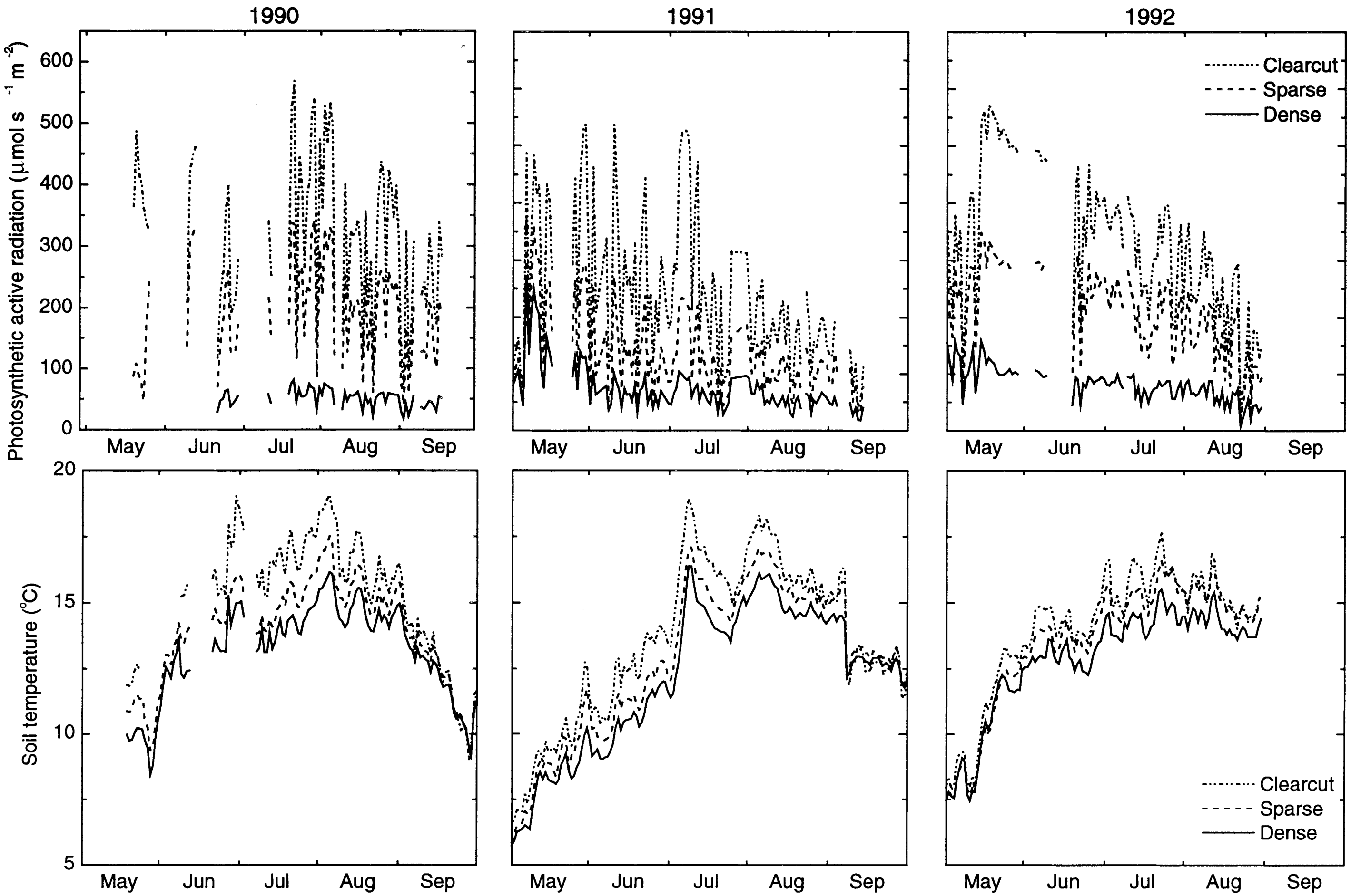

Fig. 1. Influence of shelterwood density on photosynthetic active radiation (top), and soil temperature (bottom) during the first 3 years of the experiment.

The seedlings were carefully excavated and plant height, leaf numbers and dry mass of leaves, stem and root were measured. Sampling was made at the end of the growing seasons of 1990–1992.

Additional studies of seedling mortality, damage and height growth were performed on five circular plots ($r = 1$ m) laid out on locations with high seedling density in each of the three cutting regimes. Twenty-five seedlings were labelled in each plot. The cause of damage was registered during the vegetation period, i.e. 10 times during 1990, six times during 1991, four times during 1992, three times during 1993, and twice yearly from 1994 to 1996. In addition to the above damage causes, seedlings standing in water were registered as waterlogged. The degree of damage was registered as slight (10–49% of the total leaf area damaged) or severe (more than 50% of the total leaf area damaged). The seedling height was measured in the beginning of October each year.

Soil temperatures were measured (cf. Fig. 1) 10 cm below ground on five locations in each of the three cutting regimes (Cu–Co thermocouples $\varnothing = 0.2$ mm). At the same locations, the following factors were measured: Air temperature 0.25 and 1.7 m above the ground (Cu–Co thermocouples $\varnothing = 0.05$ mm), as well as photosynthetic active radiation (Gallium phosphide photodiodes, 5 mm diameter, Model g1125-02, Hamamatsu Photonics K.K. Japan). The photodiodes were individually calibrated against quantum sensors (Model Li190SA, LiCor Inc. Lincoln, NE, USA) under natural light, before and after each growing season. The amount of precipitation was recorded with a rain gauge (Environmental Measurements Ltd., UK) placed in the clear-cut. During 1990 and 1991, the soil water potential was measured (gypsum blocks, Soil Moisture Inc. USA) 10 cm below the ground in three locations in the clear-cut and in six locations in the two shelterwoods. In 1992, measurements of the soil water potentials were made in eight locations in the clear-cut and in 12 locations in the two shelterwoods. All instruments except the gypsum blocks were connected to a Campbell CR10 datalogger (Cambell Scientific Inc.). Measurements were made each minute and average values were stored each day—except precipitation, which was summed up every day. The soil water potentials were measured weekly.

The number of seedlings per square meter was calculated for each seedbed type. A weighted mean (based on Table 1) was used to calculate the total number of seedlings in the three cutting regimes. The weights were proportional to the mean frequency of each seedbed type, i.e. 0.185 (mineral soil), 0.395 (berms) and 0.420 (undisturbed ground). Seedlings in cells with logging damage were excluded from this calculation. The proportion of plots (0.63×1.07 m) without seedlings was calculated as mean values for all areas with the same site preparation treatment and as a total for each cutting regime.

As the measurements were performed in a systematic sample of clusters (cells in a plot), the observations within one cluster could be correlated. To see if this was the case, the variance of the average seedling number for different seedbed types was compared both between cells within one plot and between plots with the same number of cells. The variance was found to differ depending on the number of cells, but not in a systematic pattern. Thus, t-tests for significance, which assume random sampling and independent observations, were used. Pooled variances were used to calculate p-values for the comparison of differences between mean values in seedling numbers and seedling heights. If not otherwise mentioned, the largest p-values for inventories during the study period are given in the text. Results of covering the nuts with soil were only compared for the inventories of the first summer (1990).

3. Results

The amount of photosynthetically active radiation (PAR) that reached the forest floor was lower in the two shelterwoods than in the clear-cut (Fig. 1). After the shelter trees had come into leaves, the percentage of PAR was 12–19% in the dense shelterwood and 43–49% in the sparse shelterwood, in relation to the PAR in the clear-cut. The daily mean air temperature was similar in the three cutting regimes (data not shown). During 1990, the average soil temperature was 1.1 °C higher in the clear-cut than in the sparse shelterwood, and 1.9 °C higher than in the dense shelterwood (Fig. 1). The differences between the clear-cut and the shelterwoods gradually decreased over the next two growing seasons. During 1992, the

Table 2
Minimum temperatures below zero and duration of below-zero temperatures for the various shelterwood densities during three frost events in May 1991

Date	Clear-cut		Sparse shelterwood		Dense shelterwood	
	Minimum temperature (°C)	Duration (h)	Minimum temperature (°C)	Duration (h)	Minimum temperature (°C)	Duration (h)
7-5-1991	−2.51	4	−0.13	2	0.31	0
9-5-1991	−2.26	7	−1.70	4	0.13	0
10-5-1991	−0.94	1	−0.05	1	1.36	0

average soil temperature in the clear-cut was 0.5 and 1.1 °C higher than in the sparse and dense shelterwoods, respectively. Frost events were recorded for three nights in May 1991. Frost occurred during all three nights in the clear-cut with a minimum temperature of −2.5 °C, and during one night in the sparse shelterwood with a minimum temperature of –1.6 °C. No frost was recorded in the dense shelterwood (Table 2).

After periods of drought, the soil water potential decreased below −0.1 MPa in August 1990 and in September 1991 (Fig. 2). During these periods, the drought was most severe in the sparse shelterwood. During the growing season of 1992, severe drought was registered in all three cutting regimes (Fig. 2).

The number of newly emerged seedlings was significantly ($p < 0.0001$) lower in the clear-cut than in the shelterwoods at the first inventory, on 2 May 1990 (Fig. 3). At that time, 1.6% of the beechnuts had formed seedlings in the clear-cut, 3.2% in the sparse shelterwood and 3.0% in the dense shelterwood. At the beginning of August 1990, the number of seedlings was still significantly ($p < 0.0001$) lower in the clear-cut than in the shelterwoods. The same situation was found at all inventories during the seven growing seasons. The number of seedlings decreased gradually over the growing seasons. The mast year in 1992 added new seedlings to the shelterwoods as first recorded in 1993 (Fig. 3). However, only 15 and 6% of the seedlings that emerged in 1993 were still alive in October 1996 in the sparse and the dense shelterwoods, respectively.

In the mineral soil, the number of seedlings was significantly higher than in the other seedbed types, in all cutting regimes and at all inventories (clear-cut $p < 0.001$, sparse shelter $p < 0.025$, dense shelter $p < 0.025$) (Fig. 4). Furthermore, the number of seedlings was significantly higher on berm than in undisturbed ground in the two shelterwoods ($p < 0.005$ and 0.00003 for sparse and dense shelter respectively), but not in the clear-cut.

The covering of beechnuts with soil significantly ($p < 0.004$) increased number of seedlings on average for the two shelterwood densities. The number of seedling was 159,300 (rel. se. 7%) for covered beechnuts and 120,700 (rel. se. 7%) for non-covered, in October 1990. However, the effect was not consistent. In the shelterwoods, covering increased the seedling number significantly ($p < 0.01$) in berms with 36 and 51% for spare- and dense-shelters, respectively. But there was only a small non-significant ($p > 0.25$) effect on seedling number in mineral soil from the soil cover. In the clear-cut, the soil cover had large (−50%) but non-significant ($p > 0.25$) negative effect.

The proportion of plots without seedlings was higher in the clear-cut than in the shelterwoods (Table 3). Moreover, the areas with untreated soil in the two shelterwoods had a higher number of plots without seedlings than scarified areas. The soil cover on the beechnuts did not effect the percentage of plots without seedlings.

On average, seedlings in the dense shelterwood were significantly ($p < 0.025$) shorter than seedlings in the clear-cut and in the sparse shelterwood during all inventories (Fig. 5). Seedlings in the sparse shelterwood were significantly ($p < 0.005$) taller than seedlings in the clear-cut in 1992 and 1994, but of similar height in 1996 (Fig. 5). There was no significant difference in height between seedlings in the various seedbed types (data not shown).

The dry mass of leaves, stem and roots was the smallest in seedlings from the dense shelterwood (Fig. 6) in all 3 years. This difference between shelterwoods increased with time. No difference was found

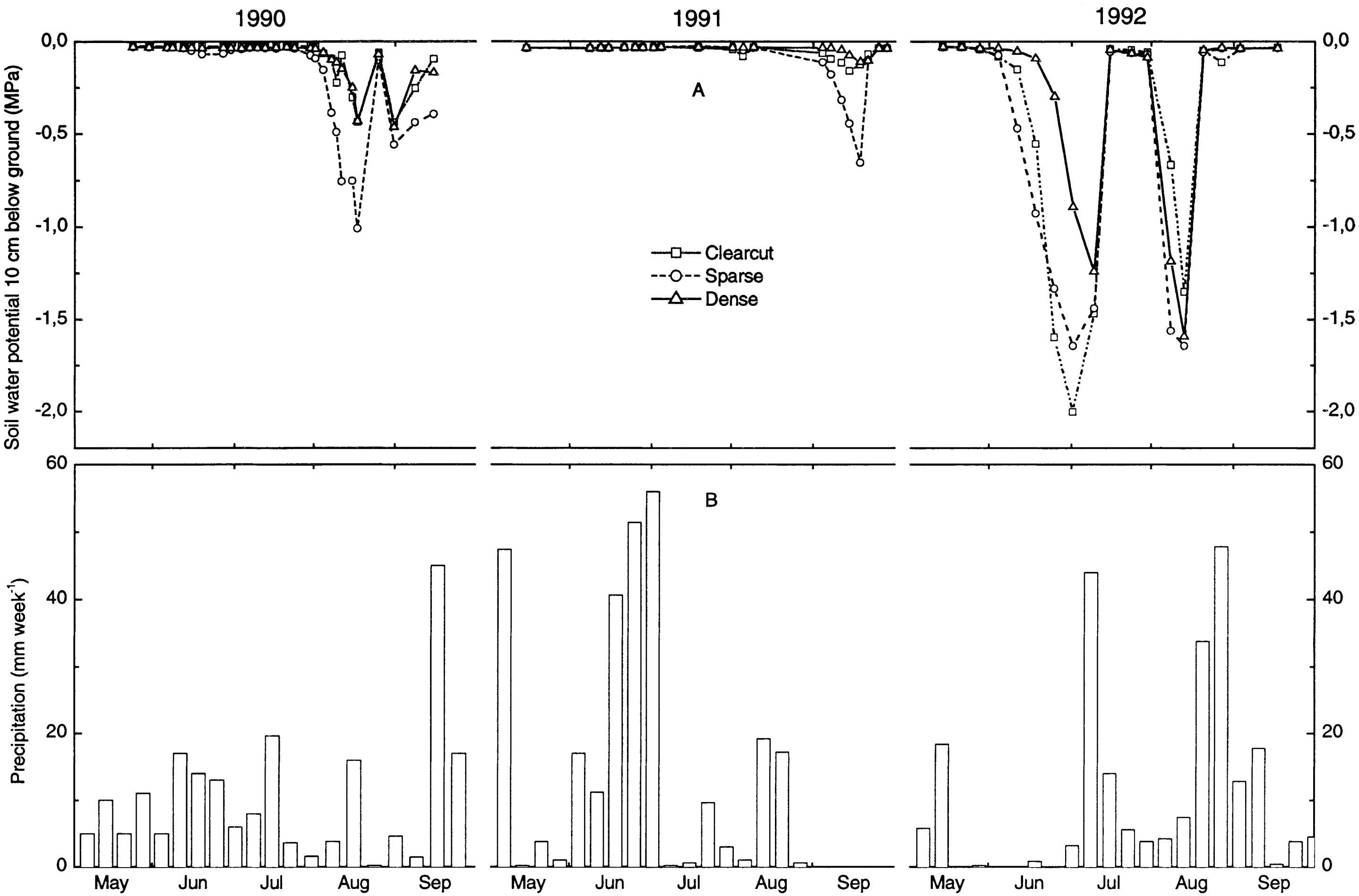

Fig. 2. Influence of shelterwood density on soil water potential (top) and precipitation (bottom) in the clear-cut during the first 3 years of the experiment.

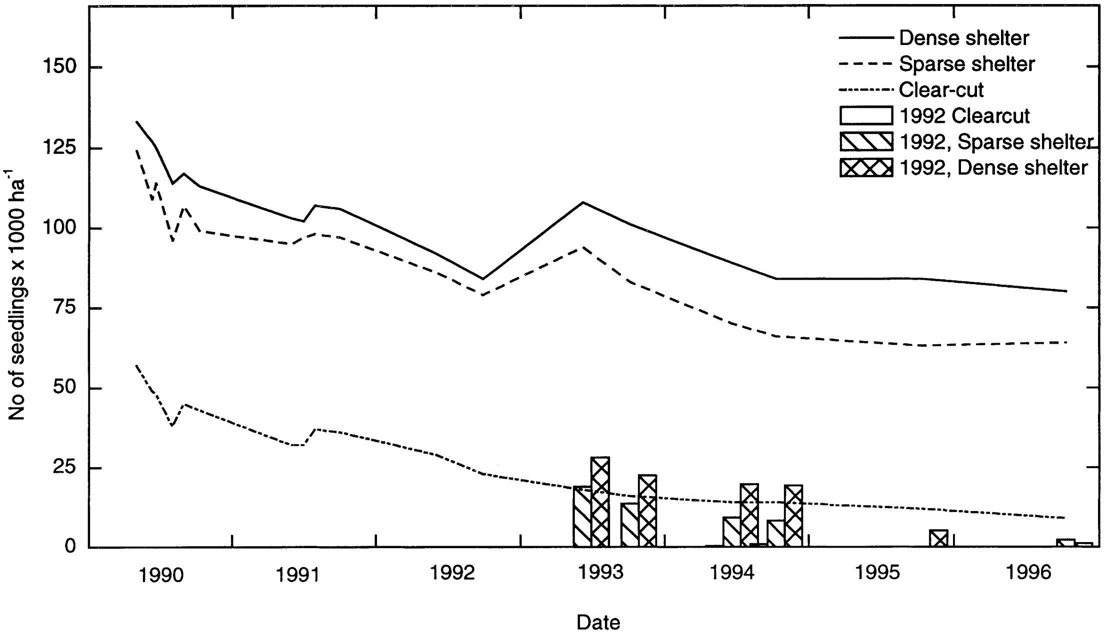

Fig. 3. Changes in the mean number of seedlings in the clear-cut, the sparse and dense shelterwoods in the period 1990–1996. Seedling numbers originating from the mast year of 1992 are indicated by vertical bars.

between seedlings in the clear-cut and the sparse shelterwood. The root/shoot dry mass ratio showed no consistent change with shelterwood density.

The frequency of damaged seedlings was higher in the additional damage study than in the systematic sample, but the overall trends were similar. Therefore, the description below refers to the damage study only.

On most occasions, damaged seedlings were more common in the clear-cut than in the shelterwoods (Fig. 7). During some inventories, a majority of all seedlings were classified as damaged. A total of eight out of 375 seedlings were undamaged during the first two summers. The most common damage was a reduction in leaf area caused by insects (Fig. 7). Severe fungi damage was mainly found in the autumns. In the summer of 1991 and 1994, frost was a common cause of damage in the clear-cut. Browsing by small herbivores was most common in the clear-cut. The proportion of seedlings that were browsed by small herbivores increased during the study period (Fig. 7). In the cases when the cause of death was identified, browsing and water logging were found to be the most common agents.

In most cases, any slight damage had only a minor influence on seedling height. If a slight damage occurred on more than ten occasions height was reduced from in average 200–150 mm or 25% (1992). However, a severe damage (more than 50% of the leaf area) reduced the height with 25–50% depending on number of occasions.

Table 3
Frequency of plots without beech seedlings at the inventory on 8 October 1996 (%)[a]

	Total (10)	Scarification (4)	Scarification + moulding (4)	No preparation (2)
Clear-cut	79	68	88	85
Sparse shelter	39	35	30	65
Dense shelter	41	35	30	75

[a] Number of surveyed areas are shown within brackets.

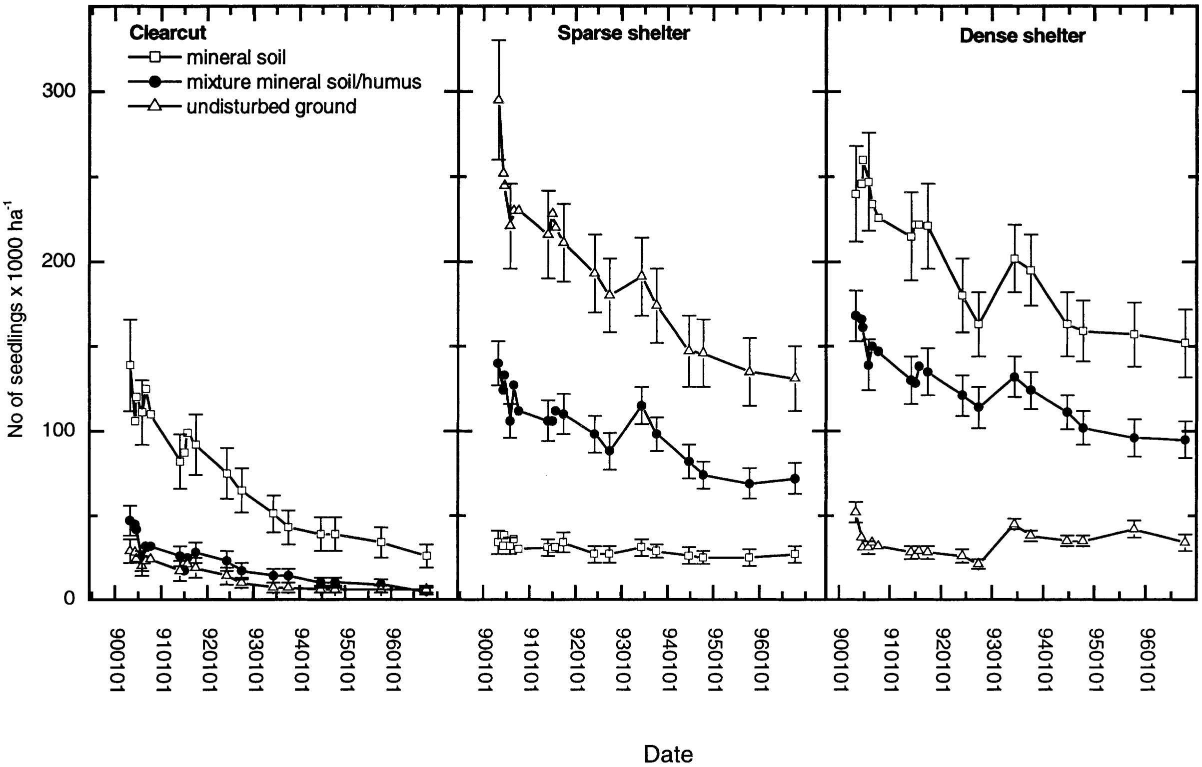

Fig. 4. Changes in the mean number of seedlings on undisturbed ground, mineral soil and berms in the clear-cut, the sparse and the dense shelterwoods in the period 1990–1996. The figure includes seedlings originating from the 1992 mast year. Standard errors of the means are indicated by vertical bars.

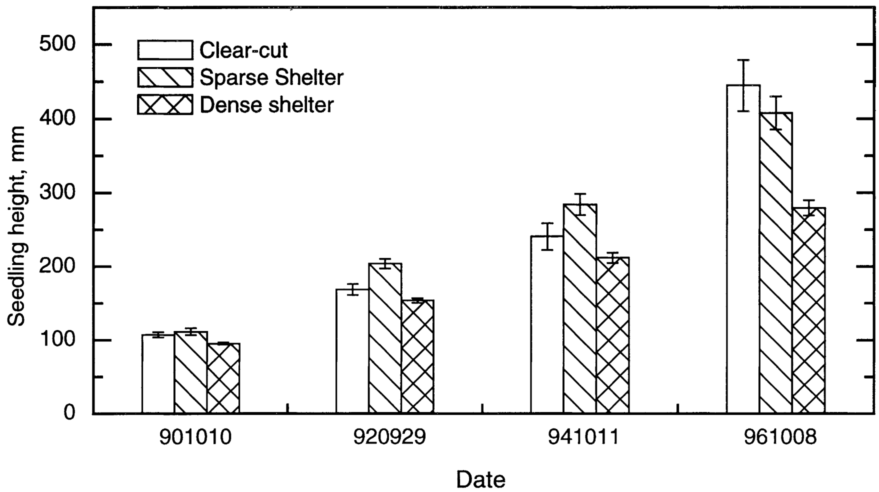

Fig. 5. Average height at the end of the growing seasons of 1990, 1992, 1994 and 1996. For seedlings from the clear-cut and the sparse and dense shelterwoods. Only seedlings originating from the mast year of 1989 are included. Standard errors of the means are indicated by vertical bars.

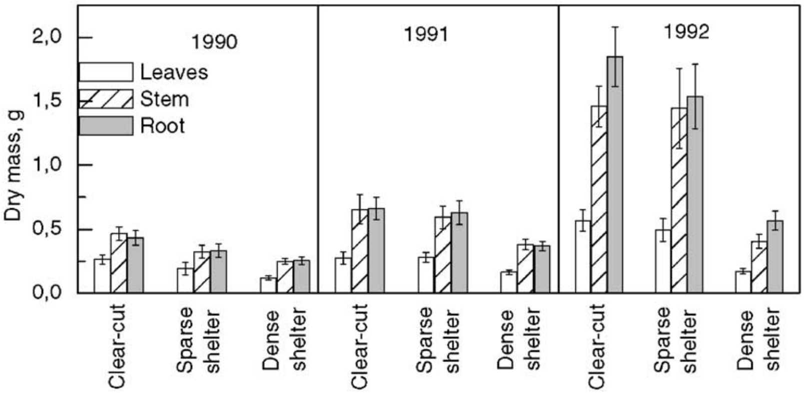

Fig. 6. Influence of shelterwood density on dry mass increase in leaves, stem and root during the first 3 years after seedling emergence. Standard errors of the means are indicated by vertical bars.

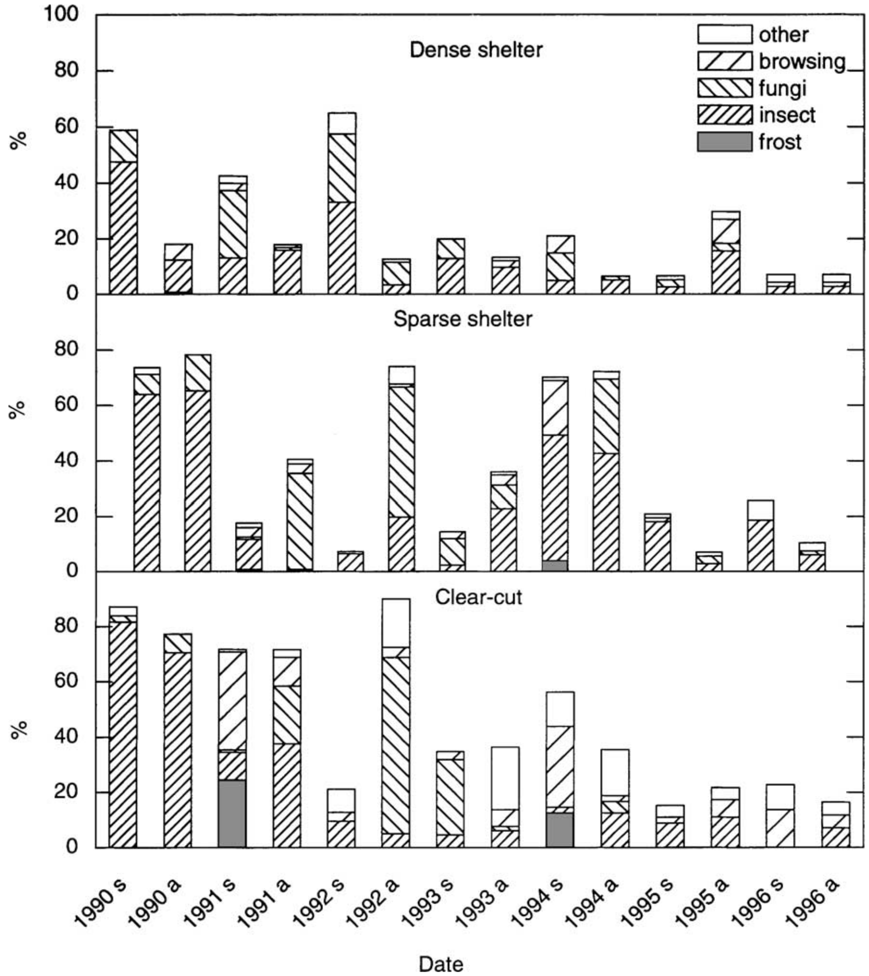

Fig. 7. Influence of shelterwood density on the frequency of various damage agents in the period 1990–1996. Year followed by ''s'' denotes inventory in June and year followed by ''a'' denotes inventory in August or September.

4. Discussion

The conditions for seedling establishment were less favourable in the clear-cut than in the shelterwoods, as indicated by the low proportion of beechnuts that produced seedlings in the clear-cut. This is in accordance with results found by Oosterbaan and van Tol (1984). Since the three cutting regimes were treated in the same way until the cutting operation at the end of March, the difference in seedling emergence was apparently caused during the first 5 weeks after cutting. Frost during this period might have caused the reduction in the number of emerged seedlings. This is supported by a similar conclusion drawn by leTacon and Malphettes (1974). In addition, mortality was higher in the clear-cut than in the shelterwoods the following years. This was probably due to more frequent events of frost and browsing in the clear-cut. Temperature measurements showed that frost occurred more frequently in the clear-cut during the second and third growing season than in the shelterwoods. This is in agreement with other studies that regard frost as a common cause of mortality in beech regeneration (Harley, 1939). The high mortality due to browsing in the clear-cut could be related to the increase in ground vegetation, which may allow small rodents to find suitable habitats (Gill, 1992).

Shelterwood density had an important impact on growth. Thus, the increase in height was the largest in the sparse shelterwood during the first years, but later height increases were larger in the clear-cut. This shift may be explained by the fact that the canopy closed, resulting in reduced light intensity in the sparse shelterwood. Similarly, the height growth also showed a decline with time in the dense shelterwood, probably also due to canopy closure. Compared to the clear-cut, only 10% of the incoming light reached the ground in the dense shelterwood in the beginning of the study period. According to Suner and Röhrig (1980), height growth is reduced when the light level is below 15% of full light.

Site preparation had a positive effect on the seedling emergence and varied depending on seedbed type. The mineral soil seedbed was hence much better for seedling emergence than berms, especially in the clear-cut. This finding is in agreement with earlier studies on regeneration of *Quercus robur* from seeds (Nilsson et al., 1996). The lower emergence rate on berms was probably an effect of reduced water availability in the top layer of the upturned mineral soil. This is not uncommon on finely textured soils on top of a humus layer (Örlander et al., 1990).

No effects on seedling survival and growth depending on site preparation were found. A probable explanation is that scarified ground may be covered by new vegetation within 2–3 years and the new vegetation cover may compete for soil resources (Godman and Krefting, 1960; Hagner, 1962; Béland et al., 2000).

When the beechnuts are covered with soil, germination is often positively affected (Watt, 1923). However, in our study, a soil cover only had a marginal positive effect on the number of emerged seedlings during the first growing season in the shelters, while the effect was negative in the clear-cut. The marginal effect in the shelters could partially be explained by the good mast year in 1989. Shaw (1968) hypothesised that the relative seed predation is smaller during good mast years. Consequently, it may be more important to cover the beechnuts with soil for protection against predation during poor mast years. The negative effect by a soil cover in the clear-cut was probably caused by a too humid soil environment for seeds and seedlings created by the soil covering in connection with a high water table.

In our study, insects were found to be the most common cause of seedling damage. In most cases, however, this damage could not be correlated to survival and height growth during the first 3 years. Height growth was not reduced for seedlings until more than 10 registrations of damage causing a reduced leaf area had been made. This indicates that a moderate reduction in leaf area does not limit the height growth for beech seedlings. A comparative result was demonstrated for oak by Shaw (1973), who found that a 50% reduction in leaf area reduced the dry weight increase in the seedlings.

In the clear-cut, the number of seedlings was higher than the minimum number generally considered necessary to achieve an acceptable timber quality. However, the distribution of the seedlings was uneven, resulting in large patches without any beech regeneration. It is therefore not likely that a pure beech forest can be attained for many decades—even with cleaning and thinning operations (Karlsson, 2001). In addition, the future timber quality may be poor.

5. Conclusions

Data from this study show that a shelterwood is necessary for natural regeneration of beech in Sweden. The main effects of the shelterwood are reduced competition from ground vegetation and a smaller risk of frost damage. The density of the shelterwood is not critical for seedling survival within a large range of shelter densities, but the seedling growth is negatively affected by increased density. Therefore, the optimal shelterwood should be a compromise between a dense shelterwood for protection against frost and competition from ground vegetation and a sparse shelterwood for maximal seedling growth. Site preparation was a prerequisite for successful regeneration on this site, although exceptions are known from other, more fertile sites (Bjäregaard and Carbonnier, 1974; Ekö and Johansson, 1995). Although the number of seedlings did not increase when the beechnuts were covered with soil, it is considered a good silvicultural treatment under many conditions. Moreover, a fence to protect the regeneration from browsing by large mammals is necessary, since damages from mammals is a large problem for regeneration of broad-leaved trees in southern Sweden today (Kullberg, 2000).

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