

# Chapter 3

## Regeneration



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### Abstract

- In the context of continuous cover forestry (CCF), natural regeneration is the preferred form of regeneration, but it is a long-lasting and complex process. Shelter density has a large effect on the regeneration process and results.
- The selection system, particularly suited for shade-tolerant species like Norway spruce, relies on continuous regeneration and ingrowth into larger size classes.

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Regeneration and ingrowth rates vary significantly among stands, influenced by site and historical factors, with no clear relationship to current stand conditions.

- In the group system, edge trees influence regeneration by providing seeds, checking weed growth, and exerting competition. Regeneration in gaps is generally satisfactory for both Norway spruce and Scots pine. However, seedlings usually grow slower, especially close to the gap edges.
- The shelterwood system promotes regeneration through a successive, uniform opening of the canopy. Shelter trees provide seeds, and reduce seedling damage and competition from ground vegetation. On the other hand, the remaining overstorey shelter trees reduce seedling growth.
- Conversion to the selection system initiates regeneration in young stands, aiming for slow and steady regeneration. Given the rapid growth and crown closure in young stands, frequent manipulation of shelter density is essential during conversion, for example by opening small gaps.

**Keywords** Natural regeneration · Seedling · Shelter density · Edge effect · Ingrowth

### 3.1 Introduction

Natural regeneration is generally considered a prerequisite for the profitability of continuous cover forestry (CCF), as artificial regeneration by direct seeding or planting is difficult and expensive where trees are present. In this chapter we will first briefly summarise the regeneration process in boreal forests, with a main focus on natural regeneration, which is most often used in the context of CCF. We will further review research results about regeneration in three silvicultural systems under CCF and during conversion to CCF. In Fennoscandia, spruce and pine are often found in more or less pure stands on the sites they are best adapted to, so we will separately review the existing knowledge for these tree species under each silvicultural system. Large differences in the regeneration processes among sites, differing in mineral soil vs. drained peatland, or lower vs. higher elevations and sites close to arctic treelines, make it necessary to sometimes look at these sites separately.

### Terms and definitions

- *Regeneration* is a term reflecting (1) a process of renewal or reestablishment of a forest after disturbance or timber harvest, or (2) the result of this process in the form of small, young trees.
- In this chapter, “*established seedlings*” refers to the end of the seedling stage, after which growth of small saplings or trees is no longer considered a regeneration process.
- *Seedling recruitment* is the process by which new individuals enter an existing population.
- *Ingrowth* is the growth of small trees past a certain size threshold into the tree stratum.
- *Advance regeneration* refers to seedlings or saplings already present in a stand before an active regeneration phase begins.

### 3.1.1 The Regeneration Process in Boreal Forests

Norway spruce and Scots pine have different successional strategies. Norway spruce is a late-successional species. In natural forests, it establishes in gaps created by death or windthrow of one or more trees. It is a shade-tolerant species, which can exist as advance regeneration even under a dense canopy of mature trees of shade-tolerant or light-demanding species (Engelmark and Hytteborn 1999). The dense canopy (high leaf area and low crowns) in mature Norway spruce stands makes for a dark understory (Goude et al. 2022). As understory light is an important factor affecting seedling establishment, survival, and growth, the dense canopy of Norway spruce stands is considered a competitive advantage, restricting other tree species' establishment underneath.

Scots pine is more of a light-demanding pioneer tree species, which regenerates well after medium- and large-scale disturbances such as forest fires or windthrows create openings in natural forests. Scots pine rapidly grows taller in high-light conditions (Engelmark and Hytteborn 1999). Norway spruce and Scots pine reach their distribution limits in Fennoscandia both at high latitudes and altitudes. Regeneration processes often limit their ranges. Seed production is infrequent, and maturation of seeds often fails in subalpine or subarctic conditions (Kullman 1996; Mork 1968). Short growth periods, low summer temperatures, and frequent summer frosts further limit seedling establishment (Kielland-Lund 1981; Mikola 1971).

The reproductive cycle of Norway spruce takes 2 years, from cone initiation to seed dispersal. Pollen-cone buds are initiated in the first summer of the cycle. Pollen release and fertilisation usually take place the following May, followed by seed ripening during summer and autumn. Seeds are subsequently dispersed between autumn of the second year and winter of the third year (Karlsson 2000).

The reproductive cycle of Scots pine lasts 3 years. This is because fertilisation, and consequently seed ripening, is delayed until the third year. The seeds are then dispersed from April until June of the fourth year (Sarvas 1962; Koski 1991).

Under optimal conditions, seed production of Norway spruce is irregular, with good seed years at intervals of several years. Scots pine produces seeds almost every year, although the amount of seeds varies greatly among years. However, seed-year intervals vary largely with site conditions, both edaphic and climatic. As summer temperatures are critical for seed production, there is a latitudinal and elevation gradient resulting in infrequent seed years at higher latitudes and elevations in Fennoscandia for both species, sometimes separated by up to 30 years (Hagner 1965; Mork 1968). For both species, the variation in seed production among years is influenced by weather conditions over the entire reproductive cycle.

Nutrients and light availability are other important factors triggering both species' reproduction. Seed production is therefore much higher in trees with large crowns and little competition from neighbours (Hagner 1965). Seed production increases with increasing site index (Sarvas 1962) and responds positively to fertilisation with nitrogen, or fertilisers combining nitrogen, phosphorus, and potassium (NPK, Mikola 1971). Differences among trees in seed production are also determined by local variation in site fertility (Sarvas 1962) and genetic factors (Koski 1978). Seed production increases several years after release cutting (Karlsson and Örlander 2002) in response to increased light, heat, water, and mineral nutrients.

Temperature and moisture control the germination of viable seeds. After establishment, light and nutrient availability determine seedling survival and growth. Predation and pathogens also kill seedlings. Mechanical site preparation is one of the most common silvicultural tools to improve soil properties, which influences seed storage and germination, seedling growth, and survival. However, the treatment's effects vary widely among the specific methods and sites (Löf et al. 2012). Mechanical site preparation creates different seedbed types; bare mineral soil is usually the most favourable for emergence (e.g. Kyrö et al. 2022; Oleskog and Sahlén 2000).

Mature shelter trees serve as a seed source (Beland et al. 2000), while reducing pine-weevil damage to seedlings (Von Sydow and Örlander 1994), frost risk (Langvall and Örlander 2001; Lofvenius 1995), and competition from ground vegetation (Hagner 1962). However, shelter trees also have negative effects, such as reduced growth due to competition (Erefur et al. 2011). Manipulating the shelter density influences understorey microclimate and light environment, and below-ground competition. Composition, abundance, and succession rate in understorey plant communities are also heavily affected by shelter density (Beland et al. 2000; Hagner 1962).

## 3.2 The Selection System

### 3.2.1 *The Selection System in Norway Spruce-Dominated Forests*

#### 3.2.1.1 **The Selection System in Norway Spruce-Dominated Forests on Mineral Soil**

A stand managed by selection cutting must contain a reserve of undergrowth to supply ingrowth into the smallest tree size class which will eventually replace trees that have been harvested, damaged by harvesting, or died. For a sustained reserve, regeneration must occur regularly or at least in bursts at shorter or longer intervals. Site conditions (moisture, fertility, vegetation) tend to control regeneration and may vary with stand structure and treatments, sometimes alternating between favourable and unfavourable periods. Moist sites have shown the greatest potential for regeneration, particularly drained and undrained peatlands (Lukkala 1946; Hökkä et al. 2011, 2012).

Seedling turnover is a major driver of regeneration in spruce selection stands. Few seedlings survive their first year, with reported mortality as high as 80–86% (Valkonen and Maguire 2005) or even 90–99% (Arnborg 1947; Leemans 1991). Later, mortality declines sharply. Average annual mortalities of 2–8% have been recorded in different studies, with lower mortality for spruce and higher for pine and birch (Lundqvist 1991; Nilson and Lundqvist 2001; Lundqvist and Nilson 2007; Eerikäinen et al. 2014).

The seedling density varies greatly among and within selection stands. Around 2000 seedlings/ha germinated each year in the Finnish ERIKA single-tree selection experiment harvested 2–4 times since the 1980s, but as mentioned above, most did not survive the first year. When looking at more-established seedlings, the average density for 11–130 cm-tall spruce was 5000 to 25,000 stems/ha (Saksa and Valkonen 2011; Saksa 2004).

The spatial distribution of regenerated seedlings is also usually uneven (Bøhme 1957; Granhus et al. 2021). In the ERIKA plots, almost half of the 4 m<sup>2</sup> sample plots completely lacked regeneration (Saksa 2004; Saksa and Valkonen 2011) despite the rather high average density level. The variation in seedling density may be credited to local variation in soil moisture, vegetation and other seedbed properties, as well as stand density.

Seedlings grow very slowly in spruce-selection stands as the canopy cover is always dense. Average seedlings grow around 2–4 cm/year (Lundqvist 1991; Eerikäinen et al. 2014). At this growth rate, it takes on average 40–60 years for a spruce seedling to reach 130 cm and constitute ingrowth into the smallest diameter class. Seedling density is highly variable, both between and within stands. It seems obvious that stand history, especially past density, structure, and treatments, is reflected in growth of regeneration and cohorts of small trees. Within a stand, the plants with the best condition, vitality, and height growth have better chances to survive and reach lower-canopy layers than those with lower vitality and slower

current growth. Understorey trees with a long-pointed crown with lots of healthy needles or leaves show good vitality. Current height growth is also a good indicator. A 5–10 cm leader shoot over a 3-year average in undergrowth spruce seems to signal a good response capacity to postharvest resource availability increases, and a marked height-growth spurt usually appears within a few years (Koistinen and Valkonen 1993; Mielikäinen and Valkonen 1995).

Due to the dynamic components of emergence, survival, and growth of seedlings and saplings, in Fennoscandia there generally seems to be sufficient ingrowth to replace losses of trees due to logging and natural mortality in spruce-dominated selection stands (Bøhme 1957; Lundqvist 1993; Eerikäinen et al. 2014; Andersson 2015; Moan Mn 2021). When tree diameter distribution is used as a key characteristic in management, it becomes essential to know how many new trees join each diameter class each period. With a minimum diameter at breast height of 0.1 cm, average spruce ingrowth has been 10–70 stems/ha/yr in comparable conditions in Finland, Sweden, and Norway (Lundqvist 1991, 1993; Saksa 2004; Eerikäinen et al. 2014; Andersson 2015; Moan Mn 2021) or as high as 170 stems/ha/yr in some studies (Lähde et al. 2002). Ingrowth of shade-intolerant trees has been minimal compared with spruce. In stands with on average 77% of standing volume consisting of spruce, ingrowth was 3 stems/ha/yr for birch and 0.1 stems/ha/yr for pine with a threshold diameter of 0.1 cm (Eerikäinen et al. 2014).

Ingrowth can be highly variable, and is often poorly correlated with current stand conditions (Lundqvist 2004, 2007; Moan Mn 2021). Indeed, current ingrowth in a selection-managed stand is deeply rooted in the seedling emergence, survival, and growth processes, usually dating back several decades. Therefore, ingrowth rates tend to vary between stands and studies (Lundqvist 2017). Studies looking into the relationship between stand density (e.g., standing volume) and ingrowth have found no significant relationship or a small negative relationship with standing volumes below 300 m<sup>3</sup>/ha (Lundqvist 2004, Lundqvist and Nilson 2007; Ahlström and Lundqvist 2015; Moan Mn 2021). This might be explained by increased seedling mortality associated with harvesting damage and large reductions in stand density (Lundqvist 2017). This increased seedling mortality counterbalances the otherwise-expected post-harvest ingrowth and height growth increases in the understorey. In contrast, Eerikäinen et al. (2014) showed a very clear relationship with stand density and seedling growth, implying that ingrowth will be much slower under high standing volumes. Minimisation of harvesting damage to undergrowth and small trees is paramount (Valkonen et al. 2020). Furthermore, current knowledge and experience do not permit us to assess what seedling densities are required to maintain sufficient ingrowth levels and sustain stand structure under given conditions. One principle is obvious though: the density of trees in the regeneration and undergrowth size classes must be much larger than the density of small trees, which must in turn exceed that of mid-size trees, and so on, because of slow growth and high mortality of seedlings, saplings, and small trees due to logging damage or natural causes (Valkonen et al. 2020). Only one tree in a small group may eventually survive and grow to become a large, mature individual. Promoting regeneration and development of an undergrowth reserve in selection management is essential. Some larger trees (diameter > 25 cm) must also be retained to produce seeds (Saksa 2004; Nygren et al. 2017).

### 3.2.1.2 The Selection System in Norway Spruce-Dominated Forests on Drained Peatland

High and constant soil moisture and abundant cover of *Sphagnum* moss (Place 1955; Sarasto and Seppälä 1964; Wood and Jeglum 1984) enhance spruce natural regeneration in peatland sites. Regeneration of uneven-aged spruce stands on peatlands has been investigated in ongoing experiments in Finland for only 5 years, so no published results are yet available. Preliminary results suggest that cutting to a low basal area of 9–13 m<sup>2</sup>/ha increases seedling establishment in post-cutting years. However, such heavy cutting also increases the risk of wind and snow damage and prolongs the cutting cycle. About one-third of the seedlings had been established after the selection cutting. In untreated control plots, one-fifth of the seedlings had been established after cutting of the treated stands. One-third of the seedlings were found on *Sphagnum* surfaces, which indicates how *Sphagnum* enhances seedling emergence.

At the above-mentioned experimental sites, the post-cutting growth of spruce seedlings has not yet been measured, but observations from the experimental sites suggest that there is large variation, which in some sites is explained by a severe lack of potassium. In sites with more balanced nutrition, strong growth responses can be seen for all spruce seedlings after 3 years of stunted post-cutting growth.

Lehtonen et al. (2023) found immediate recovery of photosynthetic capacity of previously-suppressed spruce trees on a fertile peatland in southern Finland after selection cutting removing 70% of the initial 278 m<sup>3</sup>/ha (with 71 m<sup>3</sup>/ha retained). The photosynthetic capacity of the trees was studied by measuring the carbon isotope ( $\delta^{13}\text{C}$ ) composition of increment cores (Lehtonen et al. 2023). A larger response of diameter growth was found after 5 years had passed since cutting.

At some drained peatland sites, the ground vegetation may indicate high production potential with continuous advance spruce recruitment, although Scots pine and downy birch form the dominant canopy layer. In peatlands, nitrogen availability increases over time after drainage due to peat decomposition, which, in turn, improves spruce survival and growth. In such stands, density of dominant pine and birch can be reduced by selection cutting to achieve uneven-aged spruce-dominated stands (Saarinen et al. 2020). Later on, nutrient imbalances likely need to be controlled by fertilising with phosphorus and potassium or wood ash (Paavialainen and Päiväven 1995; Saarinen et al. 2020).

### 3.2.1.3 The Selection System in Norway Spruce-Dominated Forests in Mountain Areas

The main difference for selection management in mountain areas is the less-favourable climate due to high altitude, mostly affecting seed production (Mork 1968). Most results about regeneration in mountain forests are from a method called mountain forest selection cutting, which reduces stand density to very low levels and combines selection and gap cuttings. Regeneration in selection stands in mountain areas shows similar patterns to selection stands elsewhere. The regeneration density varies greatly, with a positive effect of site quality; more seedlings grow at sites with

richer vegetation (ferns or herbs) compared to sites with bilberry and lingonberry-heather (Nilsen 1988; Granhus et al. 2020). The cutting rate and residual stand basal area showed no significant effect on either recruitment or seedling development, indicating again that these processes depend on more than current stand conditions.

The harsher conditions in these subalpine areas reduce spruce recruit density. Studies in southeastern Norway have reported 500–800 stems/ha for spruce <3 m tall (Øyen and Nilsen 2002, 2004; ). The annual ingrowth into the 5 cm diameter at breast height category in stands in southeastern Norway was reported to be on average 46 trees/ha/yr (Granhus et al. 2020). Moan Mn (2021) reported ingrowth rates comparable to stands at lower altitudes in a selection-system plot in a mountain forest at 800 m.

### 3.2.2 *The Selection System in Scots Pine-Dominated Forests*

The challenge with using the selection system to regenerate pine-dominated stands is that this light-demanding species requires large gaps or low density stands to regenerate and grow. This would require sparsely-stocked stands, resulting in lowered production.

A study of four multi-layered Scots-pine stands (77–99% of basal area) in northern and central Sweden showed that a multi-layered stand structure could be created but was not sustainable in the long run (Lundqvist et al. 2019). When basal area exceeded 12–13 m<sup>2</sup>/ha, ingrowth past 1.3 m stopped along with regeneration of new seedlings. In comparison, Moan Mn (2021) reported ingrowth rates between 15 and 20 pine stems/ha/year in pure Scots pine selection-system plots at a rather high stand basal area, approaching 20 m<sup>2</sup>/ha at the end of the observation period.

Rautio et al. (2023) studied the effect of stem density and site preparation on natural regeneration and seedling growth in mature pine forests in Lapland. Even though new seedlings emerged in their unthinned control stands, this was much less than in stands thinned to 50 stems/ha. Regeneration density in stands thinned to 150 or 250 stems/ha did not differ from that in unthinned control stands. In unthinned stands and in stands with 150 or 250 stems/ha, over 70% of the seedling-monitoring plots were empty. This suggests that although there is some regeneration under closed canopies, it is patchy and most seedlings in these patches will not survive. Patchy pine regeneration has also been observed by Karlsson and Nilsson (2005). All in all, these results suggest that creating and maintaining an uneven-aged stand using only pine can be difficult, and the long-term sustainability of multi-layered pine stands is questionable.

## 3.3 The Group System

Depending on the size of the gaps, this is the CCF system most similar to clearcutting when it comes to regeneration. Although there is less ground-level light in a group felling than in a clearcut, it is on average brighter than under the canopy of a

selectively-cut stand (Hanssen 2007). Belowground competition is also lower, and regeneration measures like soil scarification and planting are easier. Still, it is common to use natural regeneration after group felling.

The species, height and density of trees surrounding a gap influences regeneration within it, depending on site conditions, size and shape of the gap, and the regenerating species. The edge trees may both benefit (providing seeds, reducing competition from brush and weed) and harm (exerting above- and below-ground competition) regeneration. Seed dispersal of Norway spruce and Scots pine diminishes with distance from the edge (Hesselman 1938), but seed supply will usually suffice throughout CCF-sized gaps (Lehto 1956; Hanssen 2003; Valkonen and Siitonen 2016; Hallikainen et al. 2019). Furthermore, there are large within-gap gradients in the competition for light, water, and nutrients by the dominant trees surrounding a gap (Kuuluvainen et al. 1993; de Chantal et al. 2003). At high latitudes, sunlight mostly falls in the northern part of the gap (de Chantal et al. 2003), while competition for belowground resources is highest at gap edges and decreases toward the centre (Smith et al. 1997). The location of seedlings within a gap affects their emergence, survival, and growth, and spatial patterns within the gap differ among those demographic phases.

The group system initiates regeneration in individual gaps, series of gaps, or systematic grids of gaps. In the initial regeneration phases, gaps are isolated and surrounded by closed mature stands. In later phases, new gaps are created next to earlier gaps. Shading by adjacent tall trees means gaps created later have edge effects and environmental conditions different from neighbouring earlier patches. Existing studies have only investigated the establishment and development of regeneration in early gaps, which were surrounded by mature stands. The development of later regeneration phases in the group system might deviate substantially from those patterns. Later phases of the group system frequently remove the mature stand in larger patches or use periods of shelter.

There are few studies of regeneration in gap cuttings, and their coverage is uneven among regions, site types, treatments, and stand properties. Many region-site combinations are still not covered. In Finland, large experimental studies have recently begun in key areas, but it will still take several years to see conclusive results, especially in the north.

### ***3.3.1 The Group System in Norway Spruce-Dominated Forests***

#### **3.3.1.1 The Group System in Norway Spruce-Dominated Forests on Mineral Soil**

##### **3.3.1.1.1 Seedling Density**

According to experimental results, Norway spruce has regenerated rather well in stands across Finland (Table 3.1). Site preparation has enhanced seedling densities markedly on mineral soils in northern areas, but not much on fertile sites in the south, where the proliferation of vegetation has tended to counteract the benefits

**Table 3.1** Average spruce-seedling densities and heights in gap-cutting studies conducted in Finland

Region, site, and site preparation	Reference no.	Gap shape and size	Seedling density of main species (stems/ha)	Density of other conifer species + birch (stems/ha)	Main crop seedling density <sup>a</sup> , (stems/ha)	Mean height of crop seedlings, time since treatment
South, mineral, submesic, no site prep	1	Square, 40 × 40 m	7600	4000	1300	60 cm, 10–11 year
South, mineral, submesic, disc trenching	1	Square, 40 × 40 m	6700	12,300	1300	80 cm, 10–11 year
Kainuu (north), mineral, submesic, no site prep	2	Shape variable, diameter ~ 10–60 m	2400	5900	1700	50 cm, 13–15 year
Kainuu (north), mineral, submesic, disc trenching	2	Shape variable, diameter ~ 10–60 m	9300	13,900	2000 <sup>b</sup>	50 cm, 13–15 year
South, mineral, Mesic and submesic, various site prep	3	Shape variable, diameter 10–60 (80) m	11,400	5800	1770	105 cm, 7–10 year
North, drained peatland, fertile, no site prep	4	Circular, diameter 10–25 m + 0.2–0.3 ha patch cuts	10,400	3200	2300	73–84 cm, 10 year

<sup>a</sup> Main crop seedlings are defined as seedlings that would be retained in a pre-commercial thinning, i.e. healthy seedlings with adequate spacing. See Valkonen et al. (2011)

<sup>b</sup> The number of main crop seedlings was 2300 stems/ha when planted pines were included and prioritised in the survey. There were such huge numbers of natural seedlings that the average number of crop seedlings would have exceeded the target of 2000 stems/ha without the planted seedlings

References: 1 = Valkonen et al. (2011), 2 = Valkonen and Siitonen (2016), 3 = Valkonen (2019), 4 = Hökkä and Repola (2018)

**Table 3.2** Average pine-seedling densities and heights in gap cutting studies conducted in Finland and Sweden

Region, site, and site preparation	Reference no.	Gap shape and size	Seedling density of main species (stems/ha)	Density of other conifer species + birch, (stems/ha)	Main crop seedling density <sup>a</sup> (stems/ha)	Mean height of crop seedlings, time since treatment
N Karelia, Finland, mineral, xeric and subxeric, various site prep	1	Circular, diam. 10–60 (80) m	13,000	3400	1530	39 cm, 6–9 year
Northern Finland, mineral, xeric and subxeric, patch scarification	2	Circular, diam. 20, 40 and 80 m	21,700	7300	~2000 <sup>b</sup>	9 cm, 5 year
Northern Sweden, mineral, Mesic, no scarification	3	Square, 40 × 40 m	~ 7800 <sup>a</sup>	Not applicable <sup>c</sup>	3200 <sup>c</sup>	60 cm, 14 year

<sup>a</sup> See definition in Table 3.1. The Swedish study operates with closer spacing for crop trees than the Finnish studies

<sup>b</sup> Calculated using the study's model with the proportion of site preparation at 10–20%

<sup>c</sup> The Swedish study was established in a mixed pine-spruce stand, and no distinction is made between seedling species. Pine constituted 45% of the main crop seedlings, birch 36%, and spruce 19%

References: 1 = Valkonen (2019), 2 = Hallikainen et al. (2019), 3 = Goude et al. (2022)

much sooner. In southern Finland on the most mesic sites, the establishment of large gaps >40 m wide has resulted in the intensive proliferation of brush and weed, hindering regeneration (Downey et al. 2018; Valkonen 2019).

In Sweden, studies of chequered-gap systems have also shown good regeneration results, for instance in a trial with 40 × 40 m gaps in mixed pine-spruce forest in Gällivare, northern Sweden (Ackemo 2018; Goude et al. 2022, see also Table 3.2).

Seedling density is highest in the 5–10 m closest to the gap edge (Hanssen 2003; Valkonen et al. 2011; Goude et al. 2022). Brush and weed may be less prolific near the edge, so seedlings thrive better there. Goude et al. (2022) also found that there were more seedlings in the north of the gap compared to the south, although the density was generally sufficient everywhere.

Unlike studies in southern Finland, in spruce stands in Kainuu, northern Finland (Valkonen and Siitonen 2016) with a lower fertility and a cooler climate, ground vegetation barely changed and spruce-seedling density was similar throughout gaps. As discussed above, studies show a relatively small influence of the diminishing seed rain density toward gap centres in such small gaps (10–60 m diameter). It was concluded that the spruce-seed rain from edge stands may be sufficient to restock gaps up to 0.5–1.0 ha if the other main factors are favourable.

### 3.3.1.1.2 Seedling Growth

Negative edge effects on spruce-seedling growth have been found in some (Borgstrand 2014; Valkonen et al. 2011), but not all studies (Goude et al. 2022). In southern Finland, Valkonen et al. (2011) found seedling height increased substantially from stand edges into the gap centre up to a distance of at least 20 m for all major species.

Even though seedling growth in gaps is more vigorous than under a canopy (Granhus et al. 2003; Hanssen 2003, gap diameter 25–50 m), growth is usually less than in open clearcuts (Valkonen et al. 2011, gap diameter 40 m). However, there is a balance between competition from and facilitation by edge trees. Their positive effects include checking weed growth and frost protection. Thus, some studies show similar growth of spruce seedlings in gaps and on clearcuts (Borgstrand 2014, gap size 30 × 45 m).

### 3.3.1.2 The Group System in Norway Spruce-Dominated Forests on Drained Peatland

In drained-peatland spruce stands, regeneration after group felling has been studied for 10 years at two sites in northern Finland (Hökkä et al. 2011, 2012). The diameter of the cut gaps was 10–25 m, the latter being about equal to dominant stand height. Regeneration in four 0.2–0.3 ha (40 × 50 m to 50 × 60 m) patch clearcuts was also investigated.

Advance regeneration formed a significant part of the seedling stock that developed in the gaps (Fig. 3.1). Five years after cutting, surviving advance regeneration (>10 cm tall) accounted for almost half of all spruce seedlings. Within 3–5 years, many small spruce seedlings (<10 cm) were found in all gap sizes. During the monitoring period, two good seed years occurred.

Downy birch accounted for 25–57% of all seedlings 5 years after cutting (Hökkä et al. 2011). The proportion of birch increased with gap size, suggesting that its establishment requires increased light availability. Very few Scots pine seedlings were found in the gaps. Ten years after gap cutting, spruce-seedling density varied between 5500 and 12,500 stems/ha (Hökkä and Repola 2018). In the 0.2–0.3 ha gaps, the 10-year regeneration result was poorer than on smaller canopy gaps, i.e., there were 850 spruce and 560 birch crop seedlings/ha. This suggests that in bigger gaps, seedling establishment takes longer, the resulting stand is more irregular, and the proportion of downy birch is higher than in smaller gaps (Hökkä and Repola 2018).

Establishment was poor and slow in the most productive shallow-peated and herb-rich sites due to aggressive growth of tall herbs, ferns, and grass. In sites with thicker peat and *Sphagnum*, more rapid establishment of spruce seedlings took place. Patch scarification appeared to hamper seedling establishment (Hökkä et al. 2012). Site preparation destroyed part of the advance regeneration and fast-growing herbs and grasses occupied the patches, effectively out-competing spruce seedlings.



**Fig. 3.1** Regeneration in a small gap in Oulu (Finland), 12 years after cutting. Photo: Hannu Hökkä

Ten years after cutting, spruce crop seedling density in gaps averaged 2200/ha and their height varied between 73 and 84 cm (Hökkä and Repola 2018). The tallest seedlings were in the largest gaps. Taller advance-regeneration seedlings had faster height growth. High seedling densities, including competing birch seedlings, indicate that pre-commercial thinning is needed to promote good development of the established seedling stand.

An inventory study (Pulliainen 2019) revealed that the quality of advance regeneration in gaps was variable. Many seedlings had leader shoots that had diebacks. Almost one-third of the seedlings were infected with some sort of rot, making them unsuitable to produce saw timber in the future.

### ***3.3.2 The Group System in Scots Pine-Dominated Forests***

#### **3.3.2.1 The Group System in Scots Pine-Dominated Forests on Mineral Soil**

##### **3.3.2.1.1 Seedling Density**

For Scots pine, studies have also shown good seedling densities after group felling (Hallikainen et al. 2019; Ackemo 2018; Goude et al. 2022, Table 3.2). Site preparation may enhance the emergence substantially. Exposing 10–20% of the mineral

soil guaranteed abundant and evenly-distributed regeneration in a study by Hallikainen et al. (2019). In an experiment in North Karelia, seedling densities were only moderate, probably due to their measurement coming shortly after the treatment (Valkonen 2019). A later substantial increase in seedling densities is expected, and it was concluded that pure-pine stands on infertile sites are very favourable for natural regeneration of pine, including in patches established by site preparation.

#### 3.3.2.1.2 Seedling Growth

Pine seedling growth is noticeably influenced by surrounding stands (Axelsson et al. 2014; Borgstrand 2014; Hallikainen et al. 2019). However, Goude et al. (2022) found no edge effects on seedling growth (pine, birch, and spruce) in 40 × 40 m gaps in northern Sweden after 14 years. Borgstrand (2014) found seedlings in northern parts of gaps to grow 30% faster compared to other areas in gaps. However, compared to a reference clearcut, the pines in the gaps grew about 30% less.

An average stand dominated by pine or spruce clearly reduces seedling growth for at least 20 m beyond its edge (Ruuska et al. 2008; Valkonen et al. 2011). The edge influence compounds as the seedlings grow taller. A study by Ruuska et al. (2008) found that in 5–10 m tall pine sapling stands, stem density, height, and volume all decreased strongly toward the surrounding established pine stands in southern Finland. Adjacent to the edge stand, there was a zone a few metres wide where few or no pine saplings survived or grew.

#### 3.3.2.2 The Group System in Scots Pine-Dominated Forests on Drained Peatland

Pine regeneration after group felling on peatland in Finland has only been studied in a few field experiments, with 20–40 m-wide strip-formed gaps. The regeneration success has so far only been followed for a few years.

Tentative results show that, especially on dwarf-shrub-dominated sites, the biggest regeneration problem is uneven seedling establishment among gaps. It is caused by dense ground coverage of raw humus, forest moss, and dwarf shrubs. Over half of the seedlings were located on *Sphagnum* surfaces or machine tracks. Light site preparation disrupting raw-humus and forest-moss surfaces could result in more even seedling establishment.

#### 3.3.3 The Group System in Broadleaf-Dominated Forests

Downy and silver birch are shade-intolerant species. Conifers, especially spruce, strongly suppress shade-intolerant seedlings, and large-diameter gaps, at least 20 m (Valkonen et al. 2011) and maybe over 50 m, are required to allow birch

development near their centres. More experimental results are needed for more general conclusions and recommendations.

Shade-tolerant broadleaved species, for instance European beech (*Fagus sylvatica*), could possibly expand into today's boreal forest areas in southern Fennoscandia given climate change (Kramer et al. 2010). For beech, both the group and shelterwood systems are suitable silvicultural methods.

### 3.4 The Shelterwood System

Compared to the seed-tree cutting, the shelterwood cutting(s) provides several benefits in addition to seed sources (see Sect. 3.1). The shelterwood system also has higher stocking levels and longer-duration retention.

A common shelterwood density in Fennoscandia is about 10–12 m<sup>2</sup>/ha after the first regeneration cut. It should be noted however, that optimal shelter density varies among species, sites and management objectives. Generally, higher retention levels are desirable on more-fertile sites with high competition from ground vegetation, and on sites prone to frost or waterlogging. On less-fertile sites, a lower density of shelter trees may be a sufficient seed source and enhance establishment of light-demanding tree species.

Regeneration in shelterwood systems can either be planted or naturally recruited. The next generation often consists of several years of seedling cohorts, with the entire regeneration process spanning around 10–30 years; the faster end of this range is typical of Scots pine and the slower end for Norway spruce.

#### 3.4.1 *The Shelterwood System in Norway Spruce-Dominated Forests*

##### 3.4.1.1 **The Shelterwood System in Norway Spruce-Dominated Forests on Mineral Soil**

Norway spruce is generally well suited to regeneration under shelter. However, irregular seed years, high susceptibility of the shelter trees to wind damage, and shallow root systems restricting mechanical site preparation complicate shelterwood regeneration. In Fennoscandia, there have been relatively few controlled studies that assess the suitability of shelterwood regeneration of Norway spruce. Furthermore, little is known about the recruitment patterns and regeneration dynamics in such stands.

In northern Sweden, Hagner (1962) surveyed 58 Norway spruce and Scots pine shelterwood cuttings (totalling 10,000 ha), which they defined broadly as shelters of varying densities, from widely-spaced seed trees to closed forests. Based on the collected data and an estimate of the seed production after shelterwood cuttings across

Sweden, Hagner (1962) concluded that Norway spruce, with a combination of a shelter and mechanical site preparation, may naturally regenerate at satisfactory levels across the entire country. However, seed years play a decisive role in the success of the regeneration process.

Sikström (1997) examined 52 shelterwood cuttings in southern and central Sweden, representing a wide range in site fertility (site indices 18–30 m). Higher regeneration success in the southern locations (65% of sites had a density  $\geq 4000$  Norway spruce seedlings/ha, compared to 38% in the north) was thought to be due to more favourable climatic conditions, higher seed production, and more common fresh-moist and moist soils.

Leinonen et al. (1989) studied the regeneration success of spruce shelterwood cutting on mineral soil sites in south-central Finland. The amount of regeneration stocking was inventoried before cutting, during the summer after cutting, and 1 year after cutting. The mean retained volume after cutting was 120 m<sup>3</sup>/ha (observed range 39–220 m<sup>3</sup>/ha) and stem density 186/ha. Prior to cutting, the density of acceptable seedlings was 1440/ha and 1 year after cutting 1546/ha. The result was found unsatisfactory, and the method considered risky, although the monitoring period (two growing seasons) was very short.

Several authors recommend combining a shelter basal area of around 10 m<sup>2</sup>/ha with mechanical site preparation as a tradeoff between satisfactory seedling survival and growth (Leinonen et al. 1989; Nilsson et al. 2002; Örlander and Karlsson 2000). Higher seedling survival under shelter trees compared to open clearcut areas was mainly due to: (1) less-extreme temperatures that cause frost and frost heaving (Langvall and Örlander 2001; Lofvenius 1995), (2) reduced competition from ground vegetation (Hagner 1962), and (3) reduced pine-weevil damage to seedlings (Petersson 2004).

According to Nilsson et al. (2002) denser shelters (basal area 13.2–28.2 m<sup>2</sup>/ha) and mechanical site preparation promote emergence of Norway spruce seedlings in southern Sweden. However, Örlander and Karlsson (2000) concluded that denser shelters depress seedlings' height growth. In Norway, Skoklefeldt (1989) compared planting and natural regeneration in shelterwoods (250 trees/ha) with clearcutting (50 × 90 m) with or without site preparation in a bilberry spruce stand in SE Norway. After 11 years, natural regeneration was clearly denser under shelterwoods with mechanical site preparation. However, seedlings germinating after the initial cut were only 17 cm tall after 11 years, compared to 42 cm in the clearcut.

Overstorey depression of seedling growth is most likely due to the combination of above- and below-ground competition from shelter trees. Although light availability does not limit germination and initial seedling growth, it may limit growth in the longer run. Örlander and Karlsson (2000) reported relatively slow growth of all sized advance-growth seedlings during the first 3–4 years following the release cutting, but it was most pronounced for the shortest (< 100 cm) seedlings (see also Skoklefeldt 1967). Delayed growth of taller (>100 cm) seedlings was explained by needles needing time to adapt to brighter light, whereas small seedlings probably struggled with both needle adaptation and dry humus. Shade-grown seedlings suddenly exposed to bright light may suffer photosynthetic damage, something known

as the release effect. This effect is generally greater in shade-tolerant species (Grossnickle 2000) like Norway spruce. To avoid post-release seedling damage, the shelter should be removed gradually. Örlander and Karlsson (2000) tested shelter densities from 0.9–32.7 m<sup>2</sup>/ha, finding that 24% of seedlings under 20 cm died if shelter basal area was  $\leq 7$  m<sup>2</sup>/ha. The corresponding mortality under denser (basal areas  $\geq 12$  m<sup>2</sup>/ha) shelters was only 1%. Mortality was attributed to release effects (25%), pine weevils (28%), and unknown factors (47%). In Norway, Skoklefeldt (1989) reported high mortality of Norway-spruce seedlings after overstorey removal, reducing the seedling density by about 80%. Skoklefeldt (1967) reported 16 and 38% mortality after overstorey removal in two shelterwoods in southeastern Norway, with small seedlings ( $\leq 10$  cm) clearly being the most vulnerable.

Pre-cutting height and leading-shoot length are good predictors of post-release seedling survival (Örlander and Karlsson 2000; Skoklefeldt 1967). Örlander and Karlsson (2000) showed that, for shelters of basal area 12–33 m<sup>2</sup>/ha, seedling survival probability decreases dramatically, when pre-cutting seedling heights are below 50 cm. This is likely because small seedlings are more susceptible to the release effect and pine weevils compared to larger seedlings. Therefore, the authors recommended that the seedlings should not be released until a sufficient number are at least 50 cm tall.

On the other hand, taller seedlings suffer more logging-related damage (Skoklefeldt 1967; Sikström and Glöde 2000). Sikström and Glöde (2000) reported that around one-third of all saplings 1–1.5 m tall (at densities of 6400–25,400/ha) suffered serious logging damage. The proportion of damaged seedlings increased with increasing shelterwood stem volume (132–234 m<sup>3</sup>/ha). The most common causes of seedling damage were burial under slash (32–58%), machinery (12–31%), felling (3–20%) and tree dragging (up to 4%). It should be noted, however, that damage sources were often difficult to identify.

#### **3.4.1.2 The Shelterwood System in Norway Spruce-Dominated Forests on Drained Peatland**

Drained peatlands (regardless of the peat thickness) promote coniferous-seedling establishment relatively well. Dense cover of advance regeneration before shelterwood cuttings was reported in several studies (Moilanen et al. 2011; Hånell 1993; Örlander and Karlsson 2000). The shelterwood system is a possible strategy to mitigate the negative effects of clearcutting. For instance, shelterwood retention may reduce post-harvest water-level rises, competition from ground vegetation, frost and frost heaving.

Hånell (1993) and Holgen and Hånell (2000) investigated effects of two shelterwood densities (140 and 200 stems/ha) for natural and artificial regeneration on highly-productive peatlands (peat depth 1.3 m) in nine mature Norway spruce forests across Sweden. Stocking levels of large ( $\geq 10$  cm) naturally-regenerated Norway spruce seedlings (five growing seasons after the cut) were on average 4500 and 9000 seedlings/ha in stands of 140 and 200 stems/ha, respectively (Hånell

1993). The results from underplanting showed that mechanical site preparation with mounding promoted both seedling survival and height growth (Holgen and Hånell 2000). At the end of the 6-year study period, 43% and 38% of shelter trees were blown down in 140 and 200 stems/ha stands, respectively (Hånell and Ottosson-Löfvenius 1994). These results do not mean shelterwood cutting in peatland spruce forests should be avoided due to windthrow risks. However, to minimise the risks, higher shelterwood densities were recommended.

Moilanen et al. (2011) compared regeneration results after different regeneration methods in a thick-peated drained spruce mire in eastern-central Finland. Fifteen years after shelterwood cutting, spruce-, birch- and pine-seedling densities were 7000, 16,000 and 200 stems/ha, respectively. Of those, the crop-seedling densities for spruce, birch and pine were 2215, 355, and 25 stems/ha, respectively. The crop-seedling density results were comparable to treatments using different soil-preparation methods (mounding, patch scarification) and planting with spruce or pine.

Only a limited number of Fennoscandian shelterwood experiments have been carried out in fertile Norway spruce-dominated drained-peatland forests. The few published studies suggest that the shelterwood system provides quick and abundant natural regeneration of spruce and downy birch on drained-peatland sites, even without site preparation.

### **3.4.1.3 The Shelterwood System in Norway Spruce-Dominated Forests in Mountain Areas**

The shelterwood system for Norway spruce in mountain areas shows many of the same benefits and disadvantages seen elsewhere for establishment, survival and growth. Elfving (1990) studied a Norway-spruce-dominated shelterwood (240 stems/ha) and an adjacent clearcut area near the treeline in northern Sweden (latitude 63.28° N, elevation 550 m), both planted with 4-year-old seedlings at 2 × 2 m spacing. At the end of the 27-year observation period, the average sapling height under the shelter was 2.24 m, approximately 0.75 m shorter than average saplings on the clearcut. The observed slowing of height growth corresponds to 5 years of development, and a loss of 18 m<sup>3</sup>/ha over the rotation. However, the volume loss in the new generation was more than offset by the increment of the shelter trees (44 m<sup>3</sup>/ha during 27 years). At the time of the inventory, natural regeneration consisted of 1300 spruce and 700 birch seedlings/ha. The average height of naturally-regenerated Norway-spruce seedlings was 1.77 m. The reported survival rates for planted seedlings were 90% and 59% in the shelterwood and the clearcut, respectively. Higher seedling survival under the shelterwood was likely due to a reduced risk of frost damage.

### 3.4.2 *The Shelterwood System in Scots Pine-Dominated Forests*

Successful implementation of the shelterwood system in Scots pine stands may yield very dense regeneration, sometimes reaching tens of thousands of seedlings/ha. In a study in southern Sweden, Beland et al. (2000) reported that 4 years after regeneration cutting and mechanical site preparation, natural regeneration of Scots pine yielded 53,000 and 90,000 seedlings/ha in shelters with basal areas of 12 and 15 m<sup>2</sup>/ha, respectively. Kyrö et al. (2022) and Lula (2022) found comparable results. Although several reports show a clear positive effect of shelter density on seedling densities (e.g. Beland et al. 2000), a study conducted by Rautio et al. (2023) in northern boreal Finland found the opposite trend. This is likely due to shading by shelter trees limiting seed germination and seedling survival.

Thick humus layers and competing ground vegetation are among the most important constraints on natural regeneration, especially in southern Fennoscandia. Competition from ground vegetation generally increases in more-productive sites. Therefore, natural regeneration is usually applied on low- to medium-fertility sites, where mechanical site preparation is also often recommended. Mechanical site preparation promotes seedling establishment (Kyrö et al. 2022), height growth (Hagner 1962), and increases regeneration homogeneity (Fries 1979).

Kyrö et al. (2022) observed 1000–4400 and 32,000–92,000 seedlings/ha on intact and prepared ground, respectively. However, seedling emergence and survival on intact ground depended on the ground cover's species composition. The benefit of mechanical site preparation diminishes over time, primarily due to the gradual invasion of ground vegetation. However, as suggested by Beland et al. (2000) and Hagner (1962), this process is slower under a shelter, giving several years of seedling cohorts a chance to grow into future stands. Several studies have reported steadily-increasing seedling density up to 10 years after the regeneration cut (Beland et al. 2000; Kyrö et al. 2022; Lula 2022; Rautio et al. 2023). Hence, gradual and constant seedling emergence seems possible on favourable seedbeds, as some viable seeds are produced in most years.

Kyrö et al. (2022) reported that seedling mortality declined from a maximum in the first year to a fraction of the initial level 8 or more years after emergence. Therefore, these authors concluded that regeneration success can only be assessed after seedling mortality has stabilised sufficiently after emergence of the main seedling cohort. Beland et al. (2000) and Lula (2022) reported that the seedling cohort established in the first year after the regeneration cut constitutes >50% of the entire 5–6-years post-cutting seedling population.

In naturally-regenerated stands, dispersed seeds land on all types of seedbeds present. Mechanical site preparation creates different seedbed types; bare mineral soil is the most favourable for emergence, but is not necessary for seedling survival. High mortality on mineral soil, however, is outweighed by abundant emergence, resulting in a constant seedling-density increase following mechanical site preparation (Kyrö et al. 2022). A mixture of mineral soil and humus is often perceived as

the most favourable seedbed for natural regeneration, as it provides an optimal compromise among satisfactory seedling emergence, survival, and growth (Beland et al. 2000; Kyrö et al. 2022). Low seed production and insufficient seedling recruitment are two of the major limitations of natural Scots-pine regeneration in northern Fennoscandia. The frequency and viability of seed years generally decrease at higher latitudes and elevations (Valkonen 1992; Henttonen et al. 1986). Seed years occur irregularly at intervals of 2–5 years south of 60° N, and up to 100 years at the northern treeline (~ 70° N, Heikinheimo 1937; Numminen 1982; Valkonen 2000). Therefore, timing site preparation for a good seed year is recommended (Karlsson and Örlander 2000). Release cuttings lead to several years of increased cone production (Karlsson and Örlander 2002), consequently promoting pine regeneration. Furthermore, compared to fully-stocked stands, year-to-year variation in seed crops is generally lower in the released stands (Heikinheimo 1937).

Shelterwoods can help reduce the risk of pine weevil (*Hylobius abietis* L.) damage to both planted and naturally regenerated conifer seedlings. The riskiest time for pine weevil damage is when removing the shelter, as pine weevils are attracted by the odour of newly-cut stumps (Sundkvist 1994). To reduce this risk, Wallertz et al. (2005) recommend that shelter trees not be removed until most seedlings have reached the safe sizes of 9 mm basal diameter for Norway spruce and 12 mm for Scots pine.

Shelter trees inhibit growth of the next generation, especially for light-demanding species like Scots pine. The high stocking levels and long retention periods of the shelterwood system result in slower regeneration compared to seed trees. Scots pine thus has shorter shelter periods than Norway spruce. Beland et al. (2000) suggested that removal of the dense shelter with a basal area of approximately 15 m<sup>2</sup>/ha should begin when seedlings reach about 0.5 m tall, and the overstorey should be maintained until regeneration reaches about 6 m. In a contemporary Finnish shelterwood variant for pine, some overstorey trees are retained throughout the rotation to promote ecosystem services and production of very-high-quality timber (Äijälä et al. 2019; Valkonen 2020). The system generates within-stand tree-size stratification through differences in growth rates, leading to more heterogeneous stands (Lundqvist et al. 2019).

In Norway, the shelterwood system has been practised in Scots pine in some places (see picture in Chap. 2). The practice was catalysed by the impossibility of successfully regenerating pine due to excessive moose-browsing damage. Harvesting old pine trees successively created an open shelter, although the name “shelterwood” was not used. High-density natural regeneration of pine established under the shelter and has now been released and developed into young stands. These examples illustrate that pine can be successfully managed using the shelterwood system, and not just with the seed-tree method.

### 3.5 Conversion to Continuous Cover Forestry

Regeneration is an important process in the conversion to CCF. Applying the shelterwood and group systems in stands not previously managed this way needs no specific adaptation of the regeneration management, as conversion starts with the regeneration cuts. Conversion to the selection system, on the other hand, is a long process toward a multi-storied stand, and regeneration is essential in this conversion. Conversion to the selection system requires initiating regeneration at an earlier stage than usual of stand development.

A proposed method for conversion to the selection system is variable-density thinning (VDT, Brodie and Harrington 2020), which creates gaps in young stands to initiate regeneration. Another method is more homogeneous, open shelters, for example created after snow damage (Knoke and Plusczyk 2001). Openings enable natural regeneration and give good results if they stay open long enough. Rapid growth and development of young stands closes gaps and canopies, and further interventions are essential to continue regenerating seedlings and saplings. VDT creates horizontal small-scale variation in tree size rather than vertical stratification, so seems more appropriate for young stands at the beginning of the conversion period.

Low seed production in young stands is usually caused by high stand density and small crowns (Hagner 1965; Nygren et al. 2017). Reducing stand density promotes seed production, but in some methods only for edge trees next to openings.

Artificial regeneration is often used alone or in combination with natural regeneration in conversion methods, particularly to introduce new species (e.g., Knoke and Plusczyk 2001), especially in the context of climate adaptation.

A conversion concept tried in Sweden (Drössler et al. 2014), based mostly on heavy thinning, suffered low regeneration during the first 10 years. The trials have been modified to maintain more open stands (Goude et al. 2022).

Target-diameter harvest can also be used as a conversion treatment. Experiments in Sweden have used it to study early-regeneration establishment (Drössler et al. 2015, 2017). In response to the harvests, seedling and sapling density and growth have increased, not only of Norway spruce, but also of more light-demanding species.

Conversion to the selection system is a topic only addressed during recent decades, and so far little covered by regeneration studies in Fennoscandia. The few results available from other regions are not especially relevant for the Nordic region due to species and site differences, but VDT has been tried in Washington, Oregon, and Chile (Dodson et al. 2012; Donos et al. 2020; Puettmann et al. 2016). VDT creates openings that allow regeneration to establish and develop while also promoting further development of spatially-variable advance regeneration, in a way similar to the group system.

### 3.6 Conclusions

In the context of CCF, the preferred form of regeneration is natural regeneration, but this is a slow and complex process. Managing natural regeneration requires insight into all stages and processes, and above all patience. Common to all CCF silvicultural systems are the varying effects of shelter density (in the group system this refers to the adjacent tall trees) on the regeneration outcomes. Managing shelter density is therefore an essential method to optimise regeneration.

In the selection system, continuous germination of new seedlings and ingrowth into larger size classes is required to replace harvested trees for long-term sustainable management. Regeneration and ingrowth rates vary significantly between stands, influenced by historical factors, with no clear relationship to current stand conditions, particularly stand density. The system is more suitable for shade-tolerant species like Norway spruce, while pine-dominated stands struggle to achieve and sustain regeneration due to their shade intolerance and high stand densities.

In the shelterwood system, a successive, uniform opening of the canopy promotes regeneration. Shelter trees provide seeds, while reducing damage to seedlings and competition from ground vegetation. On the other hand, they can also have an adverse effect on seedlings by directly competing with them. Evidence from the reviewed literature from Fennoscandia shows that both Scots pine and Norway spruce can be successfully regenerated using the shelterwood system. Although the system is generally more suitable for Scots pine, high densities of shelter trees, especially if retained over a long period, may hinder artificial or natural regeneration of light-demanding Scots pine seedlings.

In the group system, regeneration is initiated in individual gaps, series of gaps, or systematic grids of gaps. The edge trees influence regeneration through providing seeds, checking weed growth, and exerting competition. Fennoscandian studies on regeneration in individual gaps generally show satisfactory seedling density for both Norway spruce and Scots pine. However, seedling growth is usually slowed, especially close to the gap edges. The edge effect increases as seedlings grow taller, making long-term survival difficult for light-demanding pine saplings nearest the edge.

Conversion to the selection system initiates regeneration in young stands, and tries to maintain a continual regeneration process with sustained slow recruitment. Given the rapid growth and crown closure of young stands, frequent manipulation of shelter density is essential during conversion. Initiating regeneration in small gaps, for example using variable-density thinning, might therefore be easier than a homogeneous shelter approach.

## References

- Ackemo J (2018) Naturlig trädföryngring och epifytiska hänglavlar 10 år efter en avverkning i schackruteform (Natural tree regeneration and epiphytic lichens 10 years after a Chequered-Gap-cutting). Master thesis, Swedish University of Agricultural Sciences
- Ahlström MA, Lundqvist L (2015) Stand development during 16–57 years in partially harvested sub-alpine uneven-aged Norway spruce stands reconstructed from increment cores. For Ecol Manag 350:81–86
- Äijälä O, Koistinen A, Sved J, Vanhatalo K, Väisänen P (eds) (2019) Metsänhoidon suositukset (best practices for forest management). Tapion julkaisuja, Helsinki, p 252
- Andersson S (2015) Tilvekst på bestands- og enkeltrenivå ti år etter selektiv hogst etter KONTUS-prinsippet (Stand and single-tree growth ten years after selective cuttings by the Kontus-principle). Master Thesis, Norwegian University of Life Sciences, pp 70
- Arnborg T (1947) Föryngringsundersökningar i mellersta Norrland (Regeneration studies in central Norrland). Norrlands Skogsvårdsförbunds Tidskrift, pp 247–293
- Axelsson EP, Lundmark T, Högberg P, Nordin A (2014) Belowground competition directs spatial patterns of seedling growth in boreal pine forests in Fennoscandia. Forests 5(9):2106–2121
- Beland M, Agestam E, Ekö P, Gemmel P, Nilsson U (2000) Scarification and seedfall affects natural regeneration of scots pine under two shelterwood densities and a clear-cut in southern Sweden. Scand J For Res 15(2):247–255
- Bøhme JG (1957) Bledningsskog II. Tidsskr Skogbr 65:203–247
- Borgstrand E (2014) Plantors och träds tillväxt efter schackrutehugning och i konventionellt trakthyggesbruk (Seedling and tree growth after Chequered-Gap-Shelterwood-Cutting and in conventional clear-cutting system). Master thesis, Swedish University of Agricultural Sciences 2014:23
- Brodie LC, Harrington CA (2020) Guide to variable-density thinning using skips and gaps, vol 37. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR
- de Chantal M, Leinonen K, Kuuluvainen T et al (2003) Early response of *Pinus sylvestris* and *Picea abies* seedlings to an experimental canopy gap in a boreal spruce forest. For Ecol Manag 176:321–336
- Dodson EK, Ares A, Puettmann K (2012) Early responses to thinning treatments designed to accelerate late successional forest structure in young coniferous stands of western Oregon, USA. Can J For Res Revue Canadienne De Recherche Forestiere 42(2):345–355
- Donos PJ et al (2020) Short-term effects of variable-density thinning on regeneration in hardwood-dominated temperate rainforests. For Ecol Manag 464
- Downey M, Heikkinen J, Valkonen S (2018) Natural tree regeneration and vegetation dynamics across harvest gaps in Norway spruce dominated forests in southern Finland. Can J For Res 48:524–534
- Drössler L, Eko PM, Balster R (2015) Short-term development of a multilayered forest stand after target diameter harvest in southern Sweden. Can J For Res 45(9):1198–1205
- Drössler L, Fahlvik N, Wysocka NK, Hjelm K, Kuehne C (2017) Natural regeneration in a multi-layered *Pinus sylvestris*-*Picea abies* Forest after target diameter harvest and soil scarification. Forests 8(2)
- Drössler L, Nilsson U, Lundqvist L (2014) Simulated transformation of even-aged Norway spruce stands to multi-layered forests: an experiment to explore the potential of tree size differentiation. Forestry 87(2):239–248
- Eerikäinen K, Valkonen S, Saksa T (2014) Ingrowth, survival and height growth of small trees in uneven-aged *Picea abies* stands in southern Finland. For Ecosyst 1(5):10
- Elfving B (1990) Granplantering under gles högskärm i fjällskog (Spruce planting under sparse high canopy in mountain forest). Sveriges Skogsvårdsförbunds Tidskrift 5:1–8
- Engelmark O, Hytteborn H (1999) Coniferous forests. Acta phytogeographica suecica 84:55–74

- Erefur C, Bergsten U, Lundmark T, De Chantal M (2011) Establishment of planted Norway spruce and Scots pine seedlings: effects of light environment, fertilisation, and orientation and distance with respect to shelter trees. *New Forests* 41(2):263–276
- Fries J (1979) Natural regeneration within the Siljansfors experimental park. *Sveriges Skogsvaardsfoerbunds Tidskrift*
- Goude M, Erefur C, Johansson U, Nilsson U (2022) Hyggesfria skogliga fältförsök i Sverige. En sammenställning av tillgängliga långtidsförsök (Clear-cut free forest field trials in Sweden. A compilation of available long-term trials). SLU Report 22
- Granhus A, Allen M, Bergsaker E (2020) Fjellskoghogst—produksjon, foryngelse og økonomi (Mountain selective cutting - production, regeneration and economy). NIBIO Rapport 72
- Granhus A, Brække FH, Hanssen KH, Haveraaen O (2003) Effects of partial cutting and scarification on planted *Picea abies* at mid-elevation sites in south-East Norway. *Scand J For Res* 18:237–246
- Granhus A, Ødegård E, Bergseng E, Bergsaker E (2021) Lukkede hogster - produksjon, foryngelse og økonomi (CCF - production, regeneration and economy). NIBIO Rapport 7(148):42
- Hagner S (1962) Naturlig förnygring under skärm. En analys av förnygringsmetoden, dess möjligheter och begränsningar i mellannorrländskt skogsbruk (Natural regeneration under canopy. An analysis of the regeneration method, its possibilities and limitations in mid-northern forestry). *Meddelande från Statens skogsforskningsinstitut* 52(4):1–263
- Hagner S (1965) Om fröproduktion, fröträdsval och plantuppslag i försök med naturlig förnygring (About seed production, seed tree selection and seedling selection in experiments with natural regeneration). *Studia Forestalia Suecica* 27:113
- Hallikainen V, Hyppönen M, Hökkä H et al (2019) Natural regeneration after gap cutting in scots pine stands in northern Finland. *Scand J For Res* 34:115–125
- Hånell B (1993) Regeneration of *Picea abies* forests on highly productive peatlands—clearcutting or selective cutting? *Scand J For Res* 8(1–4):518–527
- Hånell B, Ottosson-Löfvenius M (1994) Windthrow after shelterwood cutting in *Picea abies* peatland forests. *Scand J For Res* 9(1–4):261–269
- Hanssen KH (2003) Natural regeneration of *Picea abies* on small clear-cuts in SE Norway. *For Ecol Manag* 180:199–213
- Hanssen KH (2007) Endringer i mikroklima ved lukkede hogster (Changes in microclimate with CCF). In: Nygaard PH and Fløistad IS (eds). *Foryngelse for et bærekraftig skogbruk (Regeneration for sustainable forestry)*. Forskning fra Skog og landskap 2(7):17–21
- Heikinheimo O (1937) Metsäpuiden siementämiskyvystä II (of the seeding capacity of forest trees II). *Commun Inst For Fenn* 24(4):67
- Henttonen H, Kanninen M, Nygren M, Ojansuu R (1986) The maturation of *Pinus sylvestris* seeds in relation to temperature climate in northern Finland. *Scand J For Res* 1(1–4):243–249
- Hesselman H (1938) Fortsatta studier över tallens och granens fröspridning samt kalhyggets besåning (Continued studies on pine and spruce seed dispersal on clear-cuts). *Medd Stat Skogförsöksanstalt* 31:1–64
- Hökkä H, Repola J (2018) Pienaukkohakkuun uudistumistulos Pohjois-Suomen korpikuusikossa 10 vuoden kuluttua hakkuusta (Regeneration results in small gaps on fertile peatlands in Northern Finland 10 years after cutting). *Metsätieteen aikakauskirja* 2018–7808, p 17
- Hökkä H, Repola J, Moilanen M et al (2011) Seedling survival and establishment in small canopy openings in drained spruce mires in northern Finland. *Silva Fenn*:45633–45645
- Hökkä H, Repola J, Moilanen M et al (2012) Seedling establishment on small cutting areas with or without site preparation in a drained spruce mire—a case study in northern Finland. *Silva Fenn* 46:695–705
- Holgen P, Hånell B (2000) Performance of planted and naturally regenerated seedlings in *Picea abies*-dominated shelterwood stands and clearcuts in Sweden. *For Ecol Manag* 127(1–3):129–138. [https://doi.org/10.1016/S0378-1127\(99\)00125-5](https://doi.org/10.1016/S0378-1127(99)00125-5)
- Karlsson C (2000) Effects of release cutting and soil scarification on natural regeneration in *Pinus sylvestris* shelterwoods. Swedish University of Agricultural Sciences

- Karlsson C, Örlander G (2000) Soil scarification shortly before a rich seed fall improves seedling establishment in seed tree stands of *Pinus sylvestris*. *Scan J For Res* 15(2):256–266
- Karlsson C, Örlander G (2002) Mineral nutrients in needles of *Pinus sylvestris* seed trees after release cutting and their correlations with cone production and seed weight. *For Ecol Manag* 166(1–3, 183):–191
- Karlsson M, Nilsson U (2005) The effects of scarification and shelterwood treatments on naturally regenerated seedlings in southern Sweden. *For Ecol Manag* 205:183–197
- Kielland-Lund J (1981) Hva er fjellskog? (What is a mountain forest?). *Tidsskr Skogbr* 89:46–61
- Knoke T, Plusczyk N (2001) On economic consequences of transformation of a spruce (*Picea abies* (L) Karst) dominated stand from regular into irregular age structure. *For Ecol Manag* 151:163–179
- Koistinen E, Valkonen S (1993) Models for height development of Norway spruce and scots pine advance growth after release in southern Finland. *Silva Fennica* 27(3):179–194
- Koski V (1978) Results of long-time measurements of the quantity of flowering and seed crop of forest trees
- Koski V (1991) Generative reproduction and genetic processes in nature. *Genetics of Scots pine*:59–72
- Kramer K, Degen B, Buschbom J, Hickler T, Thuiller W, Sykes MT, De Winter W (2010) Modelling exploration of the future of European beech (*Fagus sylvatica* L.) under climate change—range, abundance, genetic diversity and adaptive response. *For Ecol Manag* 259(11):2213–2222
- Kullman L (1996) Norway spruce present in the Scandes Mountains, Sweden at 8000 BP: new light on Holocene tree spread. *Glob Ecol Biogeogr Lett*:94–101
- Kuuluvainen T, Hokkanen TJ, Järvinen E et al (1993) Factors related to seedling growth in a boreal scots pine stand: a spatial analysis of a vegetation-soil system. *Can J For Res* 23:2101–2109
- Kyrö M, Hallikainen V, Valkonen S, Hyppönen M, Puttonen P, Bergsten U, Winsa H, Rautio P (2022) Effects of overstory tree density, site preparation, and ground vegetation on natural scots pine seedling emergence and survival in northern boreal pine forests. *Can J For Res* 52(5):860–869
- Lähde E, Laiho O, Norokorpi Y, Saksa T (2002) Development of Norway spruce dominated stands after single-tree selection and low thinning. *Can J For Res* 32:1577–1584
- Langvall O, Örlander G (2001) Effects of pine shelterwoods on microclimate and frost damage to Norway spruce seedlings. *Can J For Res* 31(1):155–164
- Leemans R (1991) Canopy gaps and establishment patterns of spruce (*Picea abies* (L) karst) in two old-growth coniferous forests in Central Sweden. *Vegetatio* 93:157–165
- Lehtonen A, Leppä K, Rinne-Garmston KT, Sahlstedt E, Schiestl-Aalto P, Heikkinen J, Young GH, Korkiakoski M, Peltoniemi M, Sarkkola S (2023) Fast recovery of suppressed Norway spruce trees after selection harvesting on a drained peatland forest site. *For Ecol Manag* 530:120759
- Lehto J (1956) Tutkimuksia männyn luontaisesta uudistumisesta Etelä-Suomen kangasmailla. Summary (studies on the natural reproduction of scots pine on the upland soils of southern Finland). *Acta For Fenn* 66:1–106
- Leinonen K, Leikola M, Peltonen A, Räsänen PK (1989) Kuusen luontainen uudistaminen Pirkka-Hämeen metsälautakunnassa (natural regeneration of Norway spruce in the Pirkka-Häme forestry agency). *Acta Forestalia Fennica* 209
- Löf M, Dey DC, Navarro RM, Jacobs DF (2012) Mechanical site preparation for forest restoration. *New For* 43:825–848
- Lofvenius MO (1995) Temperature and radiation regimes in pine shelterwood and clear-cut area
- Lukkala OJ (1946) Korpimetsien luontainen uudistaminen (the natural regeneration of the riparian forests). *Communicationes Instituti Forestalis Fenniae* 34(3):150
- Lula M (2022) Regeneration methods and long-term production for Scots pine on medium fertile and fertile sites. Thesis. Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, Alnarp
- Lundqvist L (1991) Some notes on the regeneration on six permanent plots managed with single-tree selection. *For Ecol Manag* 46:49–57

- Lundqvist L (1993) Changes in the stand structure on permanent *Picea abies* plots managed with single-tree selection. *Scand J For Res* 8:510–517
- Lundqvist L (2004) Stand development in uneven-aged sub-alpine *Picea abies* stands after partial harvest estimated from repeated surveys. *Forestry* 77:119–129
- Lundqvist L, Ahlström MA, Axelsson EP, Mörling T, Valinger E (2019) Multi-layered scots pine forests in boreal Sweden result from mass regeneration and size stratification. *For Ecol Manag* 441:176–181
- Lundqvist L, Nilson K (2007) Regeneration dynamics in an uneven-aged virgin Norway spruce forest in northern Sweden. *Scand J For Res* 22:304–309
- Lundqvist L (2017) Tamm review: selection system reduces long-term volume growth in Fennoscandic uneven-aged Norway spruce forests. *For Ecol Manag* 391:362–375
- Mielikäinen K, Valkonen S (1995) Kaksijaksoisen kuusi-koivu-sekametsikön kasvu (growth of a biennial spruce-birch mixed stand). *Folia Forestalia* 2:81–97
- Mikola P (1971) Reflexion of climatic fluctuation in the forestry practices of northern Finland. *Reports from the Kevo Subarctic Research Station* 8:115–121
- Moan Mn Å (2021) Effects of stand structure and stand density on volume growth and ingrowth in selectively cut stands in Norway. Master Thesis, Norwegian University of Life Sciences, pp 61
- Moilanen M, Issakainen J, Vesala H (2011) Metsän uudistaminen mustikkaturvekankaalla—luontaisesti vai viljellen? (Forest regeneration in blueberry bog - natural or cultivated?). *Metlan työraportteja* 192. <http://urn.fi/URN:ISBN:978-951-40-2287-6>
- Mork E (1968) Ecological investigations in the mountain forest at Hirkjølen experimental area. *Nor For Res Inst Report* 93:463–614
- Nilsen P (1988) Fjellskoghogst i granskog - gjenvekst og produksjon etter tidligere hogster (Selective cutting in mountain spruce forests - regeneration and production after earlier cuttings). *Raport Nor Inst Skogforsk* 2(88):1–26
- Nilson K, Lundqvist L (2001) Effects of stand structure and density on development of natural regeneration in two *Picea abies* stands in Sweden. *Scand J For Res* 16:253–259
- Nilsson U, Gemmel P, Johansson U, Karlsson M, Welander T (2002) Natural regeneration of Norway spruce, scots pine and birch under Norway spruce shelterwoods of varying densities on a Mesic-dry site in southern Sweden. *For Ecol Manag* 161(1–3):133–145
- Numminen E (1982) Pohjois-Lapin metsäpuiden siementuotanto (Forest tree seed production in Northern Lapland)
- Nygren M, Rissanen K, Eerikäinen K, Saksa T, Valkonen S (2017) Norway spruce cone crops in uneven-aged stands in southern Finland. *For Ecol Manag* 390:68–72
- Oleskog G, Sahlén K (2000) Effects of seedbed substrate on moisture conditions and germination of *Pinus sylvestris* seeds in a clearcut. *Scand J For Res* 15(2):225–236
- Örlander G, Karlsson C (2000) Influence of shelterwood density on survival and height increment of *Picea abies* advance growth. *Scand J For Res* 15(1):20–29. <https://doi.org/10.1080/02827580050160439>
- Øyen BH, Nilsen P (2002) Growth effects after mountain forest selective cutting in Southeast Norway. *Forestry* 75:401–410
- Øyen BH, Nilsen P (2004) Growth and recruitment after mountain forest selective cutting in irregular spruce forest. A case study in northern Norway. *Silva Fenn* 38:383–392
- Paavialainen E, Päiväven J (1995) Peatland forestry—ecological principles. Springer Verlag, p 248
- Pettersson M (2004) Regeneration methods to reduce pine weevil damage to conifer seedlings
- Place ICM (1955) The influence of seedbed conditions on the regeneration of spruce and balsam fir. Canada Department of Northern Affairs and Natural Resources. Forestry Branch, Bull 117:87
- Puettmann KJ, Ares A, Burton JI, Dodson EK (2016) Forest restoration using variable density thinning: lessons from Douglas-fir stands in Western Oregon. *Forests* 7(12)
- Pulliaainen L (2019) Taimikon laatu ja jatkokehityksen edellytykset Lounais-Lapin turvemaakuusikoiden pienaukkohakkuissa (The quality of spruce seedlings and the condition for further development of spruce mire stands in southwest Lapland canopy gaps). Master's Thesis. Helsingin yliopisto. Maatalous-metsätieteellinen tiedekunta, metsätieteiden osasto, p 67

- Rautio P, Hallikainen V, Valkonen S, Karjalainen J, Puttonen P, Bergsten U, Winsa H, Hyppönen M (2023) Manipulating overstorey density and mineral soil exposure for optimal natural regeneration of scots pine. *For Ecol Manag* 539:120996
- Ruuska J, Siipilehto J, Valkonen S (2008) Effect of edge stands on the development of young *Pinus sylvestris* stands in southern Finland. *Scand J For Res* 23:214–226
- Saarinen M, Valkonen S, Sarkkola S, Nieminen M, Penttilä T, Laiho R (2020) Jatkuvapeitteisen metsänkasvatuksen mahdollisuudet ojitetuilla turvemaidilla (Possibilities for continuous cover forestry in drained peatland forests). *Metsätieteen aikakauskirja* 2020–10372 p. 21. <https://doi.org/10.14214/ma.10372>
- Saksa T (2004) Regeneration process from seed crop to saplings - a case study in uneven-aged Norway spruce-dominated stands in southern Finland. *Silva Fenn* 38(4):371–381
- Saksa T, Valkonen S (2011) Dynamics of seedling establishment and survival in uneven-aged boreal forests. *For Ecol Manag* 261(8):1409–1414
- Sarasto J, Seppälä K (1964) Männyn kylvöistä ojitettujen soiden sammal- ja jäkäläkasvustoihin (On sowing of pine in moss and lichen vegetation on drained swamps). *Suo* 15(3):54–58
- Sarvas R (1962) Investigations on the flowering and seed crop of *Pinus sylvestris*. *Metsätieteellisen tutkimuslaitoksen julkaisuja* 53(4)
- Sikström U (1997) Avgång i skärmen och plantetablering vid förnygring av gran under högskärm (Decreasing in shelterwood and establishment of plants spruce under shelterwood). *Skogforsk Arbetsrapport nr 369*, p 147
- Sikström U, Glöde D (2000) Damage to *Picea abies* regeneration after final cutting of shelterwood with single- and double-grip harvester systems. *Scand J For Res* 15(2):274–283
- Skoklefald S (1967) Fristilling av naturlig gjenvekst av gran (Release of natural Norway spruce regeneration). *Medd Norske Skogforsves* 23:381–409
- Skoklefald S (1989) Planting og naturlig förnygelse av gran under skjerm og på snauflete (Planting and natural regeneration of Norway spruce under shelterwood and on clear-cut area). *Norsk Inst Skogforsk, Rapp* 6, pp 39
- Smith DM, Larson BC, Kelty MJ, Ashton PMS (1997) *The practice of Silviculture - applied Forest ecology*, no Ed 9. Wiley & Sons, New York
- Sundkvist H (1994) Extent and causes of mortality in *Pinus sylvestris* advance growth in northern Sweden following overstorey removal. *Scand J For Res* 9(1–4):158–164
- Sydow F, Örlander G (1994) The influence of shelterwood density on *Hylobius abietis* (L.) occurrence and feeding on planted conifers. *Scand J For Res* 9(1–4):367–375
- Valkonen S (1992) Metsien uudistaminen korkeilla alueilla Pohjois-Suomessa (Regeneration of forests in high areas in Northern Finland). *Metsäntutkimuslaitos*
- Valkonen S (2000) Effect of retained scots pine trees on regeneration, growth, form, and yield of forest stands. *For Syst* 9:121–145
- Valkonen S (2019) Pienaukkojen ja osittaishakkuuaukkojen taimettuminen Häiriödynamikka -hankkeen tutkimusalueilla (Tree regeneration in cut gaps of variable sizes in the experimental sites of the DistDyn project). *Luonnonvara- ja biotalouden tutkimus*, 69/2019
- Valkonen S (ed) (2020) *Metsän jatkuvasta kasvatuksesta (On Continuous-Cover Forestry)*. Metsäkustannus ja Luonnonvarakeskus, Helsinki, p 127
- Valkonen S, Aulus Giacosa L, Heikkinen J (2020) Tree mortality in the dynamics and management of uneven-aged Norway spruce stands in southern Finland. *Eur J For Res* 139(6):989–998. <https://link.springer.com/article/10.1007/s10342-020-01301-8>
- Valkonen S, Koskinen K, Mäkinen J et al (2011) Natural regeneration in patch clear-cutting in *Picea abies* stands in southern Finland. *Scand J For Res* 26:530–542
- Valkonen S, Maguire DA (2005) Relationship between seedbed properties and the emergence of spruce germinants in recently cut Norway spruce selection stands in southern Finland. *For Ecol Manag* 210:255–266
- Valkonen S, Siitonen J (2016) Tree regeneration in patch cutting in Norway spruce stands in northern Finland. *Scand J For Res* 31:271–278

- Wallertz K, Örlander G, Luoranen J (2005) Damage by pine weevil *Hylobius abietis* to conifer seedlings after shelterwood removal. *Scand J For Res* 20(5):412–420
- Wood JE, Jeglum JK (1984) Black spruce regeneration trials near Nipigon, Ontario: Planting versus seeding, lowlands versus upland, clearcut versus stripcut. Canadian Forestry Service, Sault Ste. Marie, Information Report O-X-361 p 19

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