Chapter 4
Growth and Yield

Simone Bianchi, Andreas Brunner, Kjersti Holt Hanssen, Hannu Hökkä, Urban Nilsson, Nils Fahlvik, and Jari Hynynen

Abstract

- There is still a lack of knowledge on growth and yield (G&Y) in continuous cover forestry (CCF). Most published studies are on the selection system with Norway spruce.
- Published comparisons of the selection system with rotation forestry (RF) show contrasting results. Generally, there seems to be a trend toward faster stand growth in RF.
- However, there are many uncertainties due to several confounding factors, such as stand-density effects, site-quality classification, and/or growth models used.

S. Bianchi (✉)
Natural Resources Institute Finland (Luke), Helsinki, Finland
e-mail: simone.bianchi@luke.fi

A. Brunner
Norwegian University of Life Sciences (NMBU), Ås, Norway
e-mail: andreas.brunner@nmbu.no

K. H. Hanssen
Norwegian Institute of Bioeconomy Research (NIBIO), Ås, Norway
e-mail: kjersti.hanssen@nibio.no

H. Hökkä
Natural Resources Institute Finland (Luke), Oulu, Finland
e-mail: hannu.hokka@luke.fi

U. Nilsson
Swedish University of Agricultural Sciences (SLU), Alnarp, Sweden
e-mail: urban.nilsson@slu.se

N. Fahlvik
Forestry Research Institute of Sweden (Skogforsk), Svalöv, Sweden
e-mail: nils.fahlvik@skogforsk.se

J. Hynynen
Natural Resources Institute Finland (Luke), Savonlinna, Finland
e-mail: jari.hynynen@luke.fi

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Most studies do not properly account for all these factors, making it difficult to generalise their results.

- The optimal stand density trade off for the selection system between stand growth and recruitment should be better investigated. Preliminary results show this could strongly affect stand growth.
- There is even less knowledge related to G&Y during conversion, a potential bottleneck for full implementation of CCF in the region.

Keywords Growth modelling · Site quality · Stand density · Stand structure · Stand dynamics

4.1 Introduction

4.1.1 Main Drivers of Forest Growth and Yield

Growth and yield (G&Y) studies investigate the dynamics of forest increment, usually to formulate growth models able to predict the future development of forest stands, and thus support decision making for their management. G&Y has been widely studied in even-aged stands of the clearcutting system. However, it has been less studied in continuous cover forestry (CCF) where there are additional intrinsic challenges, briefly mentioned in this introduction and expanded on in later sections.

In even-aged stands, trees have similar ages, the structure is relatively homogeneous, and average stand variables are highly correlated to stand age. Age is often used directly or indirectly as a predictor in modelling. An important example of this is the site index, a system widely used to evaluate stand productivity based on the height of the dominant trees at a given age (Skovsgaard and Vanclay 2008). However, this index is not directly applicable to CCF, as we will see in Sect. 4.2.3.

Stand density is also an important driver of growth and yield. In CCF, stand density varies greatly in space, much more than in even-aged stands. It is often not even possible to accurately assess stand density with simple metrics in structurally-complex multi-layered stands.

Ingrowth is a major contribution to total production in CCF. This complicates G&Y studies. Regeneration and ingrowth are complex processes (see Chap. 3) that vary greatly in space and time, and are too poorly understood to be represented in process-based models. Empirical models of regeneration or ingrowth need extensive data which often does not exist, and need to incorporate many random effects. G&Y models without such tools are incomplete for CCF studies (cf. Ekholm et al. 2023).

In Chap. 12 an analysis of various disturbances will be presented. G&Y studies often do not include losses due to episodic events, like windthrow, snow breakage, or bark-beetle attacks, which are likely to be less significant in CCF than in even-aged stands. On the other hand, during conversion of even-aged stands to CCF windthrow risk may be higher (see Sect. 4.3). The limited knowledge about damage further hinders the comparison of G&Y between CCF and even-aged stands.

4.1.2 Forest Growth Models for CCF

All factors mentioned in Sect. 4.1.1 influence what types of forest growth models can be suitable for CCF stands. Kuuluvainen et al. (2012) suggest developing "growth models general enough to describe both [even-aged and CCF] management alternatives relatively well," whereas Lundqvist (2017) argues that it "is difficult to know whether the model used can handle different stand structures and silvicultural systems equally well." Forest planning needs simulators adequate for stands managed under any system, without over-predicting yields from one system relative to the other (see Chap. 5). At a minimum, forest growth models need to comprise tools for regeneration or ingrowth, growth, and mortality.

Stand-level models, where only average stand characteristics are simulated, cannot be used for CCF due to the high variation of tree age, size, and spatial distribution. The best alternative is individual-tree models, which track each tree in the simulation unit. Another important characteristic of individual-tree models is their approach to spatial distributions. In distance-independent models, resource competition is based only on average stand conditions. If asymmetric competition is considered, i.e., where larger individuals obtain more resources and suppress the growth of smaller individuals (Weiner 1990), it is only based on competitors' size and not on their location. In distance-dependent or spatially explicit models, resource competition is also a function of the subject tree's location relative to its competitors. Some studies find that distance-dependent models only slightly improve on distance-independent models, even in spatially- and structurally-complex stands, questioning if their higher complexity is worth the small improvements (Kuehne et al. 2019; Bianchi et al. 2020). However, those studies only simulated single growing periods. Assuming that competition pressure is equal for all trees of the same size within an irregular stand may have big consequences in long-term simulations. For example, simulated tree growth would not be influenced by local density, and trees released from competition due to nearby harvesting would not increase their growth more than trees further from newly opened gaps. This issue should be investigated more.

In Finland, Pukkala et al. (2013, 2021) prepared distance-independent tree-level models claimed to be suitable for both CCF and even-aged forestry, comprising tools for simulating ingrowth, growth, and mortality. The most recent models (Pukkala et al. 2021) have been fitted to Finnish national forest inventory (NFI) plots, and a version based on Swedish NFI plots is in preparation. Both models have been used widely for simulation studies comparing CCF and even-aged forestry (e.g, Parkatti et al. 2019; Österberg et al. 2023). Bianchi et al. (2023) independently validated their basal area increment component together with a new alternative fitted to most recent Finnish NFI plots, confirming that all those models could be used both in even-aged forestry and CCF, although with slight differences in accuracy.

Other existing forest growth models in Fennoscandia are fitted and targeted to even-aged stands. In Finland, MELA and MOTTI are simulators using the same growth models. They use stand- and tree-level tools to simulate full-rotation development. MOTTI implements regeneration models by Eerikäinen et al. (2007) for uneven-aged stands and CCF, based on the permanent experimental ERIKA plots. They cover establishment and height development of the established seedlings. For trees past the regeneration phase, there are calibration functions for diameter and height growth to adapt the original growth models to CCF (Lee et al. 2024). In Sweden, the models of Elfving and Nyström (2010) within HEUREKA, originally suited only for even-aged stands, were independently validated with CCF data by Fagerberg et al. (2022), showing some biases. CCF results from HEUREKA are less precise than for the clearcutting system (Lämås et al. 2023). In Norway, the models of Andreassen and Øyen (2002), Bollandsås and Næsset (2009), and Øyen et al. (2011) could be used on CCF data although they need a site index, whose limitations for CCF were previously noted. Also in Norway, a transition-matrix model from Bollandsås et al. (2008) was used to compare CCF and even-aged stands in Parkatti et al. (2019). All these simulators use distance-independent models.

4.2 The Selection System

Productivity of forest stands managed with the selection system may vary over time, among sites, with stand density, and with stand structure. All of these factors affect all productivity-related processes (growth, mortality, and ingrowth), and must be considered in growth and yield studies. Comparing productivity under the selection system and even-aged forestry is a topic of great interest that needs to consider these effects (Sect. 4.2.6).

The selection system in Fennoscandia has mostly been studied for stands dominated by Norway spruce, as it is the most shade-tolerant of the important timber species. In this chapter, we therefore focus mostly on spruce and only briefly discuss this system in Scots pine or mixed-species stands. In addition, mountain forest selection cutting is practised in Norway and Sweden (Sect. 4.2.7).

4.2.1 Variation in Time

In contrast to clearcutting and most other CCF methods, the selection system maintains a long-term target stand structure with frequent cuts. Therefore, stand density and productivity vary less over time compared to other systems. Current annual increment (CAI) is defined as the annual volume increment for a specific and short period, while mean annual increment (MAI) is the total volume increment averaged over the full rotation. For the clearcutting system, MAI is calculated over a rotation from planting to final felling to provide the long-term productivity estimate, while

CAI varies greatly within the cycle (Fig. 4.1). For the selection system, CAI increases slightly as density increases within a period between two cuts, but stays relatively constant among cut periods in optimal management and remains very similar to MAI (Fig. 4.1). Given optimal management, including adequate ingrowth, observation periods of only a few decades might suffice for estimating long-term productivity in the selection system. This possibility is frequently overlooked in studies comparing the selection system with the clearcutting system (Ekholm et al. 2023).

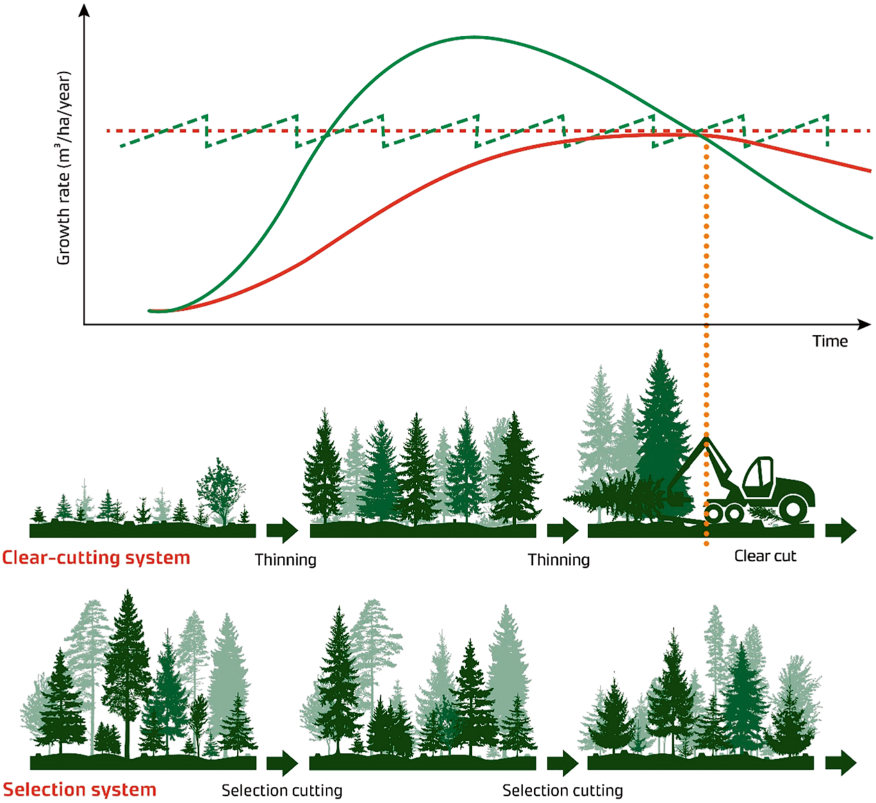

Fig. 4.1 Comparison of forest growth between the clear-cutting and selection systems during their corresponding cycles. Top: how current annual increment (CAI, green) and mean annual increment (MAI, red) vary between clearcut forestry (continuous line) and the selection system (dashed line) over time. In this example, MAI was set to be the same for both systems over the full cycle. Bottom: simplified phases of stand development and removals. Redrawn from Ekholm et al. (2023) and Routa and Huuskonen (2022)

4.2.2 Site Quality Effects

Site quality, defined as “the combination of physical and biological factors characterizing a particular geographic location or site,” has large effects on forest productivity (Skovsgaard and Vanclay 2008). While site quality is a descriptive assessment, site productivity is “a quantitative estimate of the potential of a site to produce plant biomass” (Skovsgaard and Vanclay 2008). For even-aged stands, site productivity has been often quantified with a dendrocentric classification such as site index (SI), the dominant stand height at a given age. SI was developed for stands managed with thinning from below, mainly removing non-dominant trees without affecting the dominant height. SI cannot be easily applied to uneven-aged CCF stands; tree age is unknown or does not relate in the same way with average stand characteristics, and selection harvesting cutting affects the stand dominant height. There could be further confounding effects due to increased species diversity in CCF (del Río et al. 2016). Variation of G&Y with site quality is so large that other effects, like stand density, cannot be studied without correcting for site quality effects.

In the Norwegian selection system experiments, SI has been estimated with a number of alternative methods developed for the clearcutting system in that country (Andreassen 1994). In Finland and Sweden, there are models for calculating SI based on environmental data, including climate, geographical variables, and ground vegetation, known as the geocentric approach (Hägglund and Lundmark 1977; Hynynen et al. 2002). Such an age-independent system could in theory be applied to CCF stands, although its application should be properly validated.

Some studies outside Fennoscandia have explored height-diameter relationships for site quality estimation, calculating indices where dominant diameter replaces age in determining site index. The dominant stand height is calculated at a reference dominant diameter (Huang and Titus 1993; Wang 1998; Beltran et al. 2016; Duan et al. 2018; Castaño-Santamaría et al. 2023). In two studies (Beltran et al. 2016; Castaño-Santamaría et al. 2023), the diameter-based index was well correlated with the age-based index, but not in a third study (Wang 1998). However, although these studies used uneven-aged stand data, all were unmanaged. After selection cutting, the relationship between dominant height and dominant diameter may be different. Stand density may have further confounding effects on dominant diameter. In contrast, the tree-level height-diameter relationship is more stable over time in the selection system, with a sigmoid shape (Pretzsch 2009). The asymptote of this relationship indicates maximum dominant height and might therefore indicate site quality. These concepts need to be developed further for Fennoscandian conditions. An alternative approach stemming from age-based site indices uses dynamic dominant height models derived from differential equations (Salas-Eljatib 2020). Riofrío et al. (2023) transformed an age-based site index formula into a differential time-based formula, independent of the actual age, to create a site index based on dominant-height growth rate. The geocentric approach was applied by Hennigar et al. (2017), modelling total biomass increment of naturally-regenerated stands with a non-linear function whose asymptote was estimated mainly from environmental variables. Such an asymptote could be computed for any site providing an estimate of its maximum productivity.

4.2.3 Stand Density Effects

Managing the selection system requires information about stand density effects on growth and ingrowth. Optimal management not only has to maintain the desired stand structure, but also a stand density that leads to maximum stand growth and sufficient ingrowth.

Lundqvist (2017) reviewed 14 selection system field studies starting from the 1980s, finding a positive relationship between standing volume and volume growth in all cases. The standing volume in those stands ranged up to about 300 m^3/ha. He suggested that the repeatedly-harvested study plots had yet not reached a maximum growth rate; the density-growth relationship had not peaked. He also noted that the lack of site quality corrections for these datasets might make the density-growth relationship appear linear rather than asymptotic. Ekholm et al. (2023) showed a similar positive density-growth relationship in their Fig. 5, partly based on the same data as in Lundqvist (2017). A similar trend is shown in the Swedish report from Goude et al. (2022) up to 200–300 m^3/ha, after which the increase in growth with increased standing volume tapered off. Most likely the optimal stand density for volume growth varies with site quality. However, too little data is currently available to quantify this.

Variation in growth between individual saplings in selection system plots can only be partly explained by neighbourhood stand density variables (Lundqvist 2017). However, if mean stand density changes, regeneration and therefore ingrowth might change in reaction. Moan (2021) found no correlation of mean stand density with ingrowth in the Norwegian series across a rather wide range of densities below 300 m^3/ha. Lundqvist (2017) summarises a number of ingrowth studies and reports inconsistent stand density effects, and calculates ingrowth rates above 8–10 cm diameter at breast height to be around 10 trees/ha/yr. Using the results from Moan (2021) more broadly could justify a simple non-spatial ingrowth modelling approach. The Swedish report from Goude et al. (2022) also seems to show no stand density effect on ingrowth in their Fig. 6. The Finnish models of Eerikäinen et al. (2007) found distance-dependent competition to significantly affect ingrowth, but stand-level basal area was not significantly correlated with regeneration below 28 m^2/ha.

These studies should jointly underlie investigating the optimal stand density for both stand growth and ingrowth. They suggest maximum growth at a standing volume of around 300 m^3/ha, up to which the effect of stand density seems to not be significantly correlated with ingrowth. Further research is needed to validate these results.

Recently, the selection system has also been applied to Scots pine forests, for example in recreation areas. In the context of climate adaptation, it will be necessary to include mixtures of less shade-tolerant species in the selection system. To allow sufficient ingrowth of the light-demanding species, stand density needs to be reduced with the consequence of reduced growth. Thinning appears to reduce Scots pine growth more strongly than Norway spruce growth based on the density-growth relationship observed in thinning experiments in the region (Mäkinen and Isomäki 2004).

4.2.4 Stand Structure Effects

The stand density effect on growth is further modified by the tree size distribution and the tree-size-growth relationship (Forrester 2019). In other words, given the same stand density and tree growth rate, the size distribution has a profound effect on stand growth. Lundqvist (2017) suggests that the stand structure of older CCF studies, more two-storied than full-storied, may have caused slower growth.

Stands with irregular structure have been sometimes shown to have significantly higher tree-level growth, perhaps due to better resource use efficiency (Lei et al. 2009; Bianchi et al. 2020). However, as discussed by Forrester (2019), those results must still be analysed in the complementary framework of stand density, structure, and size growth to avoid biased conclusions. For example, Moan (2021) found no significant relationships between structural diversity and stand volume growth.

4.2.5 Comparison with Clearcutting Forestry

Selection system and clearcutting system productivity can only be directly compared on the same site, under optimal management, and over a full rotation. This type of experiment has never been started, let alone completed, in Fennoscandia. All studies comparing selection and clearcutting system productivity have either used short-term experimental data or growth model predictions. For these comparisons, all factors that have been addressed in the previous sections need to be controlled or corrected for simultaneously. However, most studies of selection system productivity in Fennoscandia lack these corrections, and sometimes crucial variables like site quality are not even reported in the publications (see Sect. 4.2.3). This leads to highly contradictory published results, from underyielding to overyielding in the selection system compared to the clearcutting system (Andreassen 1994; Lundqvist 2017), and limits possible conclusions and generalisations. For example, a review by Kuuluvainen et al. (2012) found that almost half of studies show faster long-term growth in uneven-aged stands (using a definition broader for CCF than in this book) than in RF. They examined seven simulation studies and four field studies, but without considering or discussing any of the above-mentioned confounding factors.

The review and earlier studies by Lundqvist (2017) have addressed and tried to consider the density effect when analysing results from previously published studies. Problems quantifying site quality correctly for both systems appear to be a major obstacle to drawing valid conclusions. Lundqvist (2017) noted that selection system field studies often report slower growth than for the clearcutting system. However, despite an extensive description of stand density effects in an earlier section of the review, the author did not correct for it in the growth comparison section. Eventually, he suggested that selection systems should be managed with moderate harvests at relatively short intervals to maintain a larger growing stock. This could achieve sustainable volume growth approaching the site productivity estimated by environmental factors. However, Lundqvist also pointed out that the current SI system in Sweden underestimates stand productivity in newer even-aged stands (Tegnhammar 1992; Elfving and Nyström 1996; Yue et al. 2014). If true, this would suggest a bigger difference in long-term growth rates between the two systems. Lundqvist (2017) also describes in detail how systematic, but small, selection system experiments were established in the early twentieth century. Time series published for the experiments in Norway (Andreassen 1994) clearly illustrate how insufficient their diameter distributions and stand densities were during their first 60 years. Results and data from these experiments are still used for other studies (e.g. Lundqvist 2017; Moan 2021) but need to be interpreted carefully or original results often need to be corrected.

Hynynen et al. (2019) compared selection system productivity from the ERIKA experiments (see Chap. 3) with: (1) mid-rotation empirical CAI from thinning experiments, and (2) MAI from model simulations of even-aged stands at the same sites. In both cases, even-aged stands showed higher productivity. In comparison (1), selected thinning experiments were geographically close to the CCF stands, and with similar site fertility according to the vegetation type. Since a difference in the growing conditions was still possible, a modelling framework was applied to remove the effects of site quality and stand density. However, the empirical comparison was confounded by using CAI from thinning experiments instead of MAI (see Sect. 4.2.2). The model comparison (2) showed a 15% higher MAI in the clearcutting system. Using the same data, the study also suggested a faster stand-level reaction after thinning than after selection cutting.

Moan (2021) simultaneously corrected for stand density and site quality effects in data from two experimental series in Norway. She found that selection system plots managed at an optimal density had much smaller MAI differences from even-aged forests than reported by Andreassen (1994) for earlier data from one of the experimental series without correction for stand density effects.

Ekholm et al. (2023) discussed several limitations in comparisons carried out both using empirical studies and model simulations that are likely responsible for the large variation in the published results and make conclusions about productivity differences impossible. Use of CAI instead of MAI (see Sect. 4.2.1), unclear site quality effects (see Sect. 4.2.2), missing density corrections (see Sect. 4.2.3), poor experimental design (see Sect. 4.1), poor ingrowth models in simulators (see Sect. 4.1), and missing validation of growth models are discussed. However, many of the studies reviewed there do not investigate selection systems but thinning methods in transformation treatments to the selection system (see Sect. 4.5).

We must also highlight that there are continuous advancements in soil preparation methods (see Hjelm et al. 2019 and references within), fertilisation, and improved regeneration material that increase growth in clearcutting systems. A review of forest tree breeding programmes in Scandinavia found that they can currently increase volume growth by 10–25% (Jansson et al. 2017) but it might be much higher in the future (Rosvall and Wennström 2008). However, such advancements cannot be applied as easily to the selection system.

To conclude, interpretation of data on selection system productivity is difficult, mostly due to inadequate descriptions of density and site quality effects in published studies. Although the trend leans toward faster growth in the clearcutting system, the first attempts to correct for density effects alone (Lundqvist 2017; Ekholm et al. 2023) illustrate that productivity of the selection system might be closer to the productivity of clearcutting system. Simulation models have not been validated against empirical data from selection system stands, have poor representations of ingrowth, and show biased predictions compared with empirical data for the selection system (Ekholm et al. 2023).

4.2.6 Mountain Forest Selection Cutting

In general, harsh climate and low site indices in mountainous areas of Fennoscandia hinder regeneration and restrict investments in planting. This has led to the practice of mountain forest selection cutting ("fjellskoghogst"), where selection cutting is often combined with other types of CCF, especially group cuttings. The harvesting level has traditionally been high, removing damaged trees as well as most merchantable timber. Despite long harvesting cycles, low stand density reduces growth and yield, and regeneration is usually slow due to the cold climate (Chap. 3).

Reducing stand density to very low levels at harvesting inevitably leads to low forest growth. Lundqvist (2004) found that heavy partial harvests in sub-alpine stands in northern Sweden, leaving standing volumes below 50 m^3/ha, resulted in volume increments less than half the estimated site productivity. Øyen and Nilsen (2004) studied mountain-forest growth after selection cutting in four irregular spruce forests in Nordland, Norway. The volume increment amounted to approximately two-thirds of the yield table figures for dense even-aged stands. They interpreted the reductions as resulting from a low initial density after heavy cuttings (removing 50–65% of the standing volume) two to three decades before the inventory.

Granhus et al. (2020) studied growth 13–44 years after selection cutting in 16 mountain forest stands in Norway. Average harvested basal area was about 50%, ranging from 20% to 80%. The volume increment in the post-felling period varied considerably among sites but on average met the estimated production capacity for even-aged forests at the same site index. However, this was only the case many decades after the cuttings, with considerably lower growth for decades. Both basal area and volume growth between felling and measurement were positively correlated with post-felling basal area, and negatively correlated with basal-area-weighted mean diameter.

4.2.7 Selection Systems on Peatlands

There are no published studies from the Nordic countries based on empirical growth data from peatland forests treated with the selection system. In a recent simulation study, profitability of the selection system has been compared to the clearcutting system in peatland spruce stands in Finland (Juutinen et al. 2021). Stand development was predicted with the EFIMOD process model (Shanin et al. 2016). EFIMOD is a spatially-explicit individual-tree growth model, developed to simulate carbon- and nitrogen-pool dynamics in a tree-soil system, along with population dynamics of forest stands. The model was originally developed for mineral soil stands. In Juutinen et al. (2021) the EFIMOD model was calibrated to data from a peatland stand not managed with the selection system. When the retained basal area was above 10 m^2/ha, the MAI of selection system simulations was higher than for the clearcutting system on the same site. Because the calibration data originated from a naturally established drained peatland spruce stand, the simulated MAI most likely underestimated what the clearcutting system can achieve when sites are prepared and planted using present-day methods and material.

Peatland forests have two specific features needing consideration in all kinds of management: soil water level and nutrient availability. Changes in stand volume due to growth and cutting impact the water table level, which in turn may affect stand growth. In general, deeper water tables enhance growth (Hökkä et al. 2008), while high water tables (within 35 cm of the soil surface) may hinder growth. Especially if the retained volume is very low, as in heavy selection cutting, the technical drainage may require maintenance. These feedback effects and need for ditch network maintenance (DNM) where retained basal area is very low were accounted for in the Juutinen et al. (2021) study. In such situations, DNM significantly and profitably increased stand growth, but because of additional costs, the profitability was less than in scenarios where DNM was not needed. Peat-soil nitrogen content is disproportionately high compared to phosphorus and potassium. Specifically, potassium deficiency significantly reduces needle mass and growth. Hence, fertilisation with wood ash may be needed every 40 years no matter the stand-management method.

Six field experiments have been established in Finland from 2014–2016 in Norway-spruce-dominated stands to investigate the response of peatland forests to the selection system. The retained basal area after cutting varies from 6–17 m^2/ha. Results from those experiments cover only the first five-year growth period and are not yet published.

4.3 The Shelterwood System

In Sweden, Lula et al. (2021) have used growth models to study production and profit in planted and naturally regenerated stands under dense Scots pine shelterwoods, using starting values from experiments on relatively fertile sites in southern Sweden. They compared different initial tree densities, including a shelterwood maintained at around 15 m^2/ha, but production after natural regeneration was on average about 10–20% lower compared to planting. However, wood quality was found to be higher after natural regeneration than after planting (Agestam et al. 1998), which could economically offset the loss of production. Lula et al. (2021) estimated the cost and income of shelterwoods and the future stands and concluded that shelterwoods and natural regeneration could be an economically feasible alternative to clearcutting and planting due to low regeneration costs.

Since the study cited above was based on relatively fertile sites, little is known about long-term production and profit on less fertile sites in northern Scandinavia where abundant Scots pine stands are available for the shelterwood system. Elfving and Jakobsson (2006) concluded that the negative effect of retained Scots pine trees on understorey tree growth was relatively higher on low fertility sites than on more fertile sites. However, the retention time was between 30–90 years and overstory density low, so it is not totally comparable to a shelterwood that is removed when the new regeneration is established but is much denser than green-tree retention. Therefore, establishing experiments for comparing long-term growth of planted and naturally-regenerated stands along a fertility gradient should be prioritised.

The risk for windthrow increases after shelterwood cutting and may significantly affect total volume production. Örlander (1995) investigated shelterwood stability in southern Sweden. He found shelter tree windthrow rates of 18% for Scots pine vs. 35% for Norway spruce. Nilsson et al. (2006) investigated 22 Scots pine shelterwoods from all regions of Sweden. On average, windthrow was 9% in the south and north and 18% in central Sweden. Sikström (1997) studied damage to shelter trees in 52 Norway spruce-dominated shelterwoods. The shelterwoods were measured 2–6 growing seasons after cutting, showing on average 15% windthrow of shelter trees. Different weather conditions and variable length between cutting and measurement could have caused these differences among studies. In Finland, Pukkala et al. (2016) showed that shelterwood stands have higher windthrow risk than clearcutting system stands, which in turn are at higher risk than selection system stands. Such risks must be considered in G&Y forecasting.

4.4 The Group System

The only available results related to G&Y in gap cutting are on their regeneration dynamics, which are discussed in Chap. 3. For G&Y studies, the edge effects on the growth of both adult trees and the regeneration are important and need to be considered in experimental designs and modelling approaches (e.g., Shell et al. 2022). Edge trees next to gaps also have higher mortality risks.

Strip cutting in pine peatland relies on seed production from the edge stand to naturally regenerate the clearcut strip, for example 16–25 m wide in Stenberg et al. (2022). As a pioneer species, Scots pine needs light for seedling establishment and growth, so as a variation of the group system, strip clearcutting may provide such conditions. Strip cutting is chosen over larger clearcuts in pine on drained peatlands to mitigate the water table rise (Stenberg et al. 2022) commonly observed after peatland clearcuts (e.g., Heikurainen 1970). Rising water tables after stand removal cause problems by releasing nutrients (specifically phosphorus) and metals (iron, aluminium) from the surface peat into watercourses (Kaila et al. 2015). By cutting only half of the peatland area and keeping the other part forested, a sufficiently deep water table (at least 35 cm below ground) can be maintained without additional ditch cleaning.

Ahtikoski et al. (2022) used a simulation to compare the financial performance of rotation forestry (clearcutting with site preparation, planting, and regular ditch cleaning) and cutting in 20, 35, and 50 m-wide strips in drained peatland Scots pine stands in southern, central, and northern Finland. Growth of sapling and edge stands was modelled using a stand-level model that accounted for edge stand height and the variation in shading when different strip widths were used. Changes in ditch depth and mean water table depth due to cuttings were incorporated to guarantee that water tables remained sufficiently far from the soil surface. The second strip cutting (of the edge stands) was done when the sapling stand reached a volume of 80 m^3/ha. The simulation showed that the geographical location and strip width had a significant impact on the cutting removals and the length of the conversion phase before the steady state in strip cutting management. The wider the strip and the more southern the location the faster was the development of the sapling stand. However, with 50 m strip width the clearcut area is so wide that water level may rise and cause harmful loads to water courses before the sapling stand has established. Strip cutting is thus balancing between good growth of the sapling stand and sufficiently deep water level (Ahtikoski et al. 2022).

4.5 Conversion to CCF

Finding efficient conversion methods is crucial for adoption of CCF in northern Europe, where even-aged forest management has long been dominant. At present, a lack of experience in transforming from the clearcutting system to CCF is a major obstacle for wider scale introduction of CCF (Mason et al. 2022). Concepts for conversion of even- to uneven-aged forests have been discussed and general strategies to achieve this goal formulated (Schütz 2001; Nyland 2003). These concepts normally include repeated thinning, target diameter cutting, and patch cutting. The overall goal of the cuttings is to increase dimensional variation by manipulating the existing stand's size distribution and favouring regeneration. Recruitment is essential for the long-term transition to CCF (Hanewinkel and Pretzsch 2000). Conversion concepts typically include greater initial removals than in conventional thinnings to initiate regeneration (Drössler et al. 2014; Juutinen et al. 2018). However, heavy cuttings might decrease volume production (Hanewinkel and Pretzsch 2000) and increase the risk of storm damage losses (Wallentin 2007). Schütz (2001) stressed the importance of timely onset of conversion measures to allow stabilising measures and to assure the present stand lives long enough to complete the transition. In the Nordic context this consideration is even more important because target diameters of only around 40 cm limit the life time of shelter trees much more.

There is a great need for empirical data to evaluate and formulate conversion concepts adapted to regional conditions in northern Europe. There are ongoing efforts to establish field trials but currently few experiments are available, and they have been monitored for a limited time. One experimental series exists in Sweden to study the conversion of an even-aged Norway spruce stand to a multi-layered forest (Drössler et al. 2014). A heavy first thinning (60% of basal area) was carried out focusing on removing medium-sized trees and leaving the smallest and the largest ones. Simulations of continuous conversion measures during a 50-year period indicated a transition to a multi-layered stand in central but not southern Sweden. The estimated volume production of the conversion forestry was one-third lower than a conventional clearcutting system (Drössler et al. 2014). Recent measurements of the series showed adequate regeneration in central Sweden but no regeneration in the south (Goude et al. 2022). This calls for modifications of the treatment to adapt the conversion strategies to local conditions.

Another experiment was established in a structured mature stand dominated by Scots pine in southern Sweden (Drössler et al. 2012, 2015, 2017). The treatments included target diameter cutting with or without silvicultural actions to favour regeneration. Continuous target diameter cutting was simulated for 50 years and compared to an alternative scenario where the present stand was clearcut and replaced by a Norway spruce plantation. The estimated basal area growth was one third lower for scenarios with target diameter cutting compared to replanting with spruce (Drössler et al. 2012). Later revisions of the experiment indicated that simulated growth in the target diameter cutting scenarios might have been underestimated (Drössler et al. 2012; Goude et al. 2022). The revisions reveal an increasing share of spruce in the regeneration after initial establishment of birch in the new gaps.

In northern Sweden, larger scale conversion to CCF was tested in field experiments by cutting chequered patches (0.135–0.16 ha) in 35–120 year-old coniferous stands from 2005 to 2012 (Erefur 2010; Goude et al. 2022). Production and the abundance and growth of the regeneration have been followed. Preliminary results indicate adequate regeneration in the patches with a more hindering edge effect on tree growth in smaller gaps (Goude et al. 2022).

Due to the rarity of conversion experiments in northern Europe and their variety of initial stand and site conditions, it is difficult to draw firm conclusions. Conversion might also span several decades (Schütz 2001; Drössler et al. 2014), requiring long-term studies. Growth modelling could help elaborate different conversion alternatives (Sterba 2004).

Several papers have been recently published summarising 30 years of experiments in Washington and Oregon (USA) dealing with G&Y in variable-density thinning conversions (e.g. Roberts and Harrington 2008; Dodson et al. 2012; Willis et al. 2018). They are difficult to transfer to Fennoscandian conditions due to differences in the conversion objective, tree-marking methods, and tree species. New experiments with this method adapted to the Nordic conditions are being established in Norway.

4.6 Conclusions and Future Research Needs

Knowledge is still lacking on the many drivers of G&Y in CCF. Most published studies are on the selection system with Norway spruce. Furthermore, the few field experiments are sometimes managed with different criteria (some are even misclassified in terms of system), resulting in different or unknown tree size distributions.

Most growth modelling tools, from site quality classification to forest growth simulators, are targeted at even-aged stands. Site quality assessment is crucial for choosing the best species or treatment for a given site. Alternative, age-independent site classifications are being published and should be further developed for Fennoscandia. Existing forest growth simulators (such as MOTTI and HEUREKA) are being patched with additional tools for CCF, but work is in progress, and they have not been independently validated.

Many empirical studies show stand growth in the selection system increasing with stand density until values around 300 m^3/ha. Stand density also affects regeneration, and high density may not provide sustainable levels of ingrowth. However, empirical studies have found no significant relationship between stand density and ingrowth up to 300 m^3/ha. Thus, more research is needed into investigate what stand density optimises the growth and ingrowth simultaneously.

Lack of knowledge on aspects of G&Y such as site quality, stand density, and ingrowth makes it difficult to compare CCF and the clearcutting system productivity in field experiments. Similarly, a lack of proper growth models limits simulation studies. There are contrasting results in the published literature that are difficult to reconcile. However, the trend leans toward higher growth in the clearcutting system. New CCF field experiments should comprise adjacent thinned and unthinned clearcutting system plots to minimise site quality effects. Growth models should better analyse ingrowth with larger datasets and investigate the feasibility of spatial or non-spatial approaches for long-term simulations. Mortality also affects G&Y and needs to be represented with empirical models for all silvicultural systems.

Some important topics, such as peatland CCF and the conversion to CCF have been even less studied. There are ongoing efforts to establish more experiments (peatland in Finland, conversion in Norway and Sweden), but existing data are insufficient.

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