Analysing Natural Regeneration

Exploring Gap Cutting and Target Diameter Cutting in Continuous Cover Forestry

Malin Svensson & Paula Vargas

Independent project • 15 credits
Swedish University of Agricultural Sciences, SLU
Southern Swedish Forest Research Centre
Forest and Landscape
Alnarp 2024

Analysing Natural Regeneration. Exploring Gap Cutting and Target Diameter Cutting in Continuous Cover Forestry.

En analys av naturlig föryngring med granskning av luckhuggning och måldiameterhuggning inom hyggesfritt skogsbruk.

Malin Svensson & Paula Vargas

Supervisor:	**Urban Nilsson, Swedish University of Agricultural science, Southern Swedish Forest Research Centre, Alnarp**
Examiner:	Karin Hjelm, Swedish University of Agricultural science, Southern Swedish Forest Research Centre, Alnarp

Credits:	15
Level:	First cycle, G2E
Course title:	Independent project in Forestry science
Course code:	EX1012
Programme/education:	Forest and Landscape
Course coordinating dept:	Southern Swedish Forest Research Centre
Place of publication:	Alnarp
Year of publication:	2024
Cover picture:	Control site #5 in Rogberga, Jönköping. Photo: Malin Svensson
Copyright:	All featured images are used with permission from the copyright owner.
Keywords:	CCF, TDC, RFM, Non-Clearcut Forestry, Clearcut Forestry, Rotation Forest management, Forestry, Silviculture

Swedish University of Agricultural Sciences
Faculty of Forest Sciences
Southern Swedish Forest Research Centre

Abstract

Since the 1950s, forestry in Sweden have predominantly relied on Rotation Forestry Management (RFM), replacing the high-grading system due to its previously unsustainable practices which left Sweden's forests exceedingly sparse. Despite RFM's dominance, interest in Continuous Cover Forestry (CCF) has recently gained traction as a complimentary approach to RFM. CCF has emerged as an important topic, offering forest owners diverse strategies for sustainable forest management. Since RFM has historically dominated as the primary forestry method, research has primarily revolved around this silvicultural practice, resulting in a scarcity of long-term studies of CCF and thus restricted the understanding of this practice.

CCF practices, known as non-clearcut forestry in Sweden, maintain tree cover without large clearcuts with the purpose of creating diverse structures both vertically and horizontally containing mixed species. Techniques such as gap cuttings and target diameter cutting (TDC) are employed to manage forests and maintain a continuous tree cover. Gap cuttings create openings to facilitate natural regeneration, while TDC involves harvesting trees once they reach a predetermined diameter. However, CCF include the risk of insufficient regeneration, which could undermine the forest's ability to maintain its continuity and function. This study assesses the natural regeneration and species diversity within these CCF practices and examines its success in Rogberga in southern Sweden.

The study evaluates the effectiveness of various CCF methods in promoting natural regeneration using 17 sample plots: six controls, five TDC, and six gap cuttings. Results showed higher regeneration rates within gap cuttings compared to TDC and control. However, gap size and seedling placement did not significantly impact the regeneration outcome at this stage in the stand's development. While spruce and birch seemed to thrive in CCF, other species like pine seemed to face challenges with establishment and will probably be phased out in the future, creating a mixed stand of spruce and birch. Despite the risk of insufficient seedling regeneration involved in CCF, this site showed promising results with high seedling counts per hectare at this stage. However, findings are site specific and may not be applicable at other sites and may change with time. Continued monitoring and data collection are crucial for future forest management decisions.

Keywords: CCF, TDC, RFM, Non-Clearcut Forestry, Clearcut Forestry, Rotation Forest management, Forestry, Silviculture

Table of contents

List of tables

List of figures

Abbreviations

CCF	Continuous Cover Forestry
DBH	Diameter at Breast Height
EMF	EctoMycorrhizal Fungi
HA	Hectares
RFM	Rotation Forest Management
SFA	Swedish Forest Agency
SLU	Swedish University of Agricultural Sciences
TDC	Target Diameter Cutting

1. Introduction

Sweden has a land coverage of 40.7 million hectares (Roberge et al. 2023). More than half of this, 27.9 million hectares, consists of forest land, where as much as 23.5 million hectares are productive forest land (Roberge et al. 2023). Since the 1950s, Rotation Forest Management (RFM) has been the dominant silvicultural practice used in Swedish forestry (Goude et al. 2022). This approach increased in popularity in response to the high-grading conducted during the late 1800s and early 1900s (Goude et al., 2022). The use of high-grading led to the largest and most valuable trees continuously being harvested without regard for the remaining forest, resulting in stands that were sparse and lacked any significant value (Andersson & Appelqvist, 2020). The RFM emerged and the remaining sparse forests were harvested and planted to increase the productivity and ensure regeneration (Goude et al. 2022). The way that high-grading was used as selective cutting, gave Continuous Cover Forestry (CCF) a bad reputation and led to a decreasing interest for CCF methods, which persisted for a long time (Andersson & Appelqvist 2020; Goude et al. 2022).

Today, CCF has become a widely discussed topic (Espmark 2017; Lantbrukarnas Riksförbund 2023; Holmström 2024) as an important complementary method to the dominating traditional RFM (Appelqvist et al. 2021). Forest owners often have diverse goals for their forests, leading to multiple choices of silvicultural practices (Appelqvist et al. 2021). The adoption of CCF in specific areas does not necessarily exclude all use of RFM throughout the estate; rather, it can be seen as a supplementary strategy for suitable locations, for example sites with high nature values (Appelqvist et al. 2021).

However, due to the historical dominance of RFM as the primary forestry practice, research endeavours have predominantly focused on this silvicultural practice (Andersson & Appelqvist 2020; Goude et al. 2022). Consequently, CCF has been somewhat overlooked, resulting in limited long-term studies, and therefore limited available knowledge of the practice (Appelqvist et al. 2021; Goude et al. 2022).

1.1 Rotation Forest Management

Since the 1950's RFM, also known as clearcut forestry, has been the dominant silvicultural practice in Sweden (Goude et al. 2022). It works in a cyclic manner where each stand goes through various phases from regeneration to final felling (Ekholm et al. 2023) during a relatively short time (Appelqvist et al. 2021). That usually means that the forests consist of single-story monocultures that upon reaching financial maturity (between 50-120 years), are final felled, leaving a clearcut marking the end of the rotation (Ekholm et al. 2023). The stand will thereafter go through the regeneration phase which typically is initiated with site preparation and thereafter seedlings are either planted, naturally regenerated, or sowed to initiate a new rotation cycle (Skogskunskap 2024). For fertile sites with site indices of T28/G34, regeneration typically involves between 2000-3000 seedlings/ha, varying depending on species (Skogskunskap 2023a). During the period between regeneration and final felling, various interventions can be performed, such as Pre-Commercial Thinning (PCT) and additional thinnings (Skogskunskap 2023b).

1.2 Continuous Cover Forestry

Continuous Cover Forestry (CCF) is a broad term that encompasses several silvicultural practices, all of which involve management of forest stands without completely clearing them (Andersson & Appelqvist 2020; Goude et al. 2022). While CCF has been a standard practice in Central Europe for over 50 years, with a history spanning more than a century, it remains relatively new in areas like United Kingdom, Scandinavia, North America and China (Pommerening 2023). The purpose of employing CCF practices often include creating diverse structures, both vertical and horizontal, as well as multi-species forests which is generally achieved through selective thinnings and natural regeneration (Pommerening 2023).. Employing CCF practices does not imply a lack of management but rather highlights the need to avoid clearcutting over large areas (Pommerening 2023). Within the broad term of CCF, there are several methods available, including Selective Thinning, Shelterwoods, Gap Cuttings and Target Diameter Cutting (TDC). This study will focus on gap cuttings and TDC. As the terms can vary and sometimes conflict in definitions (Pommerening 2023), this study will focus on the Swedish definition of CCF. In Sweden, CCF is called non-clearcut forestry and is defined as followed by The Swedish Forest Agency (SFA):

> "Non-clearcut forestry on forest land intended for wood production implies that the forest is managed in such a way that the land always has a tree cover, without any larger clear-cut areas." (Appelqvist et al. 2021:10)

This indicates that the forest manager must have the intention to continuously employ CCF methods, ensuring that the area maintains trees at a minimum height of 10 meters and a density that is exceeding the §5-curve (Figure 1) stated in the Forestry Act (Appelqvist et al. 2021). If volume (m3sk) falls below the §5-curve, there are legal measures that will enforce regeneration (Appelqvist et al. 2021). There are however a few exceptions to the §5-curve, including shelterwood and gap cutting. In shelterwood management, once satisfactory regeneration is achieved, the overstory can be reduced to half the density required by the §5-curve, with the option to remove it once regeneration reaches a height of at least 2,5 meters (Appelqvist et al. 2021). Exceptions to the §5-curve concerning Gap Cutting will be elaborated on in the upcoming section.

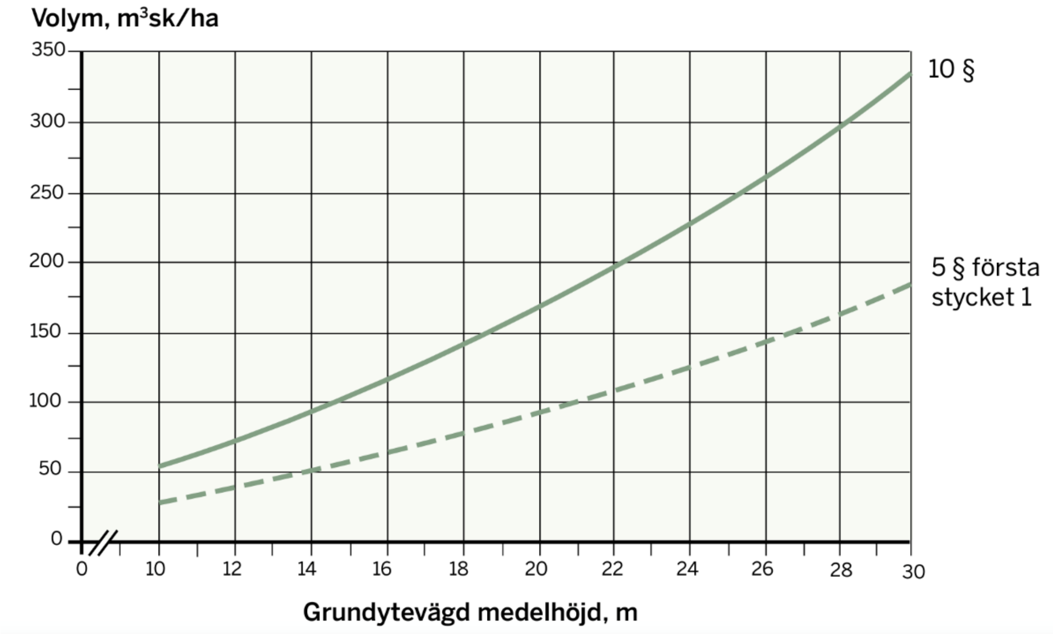

Figure 1: Timber volume diagram. The diagram specifies the lower limit of the stand's standing volume, indicating the minimum volume required for the stand post-thinning (solid line). Should the volume fall below the threshold on the curve outlined in §10-curve, the stand should be scheduled for clearcutting (solid line). If the volume falls below the threshold of §5-curve, regeneration is enforced, with a few exceptions (dashed line). X-axis = Average stand height (meter), Y-axis= Volume (m^{3}sk/ha). Source: Andersson & Appelqvist (2020),

The adaptation to CCF can lead to reduced regeneration costs, as many CCF-practices do not involve site preparation and rely on natural regeneration (Andersson & Appelqvist 2020). As a result, this type of management may not only reduce expenses but could potentially also decrease the risk of environmental damage. The exclusion of site preparation in CCF enhances the potential for retaining a diverse array of species compared to RFM, including species-groups such as mycorrhiza, birds, and lingon/bilberries (Andersson & Appelqvist 2020). Relying on natural regeneration can include risks as adequate regeneration and ingrowth are vital for the success of CCF, as the regeneration eventually replaces harvested trees (Knoke 2012; Goude et al. 2022). Another factor to consider is that relying on natural regeneration excludes the use of genetically improved material, which typically has higher growth potential as well as the possibility for seedling adaptation for future climate (Andersson & Appelqvist 2020; (Södra Kommunikationsavdelningen 2022).

There are however divided opinions as to how well CCF works economically. According to research, CCF typically results in lower timber production and higher harvesting costs compared to RFM, mainly due to additional time spent on planning and harvesting as well as increased terrain transport expenses associated with partial timber harvest in CCF (Andersson & Appelqvist 2020; Appelqvist et al. 2021; Södra Kommunikationsavdelningen 2022). Knoke (2012) argues that the reluctance towards CCF is uncalled for, especially in the northern hemisphere where timber production spans over more than one decade and individual tree productivity varies. In such context, CCF shows promise for achieving improved economic outcomes (Knoke 2012). According to Ersson (2020), this is especially true on low fertility sites.

One reason CCF could be more economical than RFM is the reduced need for interventions (Espmark 2017). For instance, CCF often involves lower regeneration costs as it commonly excludes site preparation and planting since it relies on natural regeneration, resulting in decreased expenses for regeneration (Espmark 2017; Appelqvist et al. 2021). Other interventions that are commonly excluded from CCF, leading to lower management cost, includes PCT and additional thinning interventions (Espmark 2017; Appelqvist et al. 2021).

1.2.1 Gap Cutting

Gap cutting, also called group system outside of Sweden (Pommerening 2023), involves managing the forest by removing groups of trees to create small openings, allowing natural regeneration, or sometimes planting of new trees in these gaps (Andersson & Appelqvist 2020). The gaps created typically have a diameter ranging from 20 to 50 m (Andersson & Appelqvist 2020). Expanding the gaps within a stand can be achieved by either further cuttings of the current gaps or by creating new ones until the entire area is regenerated (Goude et al. 2022). This process results in a forest that is layered in tree groups of various ages (Goude et al. 2022). For example, a uniformly planted monoculture could be transformed into a structurally and compositional diverse forest by selectively removing small patches of trees that is left to naturally regenerate (Pommerening 2023). To qualify as a non-clearcut method according to the SFA, the gaps created can never exceed 0.25 ha and the average density of the entire stand must be above the §5-curve (Figure 1) (Appelqvist et al. 2021). When trees within a previously formed gap have grown to an average height of 2.5 meters, a new gap near the existing one can be formed, with the exception to the §5-curve (Appelqvist et al. 2021).

The gap cutting system is suitable for both light-demanding species like birch (*Betula spp.)* and Scots pine *(Pinus sylvestris,* hereafter pine*)*, as well as shade-tolerant species such as Norway spruce *(Picea abies,* hereafter spruce*)* and beech *(Fagus sylvatica)* (Andersson & Appelqvist 2020). To facilitate the ingrowth of the light-demanding tree species, larger gaps that allow more light penetration, are needed compared to the shade-tolerant species that can grow well in smaller gaps (Andersson & Appelqvist 2020; Pommerening 2023).

1.2.2 Target Diameter Cutting

Target Diameter Cutting is a single-tree selection system in which trees of all sizes and developmental stages are present in a mixture within one forest stand (Pommerening 2023). In this system, individual trees are harvested when they reach a predetermined diameter, indicating maturity for harvest (Andersson & Appelqvist 2020; Appelqvist et al. 2021; Goude et al. 2022). The set target diameter may vary among species and quality within species but remains constant once established (Andersson & Appelqvist 2020; Appelqvist et al. 2021; Goude et al. 2022). Only trees that have reached the set diameter are harvested which results in small gaps from harvested trees creating favourable conditions for natural regeneration of the remaining trees (Andersson & Appelqvist 2020; Appelqvist et al. 2021; Goude et al. 2022). Harvests are conducted periodically as enough trees reach the target diameter (Andersson & Appelqvist 2020; Appelqvist et al. 2021; Goude et al. 2022). It is crucial to perform interventions in order to preserve the size structure of the TDC stand (Pommerening 2023). If interventions are too infrequent or minimal, the overstory becomes dense with a closed canopy, which could suppress and eventually phase out regeneration in the understory and midstory (Pommerening 2023). However, if interventions are done too frequent or intensive it can drastically reduce the number of dominant trees in the overstory (Pommerening 2023). This can cause excessive regeneration, with relatively similar establishing time leading to seedlings of similar size, that ultimately could result in an even-aged succession (Pommerening 2023).

To sustain this method over time, a full storied stand is needed where trees in all size-classes are present at all times (Ekholm et al. 2023). It is especially important to have a higher abundance of smaller sized trees that can replace the large trees as they are harvested (Ekholm et al. 2023). As the gaps created in TDC are relatively small, shade-tolerant species are particularly suitable for this silvicultural practice. (Pommerening 2023).

1.2.3 Choosing method

The choice of CCF method depends both on the current state of the forest and the desired future outcome (Goude et al. 2022). Target Diameter Cutting could be suitable for a stand with a multilayered forest structure, especially if the desired future state is to maintain this multilayered characteristic (Goude et al. 2022). Species composition may vary over time as shade tolerant species may dominate the understory, making establishment for light-demanding species challenging (Goude et al. 2022). A single-story stand might be more suitable for gap cutting as that can generate a groupwise layered stand (Goude et al. 2022).

While research on how site conditions dictate the choice of CCF method is still ongoing, practical experience with natural regeneration can inform the selection process (Goude et al. 2022).

1.2.4 Nature values

Different forest systems provide various structures supporting a diversity of species. Continuous Cover Forestry provide forests with stable conditions where temperatures and humidity are more even due to the closed canopy (Appelqvist et al. 2021). Those conditions are particularly favourable for shade tolerant species with poor dispersal abilities and birds that mainly live in the forest where they can find shelter (Appelqvist et al. 2021).

Rotation Forest Management has transformed forests from multi-layered to single-storied stands, reducing habitat structures leading to decreasing numbers of species (Ekholm et al. 2023). Additionally, this management practice often lack sufficient deadwood, which is crucial for certain species (Ekholm et al. 2023). Multi-layered forests that are managed for deadwood are better supported by CCF which is essential for many threatened species as they also often rely on connected habitats (Ekholm et al. 2023). This highlights the threat numerous red-listed species are faced with (Ekholm et al. 2023). Furthermore, RFM have shown to be harmful for many fungi, to the extent that some species have become red-listed (Andersson & Appelqvist 2020; Appelqvist et al. 2021). In contrast, CCF offers greater potential for the fungi to remain, allowing them to inhabit the forest floor where mycorrhizal connections can form with the roots of newly established trees and facilitate nutrient exchange (Andersson & Appelqvist 2020; Appelqvist et al. 2021). The loss of large amounts of tree cover changes soil conditions such as temperature, moisture, and soil porosity due to mechanical stress on the ground. Rotation Forest Management includes clearcuts which disrupt the soil composition, disrupting mycorrhizal fungal communities by eliminating or changing their abundance (Visser et al. 1998). Trees have a symbiosis with ectomycorrhizal fungi (EMF) which influences their access to growth-limiting soil resources. Fast tree growth has been associated with EMF communities (Anthony et al. 2022). This is not the only factor that can influence tree growth, site preparation also contributes to setting the right soil conditions and reducing competition for the seedlings. Ectomycorrhizal fungi are also key to nutrient acquisition, plant protection against root pathogens and drought stress (Heinonsalo 2004). Therefore, a large disturbance in fungal species composition can have implications on seedling establishment and competition (Jones et al. 2003). With CCF management there is less soil disturbance causing less stress on EMF communities as site preparation often is discarded or limited to smaller areas where the canopy remains partially intact.

However, just employing any CCF method is not the answer to everything (Andersson & Appelqvist 2020). While it is a valuable approach, it is important to choose the right method for the desired forest and tree species. Evidently, a mosaic landscape with mixed forest structures and forest methods has the potential to support a greater variety of species than a unified landscape.

1.3 Aim of Study and hypotheses

This case study aims to gather data and conduct assessments of forest regeneration within the context of CCF, aiming to provide additional information and address the current knowledge gap regarding this forestry practice. Through inventorying and analysis, the study seeks to clarify the efficiency and viability of CCF methods compared to the traditional RFM. By examining the regeneration across multiple sample plots with various treatments, the research aims to gather insights into the performance and effectiveness of these alternative forestry methods. Central to this case study is the evaluation of natural regeneration, including establishment of seedlings and species diversity.

The hypotheses are as follows:

1. Number of seedlings will increase with increased gap size and there will be more seedlings in the gaps compared to TDC and Control.
2. The seedlings will be taller in the gap cuttings compared to the TDC and Control.
3. Within the gaps, there will be more regeneration towards the centre of the plots compared to the edges.
4. Within the gaps, seedlings will be taller in the centre compared to the edges of the gaps.

2. Material and Methods

The site for this case study was situated in Rogberga, outside of Jönköping and serves as an experimental collaboration between SLU and Sveaskog (Figure 2). The experiment's objective was to evaluate various CCF methods and their ability to naturally regenerate. The stand was 10 hectares (ha) and was established in 1917. It was a heterogeneous stand where pine dominated in the overstory, spruce was present in all layers, and broadleaves, including birch, rowan (*Sorbus aucuparia),* goat willow (*Salix caprea,* hereafter willow*),* and pedunculate oak (*Quercus robur,* hereafter oak*)*, occur in the understory. Site conditions were clay-sandy soil over till but may intermittently vary in moisture levels from dry to wet. The site index was T28/G34 which indicates a fertile site. The experiment started in 2012 when 17 sample plots were made with various treatments (Figure 2). Before the treatments were made there were 781 trees per ha: 260 pines, 335 spruces, 125 birches, and 61 other broadleaves. The standing volume was 370 m^3sk/ha and basal area was 37 m^2/ha. Among the treatments, six sample plots served as control sites, while five underwent TDC. In the sample plots treated with TDC, all trees with the diameter at breast height (DBH) of 38 cm or larger were cut, leading to approximately one third of the stand volume being removed. Additionally, six sample plots were made for gap cuttings, with diameters varying between 10 – 30 meters. This comprised two plots each of 10 meters, 20 meters, and 30 meters.

For the inventory of the gaps, the first thing that was done was to lay out two transect lines. A measuring tape was used to lay out the transect and a compass was used to have the transect start from North to South and West to East. On the transect line, plots were laid out every 3.3 meters in gap cuttings that were above 10 meters in diameter. For gap cuttings that were 10 meters in diameter, the sample plots were laid out every 2.5 meters. All sample plots had a radius of 1.25 meters, any regeneration that fell inside this radius was noted with species and height to nearest cm with a measurement stick. If the tree was too tall for the measurement stick, height was measured to the nearest dm with an electronic hypsometer. Diameter at breast height (1.3 m) were measured for trees taller than 1.3 meters using a caliper. For trees taller than 1.3 meters, the height of the first ten trees within a treatment plot were measured, thereafter, only the diameter was measured and noted. This process was repeated for both transect North to South and West to East. These transect lines intersect in the middle because of this, the middle plot was measured once during the North to South transection. Note that gap number 14 had sample plots with a different radius of 1.5 meters. For the control and TDC-plots, the same process was conducted, sample plots were laid out with 2.5 meters of spacing and with a radius of 1.25 meters.

R Statistical Softwarewas used for data-analysis to conduct T-tests and to develop graphs (R Core Team 2021). The script that was used had specific codes that described the modifications that were done in the field while gathering data. The Näslund function:

> $H=D^x/(a+bDBH)^x+1.3$ (H= tree height (m), DBH=diameter at breast height (cm), a and b= coefficients, and x has a value of 2 for pine and 3 for spruce)

was applied (Näslund 1936) for the data of the first ten trees whose height surpassed 1.3 meters, their height was measured but after the first ten trees, all whose height surpassed 1.3 meters only had their diameter taken with a caliper. To estimate the height of the trees which had only their diameter measured, the Näslund function was used. A T-test was used to find the P-value which was used to find any statistically significant differences between the treatments. If the P-value was below 0.05, differences were considered to be statistically significant.

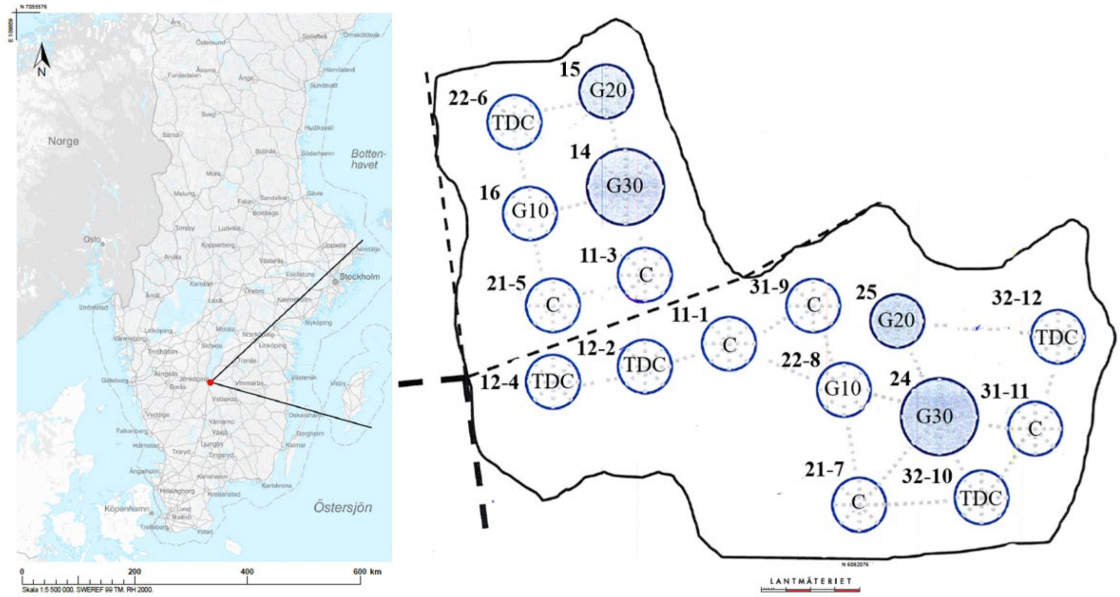

Figure 2:Maps showing the site of the experiment. To the left, the red dot marks the location of the experiment and to the right treatment layout of the experimental design. TDC=Target Diameter Cutting, C=Control, G10= Gap cutting 10 meter, G20= Gap cutting 20 meter, and G30=Gap cutting 30 meter. Left map: ©Lantmäteriet

3. Results

The total number of seedlings per ha for each treatment including the control is shown in Figure 3. Gap 10 and 20 had similar number of seedlings per ha whereas gap 30 had the lowest recording of seedlings compared to all three gap cuttings. However, there was no statistically significant difference in seedling number between gaps of different diameter, but gaps had significantly higher number of seedlings than the control and TDC (Figure 3, Table 1). The TDC and control did not have a statistically significant difference in the number of seedlings recorded but there was a difference in what species are dominating after spruce. In the Gap cuttings 20 and 30 the spruce seedlings are dominating followed by birch and pine. For Gap 10 birch was the dominating species followed by spruce and then pine. For the TDC and control spruce was dominating but for the TDC birch and pine follow with almost the same amount of seedling per ha (Figure 3).

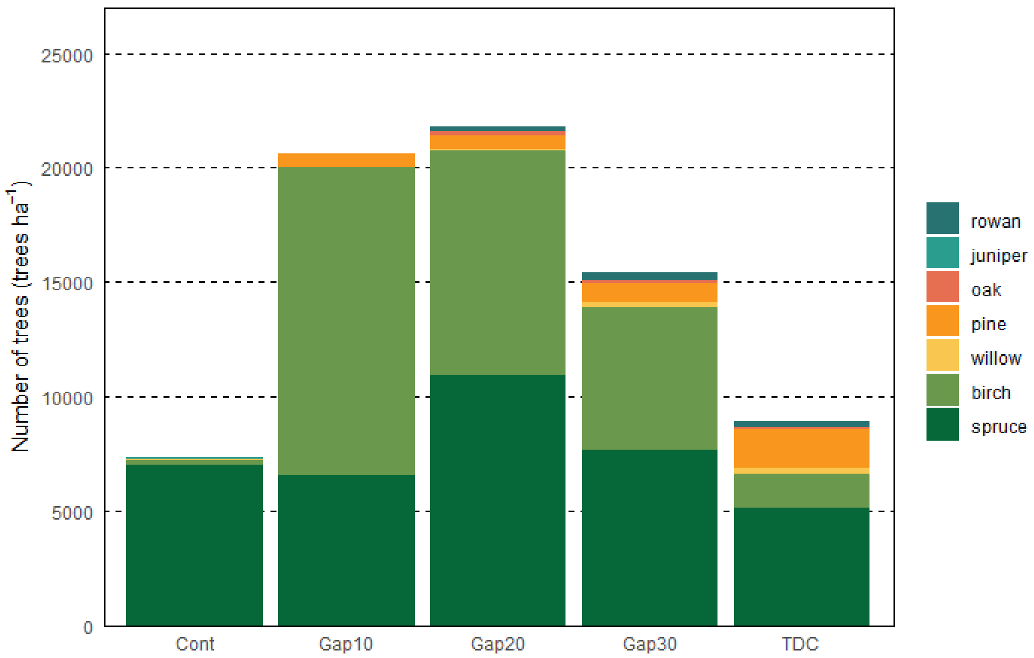

Figure 3: Number of seedlings per hectare for control (cont), Gap 10, Gap 20, Gap 30 and, target diameter cutting (TDC).

T-tests were conducted to see any statistically significant differences between treatments and the number of seedlings. In Table 1 the control is compared to gaps 10, 20, and 30 it indicates that there is a statistically significant difference, but the control and the target diameter do not have a statistically significant difference. When the TDC is compared with gaps 10 and 20, a statistically significant difference is found but not when compared to gap 30. Between gaps 10, 20 and 30, there is no statistically significant difference.

Table 1: T-test data showing P-value indicating any statistical significance between treatments and the number of seedlings. ***Bold = statistically significant difference.***

	T-test number of seedlings				
	Cont	TDC	Gap10	Gap20	Gap30
Cont					
TDC	0.4812				
Gap10	**0.0002**	**0.0050**			
Gap20	**0.0008**	**0.0078**	0.8773		
Gap30	**0.0064**	0.0522	0.3279	0.8773	

There was a statistically significant difference in the presence of birch between the control and gaps 10, 20, and 30, with higher number of birch seedling in gaps (Figure 3, Table 2). This can also be seen when TDC was compared to gaps 10 and 20. When it comes to comparing gaps 10, 20 and 30 to each other there was no statistically significant difference (Table 2). For spruce, the only statistically significant difference in the number of seedlings between treatments was that there were more seedlings in gap 20 compared to TDC (p=0.04692).

Table 2: T-test data showing P-value statistically significant differences between number of birches in various treatments. ***Bold = statistically significant difference***

	T-test number of birches between different treatments				
	Cont	TDC	Gap10	Gap20	Gap30
Cont					
TDC	**0.0115**				
Gap10	**< 0.0001**	**< 0.0001**			
Gap20	**< 0.0001**	**0.0001**	0.4607		
Gap30	**< 0.0001**	**0.0050**	0.0690	0.2609	

Rowan was the species with a max height of 300 cm in the control gap with spruce in second and willow and birch following but with small differences between species (Figure 4). For gaps 10, 20, 30, and TDC the species with the max height was birch with different heights in each treatment. In the TDC and gap 30 the species with the second max height was willow. For gap 30 the difference between the max height of birch and willow was much greater than the difference between birch and willow for the TDC. For gaps 10, 20, and the control, spruce is the second species with a max height.

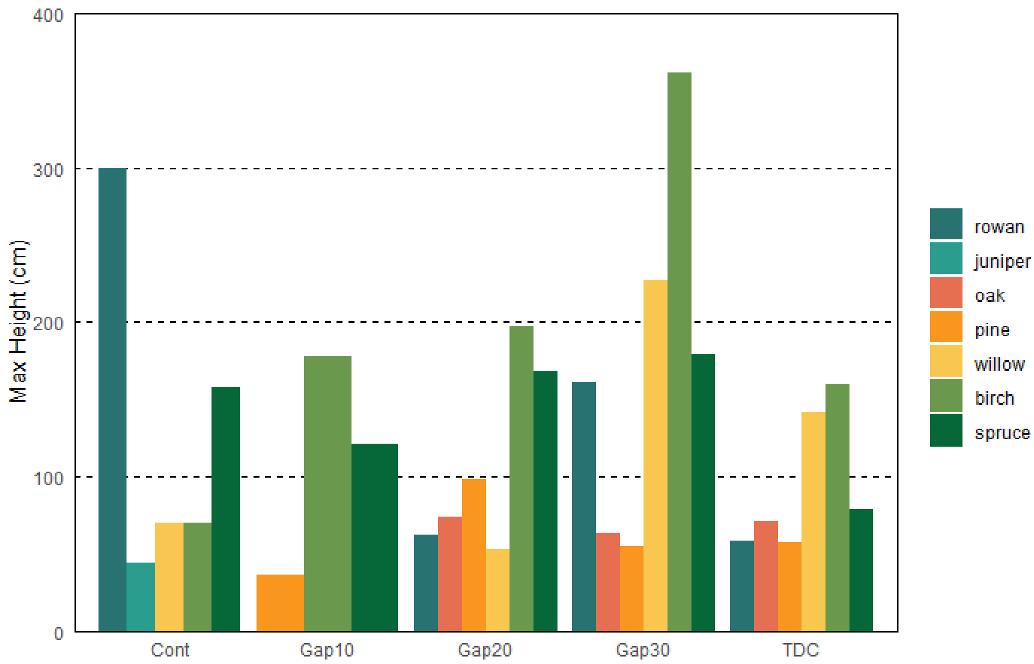

Figure 4: Species and their correlating max height for control (cont), Gap 10, Gap 20, Gap 30 target diameter cutting (TDC).

Birch was the species with the highest average height for the TDC, gap 30, and gap 10, followed by willow for the TDC and gap 30 (Figure 5). In gap 10 spruce was the second species. Gap 20 was the only treatment with spruce as the species with highest average height, followed by birch with not a big difference. For the control, rowan is leading with average height with a big leap forward compared to the rest of the species found in the control (Figure 5).

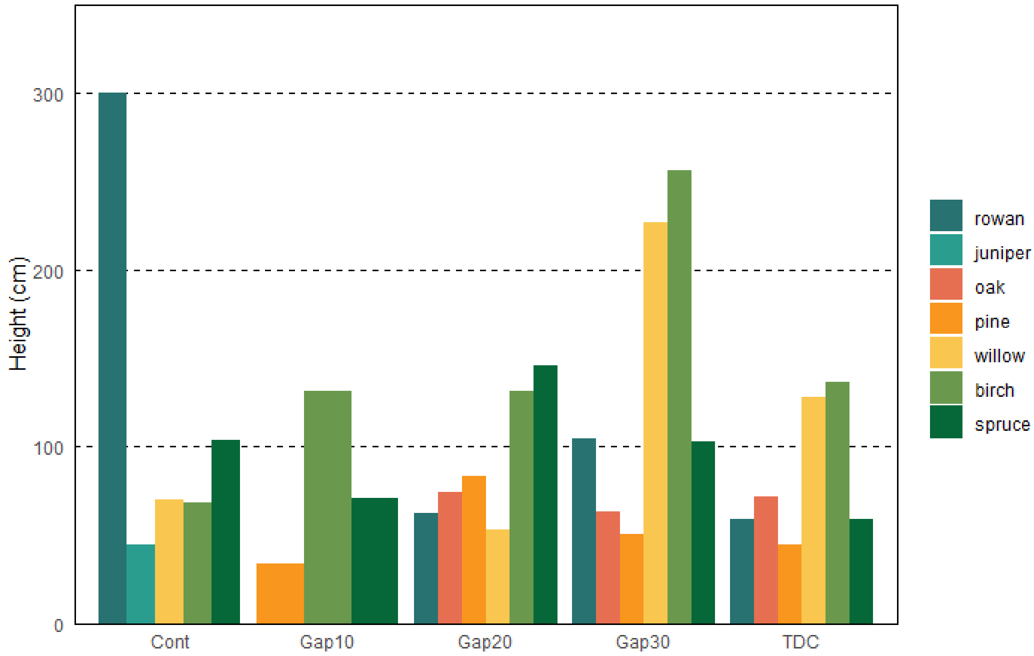

Figure 5: The average height of species in correlation with the treatment, control (cont), Gap 10, Gap 20, Gap 30, and target diameter cutting (TDC).

Spruce height was statistically significantly higher for the control compared to the TDC (Table 3). Spruce was also higher in Gap 20 and Gap 30 compared to TDC.

Table 3: T-test data shows the P-value for heights of spruce between different treatments, if there is any statistically significant difference. ***Bold= statistically significant difference***

T-test for height for spruce between different treatments					
	Cont	TDC	Gap10	Gap20	Gap30
Cont					
TDC	**0.0194**				
Gap10	0.4474	0.3480			
Gap20	0.7996	**0.0411**	0.4557		
Gap30	0.5572	**0.0109**	0.3002	0.8323	

Hight of birch was statistically significantly higher in the gaps 10, 20, and 30 when compared to the control. In addition, birch was significantly higher in Gap 30 than in Gap 20 and Gap 10 (Table 4). Birch was statistically significantly higher than spruce in Gap 30 (p=0.001018), whereas the difference in height between spruce and birch was not significant in other treatments.

Table 4: T-tests for height of birch between different treatments, P-value shows statistically significant differences between various treatments. ***Bold = statistically significant difference***

T-test for height for birch between different treatments					
	Cont	TDC	Gap10	Gap20	Gap30
Cont					
TDC	0.2601				
Gap10	**0.0242**	0.6946			
Gap20	**0.0970**	0.5057	0.6700		
Gap30	**0.0103**	**0.0051**	**0.0044**	**0.0132**	

Even though more spruce seedlings were found in the centre of the control plots, there was no statistically significant difference in the number of spruce seedlings that were found in the centre compared to the seedlings at the edge of the plots (Figure 6). The T-test comparing the variation of birch seedlings that were found in the centre of the plot to the seedlings at the edge of the plots also showed no statistically significant difference in any of the treatments.

Average height of spruce was higher in the centre of the plots compared to the edges for all gap-treatments, but the differences were not statistically significant (Figure 7). There was no statistically significant difference in height of birch seedlings in the centre of the gaps compared to birch seedlings at the edges of the gaps (Figure 7).

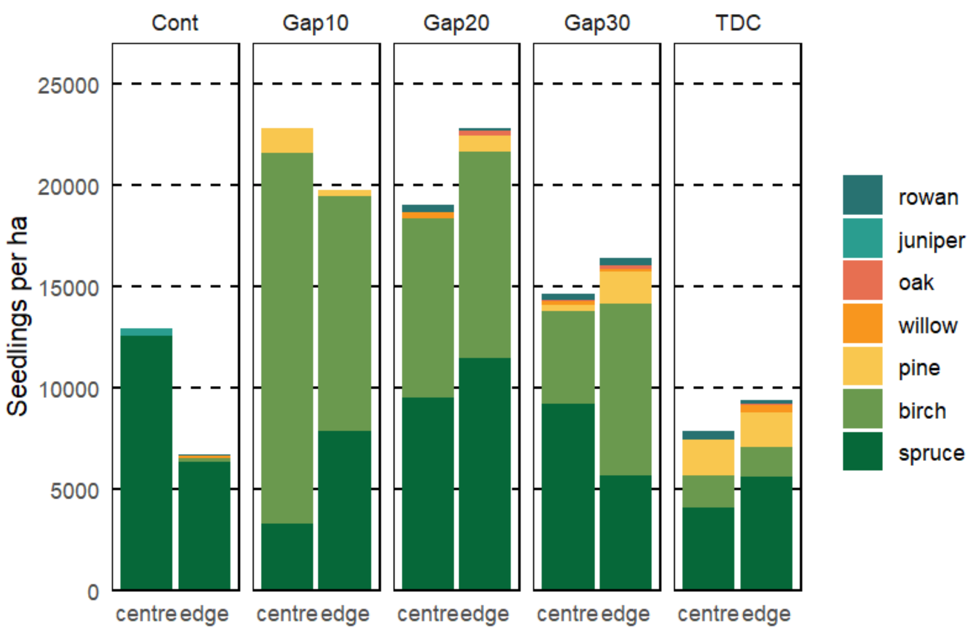

Figure 6: Number of seedlings per hectare and per species in the Centre respectively Edge of plots within different treatments.

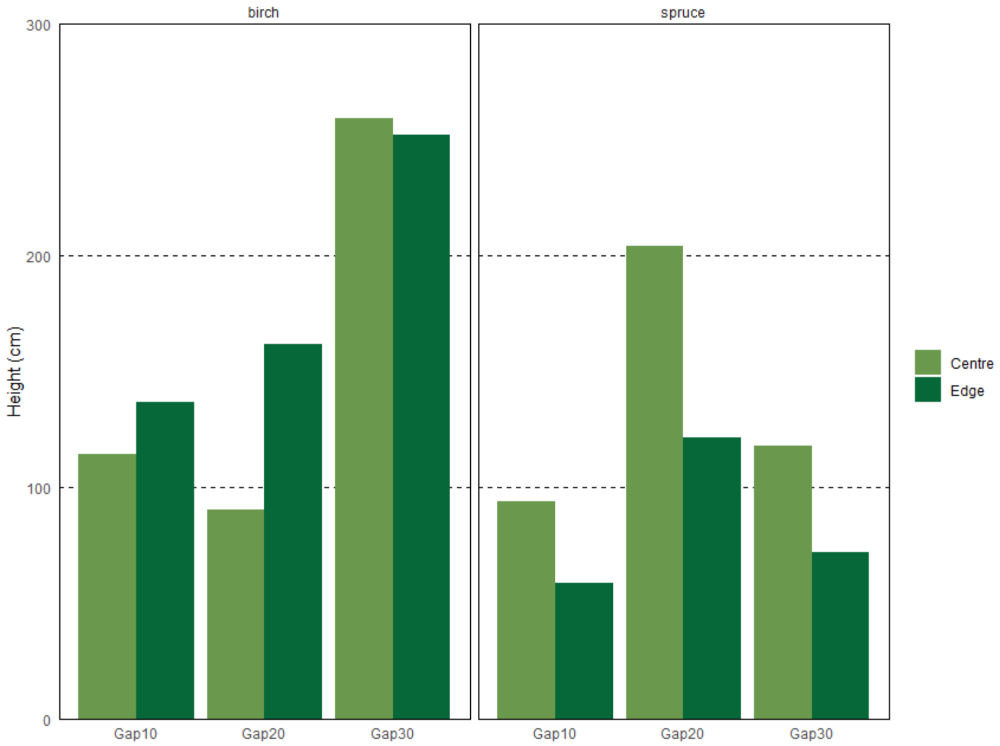

Figure 7: Seedling height of birch and spruce in the edge compared to centre within the gaps

4. Discussion

This study aimed to gather insights into the performance and effectiveness of the CCF methods TDC and gap cutting in terms of natural regeneration and species diversity. The results did partly support the first hypothesis, which proposed that the number of seedlings would increase with larger gap sizes and that there would be more seedlings in the gaps compared to TDC and control. There was no statistically significant difference in the number of seedlings among the various gap sizes. However, the results confirmed that there were more seedlings in the gaps compared to the TDC and control.

The second hypothesis was also partially confirmed. Birch regeneration was taller in the gap cuttings compared to the TDC and Control, but the results for spruce were inconclusive. Specifically, the height of birch was statistically significantly higher in Gap 30 compared to other treatments. Regarding spruce, there were no statistically significant difference in height between the gaps and control. However, spruce seedlings were the smallest in TDC indicating that all the gap cuttings produced taller seedlings compared to TDC, which was in line with the hypothesis.

Contrary to expectations, the results did not confirm neither of the hypotheses regarding increased number of regenerated seedlings and taller seedlings in the centre of gaps compared to the edges. This suggests that, up to this point in the development, gap size and placement of seedlings may not significantly impact regeneration outcomes.

When managing for CCF, knowledge on how to promote development and minimise mortality is required to have a sustainable system. In these gaps more than one species were found so competition between species will affect the future structure of the forest. Spruce has had a high survival rate when it comes CCF trials (Kerr & Mackintosh 2012). This species is shade tolerant and can reach its growth potential in these kinds of canopy openings. Spruce and birch had established the most in the treatments. Pine on the other hand can have difficulties with competition when establishing. It is shade intolerant species, and requires larger gaps to reach growth potential (Häggström et al. 2024). Shade-tolerant species will control the spatial distribution and the rate at which the canopy will develop. The results of this study indicate a potential shift in species competition in the future, as the majority of seedlings consists of spruce and birch. Other tree species present today, such as pine, rowan, willow, juniper, and oak will be phased out eventually due to reasons such as challenges establishing due to light demand and grazing pressure. These species are fodder for deer and moose but having more availability of fodder because of the surplus of seedlings compared to RFM could reduce the stress of grazing on some of the seedlings. While in RFM it is costly for the forest owner to lose their seedlings due to grazing, to prevent this forest owners need to fence their estate which can be costly depending on the size of the land and maintenance. A future mixed forest would mainly consist of spruce and birch and would have to be managed by gap cuttings to get sufficient ingrowth of birch in the stand. However, based on the results from this study, the size of the gap does not seem to matter for birch establishment at this site, despite the expectation that light-demanding species like birch require larger gaps to establish. Karlsson (2003) suggests that birch regeneration may thrive in moist sites without soil scarification. Additionally, it is recommended that if site preparation is done, it should be done during years of high seed production (Karlsson 2003)The high regeneration of birch in this site may be attributed to these factors. The gaps were not scarified, and it is possible that the soil moisture in some of the gaps were favourable for birch regeneration, as suggested by Karlsson (2003). Furthermore, it could have been a particularly good seed year when the experiment was established, contributing to the successful establishment of many birch seedlings. Pre-Commercial Thinnings can be conducted in the gaps to mitigate the risk of total dominance of shade-tolerant species like spruce to maintain a desired mix of species and promote biodiversity.

The results of this study proved that there was a statistically significant difference in number of seedlings found in the gaps 10, 20, and 30 compared to the control and TDC. Managing with CCF on this particular site showed positive results with natural regeneration present in the different gap sizes. Although there was no statistically significant difference between the sizes of the gaps. One thing that was seen in the field but then proved to not be of importance is the edge compared to the centre. In the field it visually seemed as if there were more seedlings in the centre of the gap due to light availability. When the data was analysed through a t-test it was found that there was not a statistical significance difference in the number of seedlings found in the centre compared to the edge.

Despite the risk of insufficient regeneration associated with CCF, this study's results of over 10,000 seedlings per ha within the gap cuttings and over 5,000 seedlings per ha within TDC suggests that natural regeneration within CCF can be comparable to the number of seedlings planted in RFM. These results indicate the viability of CCF as a forestry practice alongside RFM. While it is crucial to bear in mind that the findings of this study are relevant to this specific location and cannot be assumed to be applicable on other sites. It is also still early in the development of the treatments, and survival of seedlings may change with future conditions.

The site conditions affect what species will dominate the ground vegetation. Soil conditions are site specific, and this must be considered with this study as well. Seedling competition is higher in poor and dry soils compared to nutrient-rich and moist soils (Häggström et al. 2024). Therefore, regeneration outcomes may vary heavily depending on site and soil conditions, grazing pressure, and species distribution. What was observed in the field was that the whole estate is comprised of hill tops, slopes, wetlands, dense forested areas, and more open forest areas. However, due to the limited number of long-term studies, it is challenging to draw conclusive comparisons between this study and other sites.

Comparisons with long-term CCF experiments, such as the 140 compiled by Goude et al. (2022), highlight the necessity for further extensive data collection before drawing significant conclusions regarding the applicability of the results presented in this study. Out of the 140 compiled experiments, only 17 involved gap cuttings, where most regarded checkerboard cuttings, and nine regarded TDC (Goude et al. 2022). One experiment in the compilation of Goude et al. (2022), regarded TDC in Eriksköp, where it was observed that larger gaps that were established within TDC had a higher level of regeneration compared to the smaller gaps in TDC (Goude et al. 2022). This finding bears some similarity to the observation found in this study, that gap cuttings resulted in greater regeneration than the TDC and control sites in Rogberga. However, it is worth noting that there was no statistically significant effect on the number of seedlings in relation to gap size, only compared to the other treatments. Furthermore, Goude et al. (2022) compared the success of gap cuttings made in checkerboard pattern between three different trials situated in two different areas. It was concluded that checkerboard cutting is still at an experimental stage in Sweden, but the ongoing trials indicate successful natural regeneration in all gaps at all sites, with both pine and spruce establishing well. One of the trials, conducted in Nattavaaravägen, had results from two separate inventories, in 2017 and 2021. The inventory in 2017 showed similar results to this study, with sufficient regeneration and no significant relationship between seedling number or height and their placement within the gap (Goude et al. 2022). The second inventory also showed successful regeneration, but at this time there were a correlation between more main stems at the edges compared to the centre of the plots (Goude et al. 2022).

To draw any conclusions from this, there must be more experiments conducted over a longer period of time. Goude et al. (2022) found in their report that numerous experiments regarding CCF that has been established across the country has not been consistently monitored for various reasons, leading to neglect of these experiments. Therefore, it is crucial to continually monitor experiments to track changes in species composition and regeneration patterns over time. Long-term studies offer the opportunity to gather data on the efficacy of various CCF methods, enabling informed decision for future forest management.

Furthermore, the experimental design of this site is not perfect as the treatments are grouped over a relatively small area. A preferred experimental design would have been to have the treatment plots randomised in a much larger area or across several sites with diverse characteristics to be able to enhance the validity of comparisons and to help determine consistency of regeneration. Therefore, these results cannot be seen as proof of these methods working but can rather be seen as an example of how the treatments can be conducted and their suggested function on this type of site. There is also the risk when many t-tests are conducted that the P-values have an increased probability of false positives. Each test conducted increases the overall likelihood of finding a statistically significant result by chance which means that some results showing statistically significant differences might not reflect the truth but rather results of random chance.

With the success of natural regeneration on this site, CCF shows great potential to get good quality seedlings as there are plenty of seedlings per ha to choose from. This stands in contrast to RFM, where seedlings are grown in a nursery and then transported to the field where typically 2000-3000 seedlings are planted. Spruce and pine seedlings are often genetically improved by the method of crossbreeding of trees with desired traits, such as growth and stem quality (Rosvall et al. 2016). The first generation of genetically improved trees showed growth improvement of 10% compared to non-improved trees (Rosvall et al. 2016). Later generation can achieve up to 25% higher production compared to non-improved trees (Rosvall et al. 2016). Seedlings from all generations are used extensively in Swedish forestry for improved growth and quality (Egbäck et al. 2017).

Genetic improved material is an advantage in RFM that is lost within CCF as the seedlings are site adapted. It is not only the improved growth involved with planted seedlings that is lost, but also the possibility to adapt them for future climate. As climate changes, trees may be experiencing conditions to which they are not well adapted (Wang et al. 2010). Trees, which are long-lived species, often takes centuries to naturally adapt to new climates and the mismatch in rates between climate change and tree adaptation can have a considerable impact on forest growth and composition (Williams & Dumroese 2013). A possible way to overcome the problems that rapid climate change might entail could be by assisted migration (Pedlar et al. 2012). Assisted migration is a mean to maintain the health and productivity of the forest under a changing climate by intentionally moving seed sources either within their existing range or to suitable areas outside, promoting natural range expansion to shifting conditions (Pedlar et al. 2012; Williams & Dumroese 2013). There are ongoing experiments involving moving species provenances evolved in warmer climates into regions with cooler climates as a proactive measure to address future climate changes and to study their adaptability and growth in new environments (Pommerening 2023).

Gap cuttings could offer a middle ground approach where forests can maintain their natural character while simultaneously allowing planting of improved material in the gaps, providing the potential benefits of improved seedlings while preserving the forest's original character. It is important to consider the potential risks included when relocating plant material beyond its native range. Relocation may introduce pests that are not native to the area or could result in species native to the site being outcompeted.

5. Conclusion

CCF is becoming a well-discussed silvicultural practice that could be used alongside RFM. A more sustainable way to harvest timber where the whole forested area does not have to be fully cleared. With CCF there are different methods to choose from: selective thinning, shelterwood, gap cutting and TDC. The various methods can be useful management practices for forested areas with special values, such as places with specific natural values that needs to be protected, or forest owners that want to preserve historical, recreational, or ecological values.

The management with CCF has shown great results in this forest estate in Rogberga. The results of the experiment indicate that natural regeneration is present and significant in all gap sizes and in TDC. The hypothesis is confirmed with a higher amount of regeneration in the gap cuttings compared to TDC and control. Spruce and birch were the dominating species regenerated, while the other species that were found but not as abundantly were pine, willow, oak, and rowan. These species could form part of the future structure of the forest if it is not outcompeted by spruce and birch the first few years. With the number of seedlings available compared to traditional RFM, there is a better chance to get good quality seedlings with CCF practices as there are more seedlings to choose from. A suggestion for future CCF management could be planting seedlings and allowing natural regeneration as well. This way there is site adapted seedlings and genetically improved ones adapted for future climate with improved growth. For the gaps, species composition will change over the years. Initially spruce and birch will be dominating, which may change to only one dominating species in the future. To keep the mixture PCT or thinning will be needed after 5-10 years. Plots treated with TDC will likely change from the mixture of spruce and pine, into multilayered spruce plots, as pine and birch struggle to establish within the created gaps.

In conclusion, the result from this study proves that CCF is a viable option to supplement RFM. Although, it is important to note that these results are site specific and there is a need for more long-term studies to make any informed decisions about CCF in the future.

6. References

Andersson, R. & Appelqvist, C. (2020). Hyggesfritt skogsbruk. Skogsstyrelsen. https://www.skogsstyrelsen.se/globalassets/bruka-skog/olika-satt-att-skota-din-skog/hyggesfritt/broschyr-om-hyggesfritt-skogsbruk.pdf

Anthony, M.A., Crowther, T.W., van der Linde, S., Suz, L.M., Bidartondo, M.I., Cox, F., Schaub, M., Rautio, P., Ferretti, M., Vesterdal, L., De Vos, B., Dettwiler, M., Eickenscheidt, N., Schmitz, A., Meesenburg, H., Andreae, H., Jacob, F., Dietrich, H.-P., Waldner, P., Gessler, A., Frey, B., Schramm, O., van den Bulk, P., Hensen, A. & Averill, C. (2022). Forest tree growth is linked to mycorrhizal fungal composition and function across Europe. *The ISME Journal*, 16 (5), 1327–1336. https://doi.org/10.1038/s41396-021-01159-7

Appelqvist, C., Sollander, E., Norman, J., Foreberg, O. & Lundmark, T. (2021). *Rapport 2021/8 Hyggesfritt skogsbruk - Skogsstyrelsens definition*. (8). Skogsstyrelsen. https://www.skogsstyrelsen.se/globalassets/om-oss/rapporter/rapporter-20222021202020192018/rapport-2021-8-hyggesfritt-skogsbruk---skogsstyrelsens-definition.pdf [2024-04-12]

Egbäck, S., Nilsson, U., Nyström, K., Högberg, K.-A. & Fahlvik, N. (2017). Modeling early height growth in trials of genetically improved Norway spruce and Scots pine in southern Sweden. *Silva Fennica*, 51 (3). https://www.silvafennica.fi/article/5662/related/5662 [2024-05-15]

Ekholm, A., Lundqvist, L., Petter Axelsson, E., Egnell, G., Hjältén, J., Lundmark, T. & Sjögren, J. (2023). Long-term yield and biodiversity in stands managed with the selection system and the rotation forestry system: A qualitative review. *Forest Ecology and Management*, 537, 120920. https://doi.org/10.1016/j.foreco.2023.120920

Ersson, B.T. (2020). *Hyggesfritt Skogsbruk*. Swedish University of Agricultural Sciences. https://www.slu.se/globalassets/ew/org/inst/sbt/forskning/net4forest/ersson.2020.hyggesfritt_skogsbruk_erasmusplus_o2-003.pdf [2024-04-22]

Espmark, K. (2017). *Debatten om hyggesfritt skogsbruk i Sverige*. (Future Forests Rapportserie 2017:2, 2). Swedish University of Agricultural Sciences.

Goude, M., Erefur, C., Johansson, U. & Nilsson, U. (2022). *Hyggesfria skogliga fältförsök i Sverige.* (22). Swedish University of Agricultural Sciences.

Häggström, B., Gundale, M.J. & Nordin, A. (2024). Environmental controls on seedling establishment in a boreal forest: implications for Scots pine regeneration in continuous cover forestry. *European Journal of Forest Research*, 143 (1), 95–106. https://doi.org/10.1007/s10342-023-01609-1

Heinonsalo, J. (2004). *The effects of forestry practices on ectomycorrhizal fungal communities and seedling establishment*. (Diss). University of Helsinki. https://core.ac.uk/download/pdf/14917357.pdf

Holmström, E. (2024). *Vad är hyggesfritt skogsbruk? SLU.SE*. https://www.slu.se/centrumbildningar-och-projekt/future-forests/temasidor/hyggesfritt-skogsbruk2/vad-ar-hyggesfritt-skogsbruk/ [2024-04-11]

Jones, M.D., Durall, D.M. & Cairney, J.W.G. (2003). Ectomycorrhizal fungal communities in young forest stands regenerating after clearcut logging. *New Phytologist*, 157 (3), 399–422. https://doi.org/10.1046/j.1469-8137.2003.00698.x

Karlsson, M. (2003). Fakta Skog. Oscarsson, H. (ed.). (Oscarsson, H., ed.). Fakta, SLU Publikationstjänst.

Kerr, G. & Mackintosh, H. (2012). Long-Term Survival of Saplings during the Transformation to Continuous Cover. *Forests*, 3 (3), 787–798. https://doi.org/10.3390/f3030787

Knoke, T. (2012). The Economics of Continuous Cover Forestry. In: Pukkala, T. & von Gadow, K. (eds) *Continuous Cover Forestry*. Springer Netherlands. 167–193. https://doi.org/10.1007/978-94-007-2202-6_5

Lantbrukarnas Riksförbund (2023). *Samtal i skogen om skogen*. https://www.lrf.se/nyheter/samtal-i-skogen-om-skogen/ [2024-04-11]

Näslund, M. (1936). Skogsförsöksanstaltens gallringsförsök i tallskog. *Meddelanden från Statens skogsförsöksanstalt*,. https://res.slu.se/id/publ/124955 [2024-05-31]

Pedlar, J.H., McKenney, D.W., Aubin, I., Beardmore, T., Beaulieu, J., Iverson, L., O'Neill, G.A., Winder, R.S. & Ste-Marie, C. (2012). Placing Forestry in the Assisted Migration Debate. *BioScience*, 62 (9), 835–842. https://doi.org/10.1525/bio.2012.62.9.10

Pommerening, A. (2023). *Continuous Cover Forestry: Theories, Concepts, and Implementation*. John Wiley & Sons, Incorporated. http://ebookcentral.proquest.com/lib/slub-ebooks/detail.action?docID=30741006 [2024-05-27]

R Core Team (2021). *R: A Language and Environment for Statistical Computing* (R version 4.1.2). R Foundation for Statistical Computing. https://www.R-project.org/

Roberge, C., Nilsson, P., Wikberg, P.-E. & Fridman, J. (2023). *Skogsdata 2023*. Swedish University of Agricultural Sciences. https://www.slu.se/globalassets/ew/org/centrb/rt/dokument/skogsdata/skogsdata_2023_webb.pdf [2024-04-11]

Rosvall, O., Andersson Gull, B., Berlin, M., Högberg, K.-A., Stener, L.-G., Jansson, G., Almqvist, C. & Westin, J. (2016). *Skogsträdsförädling*. (Skogsskötselserien, Kapitel 19). Skogsstyrelsen. https://www.skogsstyrelsen.se/globalassets/mer-om-skog/skogsskotselserien/skogsskotsel-serien-19-skogstradsforadling.pdf [2024-05-28]

Skogskunskap (2023a). *Antal plantor*. *Skogskunskap*. https://www.skogskunskap.se:443/skota-barrskog/foryngra/plantering/antal-plantor/ [2024-04-17]

Skogskunskap (2023b). *Hur hårt ska jag röja? Skogskunskap*. https://www.skogskunskap.se:443/skota-barrskog/roja/rojningens-nar-var-hur/hur-hart-ska-du-roja/ [2024-04-22]

Skogskunskap (2024). *Sveriges skogsskötselsystem*. https://www.skogskunskap.se:443/aga-skog/fakta-om-skogen/sveriges-skogsskotselsystem/ [2024-04-11]

Södra Kommunikationsavdelningen (2022). Hyggesfria skötselmetoder. https://www.sodra.com/sv/se/skog-medlem/skogsbruk/skota-skog/hyggesfritt-skogsbruk/ [2024-04-24]

Visser, S., Maynard, D. & Danielson, R.M. (1998). Response of ecto- and arbuscular mycorrhizal fungi to clear-cutting and the application of chipped aspen wood in a mixedwood site in Alberta, Canada. *Applied Soil Ecology*, 7 (3), 257–269. https://doi.org/10.1016/S0929-1393(97)00060-7

Wang, T., O'Neill, G.A. & Aitken, S.N. (2010). Integrating environmental and genetic effects to predict responses of tree populations to climate. *Ecological Applications*, 20 (1), 153–163. https://doi.org/10.1890/08-2257.1

Williams, M.I. & Dumroese, R.K. (2013). Preparing for Climate Change: Forestry and Assisted Migration. *Journal of Forestry*, 111 (4), 287–297. https://doi.org/10.5849/jof.13-016

Acknowledgements

We would like to express our sincere gratitude to our supervisor Urban Nilsson for his excellent support and guidance throughout the process of writing our thesis. We are particularly grateful for the patience in addressing our endless questions regarding R-studio.

The experiment was established by Lars Drössler.

Publishing and archiving

Approved students' theses at SLU are published electronically. As a student, you have the copyright to your own work and need to approve the electronic publishing. If you check the box for **YES**, the full text (pdf file) and metadata will be visible and searchable online. If you check the box for **NO**, only the metadata and the abstract will be visible and searchable online. Nevertheless, when the document is uploaded it will still be archived as a digital file. If you are more than one author, the checked box will be applied to all authors. You will find a link to SLU's publishing agreement here:

- https://libanswers.slu.se/en/faq/228318.

☒ YES, I/we hereby give permission to publish the present thesis in accordance with the SLU agreement regarding the transfer of the right to publish a work.

☐ NO, I/we do not give permission to publish the present work. The work will still be archived and its metadata and abstract will be visible and searchable.