Comparison of Gap-Cutting and Clear-cutting Management and Their Ecosystem Services: A Simulation Study

Mary Motunrayo Ogunleye

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Mary Motunrayo Ogunleye

Supervisor:	**Urban Nilsson, Swedish University of Agricultural Sciences, Southern Swedish Forest Research Centre**
Examiner:	Adam Felton, Swedish University of Agricultural Sciences Southern Swedish Forest Research Centre

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

Abstract

Forests as a natural ecosystem provide many functions and services that contribute to livelihood. Moreover, to provide multifaceted services, the forest management strategy employed is vital in establishing desired ecosystem services. Thus, this study weighed up gap-cutting and clear-cutting management and their ecosystem services in a Scots pine stands in southern Sweden. The method used in this study was the simulation of old and new forest stands with the Standwise Heureka decision support system application. Three treatments were examined. First is the gap-cut with five years cutting intervals, next is the gap-cut with fifteen years intervals, and the last is the clear-cut with which the gaps were compared. The study analysed the profitability of the stands with respect to land expectation value (LEV), growth in terms of the mean annual increment (MAI), and the ecosystem services that the stand structures can provide in terms of diameter variations. The results show that the Land expectation value of gap-cut with five years interval at a 3% interest rate does not differ from clear-cut. In contrast, there is much difference in the gap-cut of fifteen years intervals. Furthermore, the growth performance of the treatments differed significantly, where the MAI of clear-cut was the highest and ranged between 6.5 to 8.75 $m^3 ha^{-1}yr^{-1}$ and that of gap-cuts 4.2 to 6.0 $m^3ha^{-1}yr^{-1}$, respectively. The diameter variation in gap-cut management was higher than that of clear-cut, and the 15-year interval resulted in higher diameter variation than the 5-year interval gap cut. This indicates that gap-cutting, especially the 15-year interval gaps, may provide more ecosystem services than clear-cut management. Thus, this study elucidates possible ecosystem benefits associated with the forest structure that each management type could produce in southern Sweden.

Keywords: Ecosystem services, Gap-cut management, Scots pine, Clear-cut, Forest management.

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Abbreviations

CCF	Continuous cover forestry
CC	Clear cut
CV	Coefficient of variance
GAP5	Gap interval of 5 years
GAP15	Gap interval of 15 years
LEV	Land expectation value
MAI	Mean annual increment
NPV	Net present value

1. Introduction

Background of the silvicultural system in Sweden

Sweden is one of the few countries whose forest ecosystem mainstream focuses on the provisioning services. The forest contributes ca. 10% export share to the national economy (Erefur 2010; Hertog *et al.* 2022). Swedish forest management approaches are tuned towards maximising the provisioning services, such as timber production, giving less attention to other ecosystem services like regulating and cultural services (Erefur 2010). One of the most dominant management practices is the clear-cutting system. Clear-cutting is an even-aged forest management operation geared toward efficient wood production (Tishler *et al.* 2020). The system entails harvesting the designated stand in one operation and subsequent regeneration, which gives rise to a new even-aged structural canopy (Jokela et al. 2019). However, this type of management simplifies the complexity of the natural forest ecosystem as compared to an unmanaged forest (Raymond *et al.* 2018). Reduction in old-growth trees, deadwood, and species homogeneity in this management type have negatively impacted forest biodiversity, recreation, and aesthetic values (Jokela *et al.* 2019; Pukkala *et al.* 2011). Conversely, this system has been ameliorated with an obligation to give equal consideration to production and environmental values that would enhance multiple forest ecosystem services (Rist *et al.* 2016). Thus, this obligation is there to improve the forest structure and values.

Clear-cut free forestry (*hyggesfritt skogsbruk*), also referred to as continuous cover forestry, is a silvicultural approach that the Swedish Forestry Agency has promoted to balance economic, social, and ecological objectives in forest management. Rather than relying on clear-cutting, which can lead to significant ecological impacts and biodiversity loss, clear-cut free forestry emphasises continuous cover forestry by selective harvesting (Hertog *et al.* 2022). Under this approach, trees are harvested selectively and in small patches, allowing for a more diverse and structurally complex forest. With this system, the forest owners are obliged to manage the forest following definitions given by the forest agency. In principle, the forest should always be covered with trees without larger clear-cut areas. This means that for the area harvested, the harvested area cannot exceed 0.25 ha, and gaps cannot be enlarged until the mean regeneration height in the original harvested area is above 2.5 m. In addition, the average density of a stand that is managed with clear-cut free forestry cannot be below the 5§-curve (Skogsstyrelsen 2018). However, clear-cut free forestry is promoted as an alternative forest management practice in Sweden, but in practice, the adoption among forest owners is still low (Hertog *et al.* 2022).

1.1 Gap-cutting Management

The idea of gap-cutting management emanated from studying natural disturbance regimes, which was proposed to bridge the ecological gap between managed and unmanaged forests (Angers *et al.* 2005). Gap formation in the natural forest could be due to disturbances or site conditions such as high water-to-drainage ratio or shallow bedrock depth (Muscolo *et al.* 2014). Natural disturbance regimes are characterised by their severity, extent, and occurrence, impacting the forest structure, growth, and mortality (Angers *et al.* 2005). For example, the micro-gap regime in a natural forest is characterised by the death of a single or small group of trees, creating a gradual or sudden canopy opening in an old-growth forest (Angers *et al.* 2005). In addition, large-scale disturbances such as wind, fires, and insect outbreaks also create larger canopy openings allowing light on the forest floor and stimulating diverse plant reproduction and growth (Hammond & Pokorný, 2020; Muscolo *et al.* 2014).

In managed forests, gap formation is done by timber harvest, usually followed by a predetermined regenerating method (Kern *et al.* 2017). The overstory of the stands is harvested in groups or individually. Seed trees, shelterwood, gap-cutting, and selection-cutting are examples of harvesting methods used in gap management (Coates & Burton, 1997). In gap-cutting, the proportion of trees removed, harvest gap size, and spatial arrangement play a crucial role in stand development (Muscolo *et al.* 2014). In order to regenerate a consistent flow of merchantable timber production in a managed forest, harvest gap size and tree density must be determined to facilitate new stand development to maturity (Kern *et al.* 2017). Gap size and spacing are important factors to consider when implementing gap-cutting management, as they can influence the amount of light and nutrients available to the remaining trees (Downey *et al.* 2018; Coates & Burton, 1997). For example, Coates & Burton, (1997) reported a positive correlative response between the size of a canopy gap and the species present. They further concluded that the light available on the forest floor is related to the gap size, the height of the standing canopy and the orientation of the stands which in turn influence the kind of species that regenerated and contribute to the species composition and abundance of the ecosystem.

Furthermore, selecting trees to be removed is also a crucial aspect of gap-cutting management, as it depends on the management goal and ecosystem services the stands are intended for. For example, creating a gap farther away from seed trees or proximate to ungulate movement could impede the success of stand regeneration and affect the management goals (Kern *et al.* 2017; Raymond *et al.* 2006; Witt and Webster 2010). However, it is essential to consider the potential risks and disturbances associated with gap-cutting management, such as increased windthrow (Gustafsson *et al.* 2012). Additionally, the timing of gap-cutting can be important, as it can affect the regeneration of the forest and the establishment of new stands (Tishler *et al.* 2020).

From an ecological perspective, gap-cutting has been discussed by scientists to facilitate species abundance in the forest stands more than species richness. This was related to the gap size, the availability of seed sources, and the microclimate that favours the proliferation of the adapted species found in the gap (Hjältén *et al.* 2017; Coates & Burton, 1997). Some studies have shown that species richness is linked to larger gap sizes that allow for more light, which benefits gap specialists and makes nutrients available for uptake (Kern *et al.* 2017; Raymond *et al.* 2006; Burton *et al.* 2014). However, the richness decreases as the canopy gap closes (Burton *et al.* 2014). On the bright side, gap-cutting has been reported to favour the recruitment of shade-intolerant species as well as the natural regeneration of overstory trees and this was a result of the gap influence on the environmental physiology of the forest ecosystem (Hallikainen *et al.* 2019).

1.2 The role of gap-cutting management in enhancing the growth and productivity of Scots pine

Scots pine (*Pinus sylvestris* L.) is a major tree species in boreal forests of the Northern Hemisphere. The silviculture of Scots pine has been studied extensively due to its ecological and economic importance in these regions. Scots pine can grow in various soil conditions and adapt to environmental conditions, such as drought and low temperatures, making it an ideal species for forestry management in boreal forests (Egnell 2000).

Scots pine forests are generally managed using either even-aged or uneven-aged management systems, such as clear-cutting, seed-tree cutting, and shelterwood cutting. However, Scots pine is liable to biotic and abiotic stressors such as frost, competing vegetation, pine weevils, and browsing (Nilsson *et al.* 2019; Lula *et al.* 2021). Hence, active management of Scots pine is required to facilitate the establishment of new stands (Lula *et al.* 2021). Gap-cutting management may be desirable for Scots pine forests, as this management approach is found to balance forest structure and timber production as well as enhance forest ecosystem services in stands dominated by other tree species (Coates & Burton, 1997; Jokela *et al.* 2019).

Furthermore, gap-cutting management plays a vital role in the regeneration, growth, and productivity of Scots pine. As mentioned above, gap sizes are crucial to regeneration in this management system, some studies have reported sufficient natural regeneration in gap-cut (Tishler *et al.* 2020). For example, a study conducted on the natural regeneration of Scots pine after a gap cut in Finland found an adequate number of seedlings emerging (on average 22 000 ha^{-1}) in the sampled sites 5 years after the gap cut (Hallikainen *et al.* 2019). Likewise, Drössler *et al.* (2017) reported four times the amount of seedling regeneration in the gap than within stands managed using target diameter gap harvest in southern Sweden. However, the displacement of the seeds from the seed source, soil moisture, and gap size influences natural regeneration (Drössler *et al.* 2017; Béland *et al.* 2000). For example, Hallikainen *et al.* (2019) recorded the highest number of seedlings at the edge of the gap, compared to farther away from the seed source. Conversely, the height development of the regenerated Scots pine seedlings was lower in gap cutting of 25m to 35m diameter compared to strip-cut and clear-cut seedling growth (Tishler *et al.* 2020). Also, Pasanen *et al.* (2016) found a weak positive correlation between the seedling's height and diameter with the gaps, attributing the result to light and gap size. This means that Scots pine growth in gap-cut can be affected by the light reaching the recruited seedlings, which in turn impedes their growth rate. Tishler *et al.* (2020) reported a 35% light reduction in transmitted light in a group gap cut of 25m to 35m diameter compared to other management types. However, studies have shown that naturally regenerated seedlings in gaps can enhance economic resilience (Knoke *et al.* 2023).

1.3 Research Justification and Objectives

Scots pine (*Pinus sylvestris* L.) is one of the dominant species in Swedish forestry, accounting for 39% of the total standing volume in the country (Lula *et al.* 2021). One of the challenges in the silviculture of Scots pine is the choice of the management strategy employed to balance economic interests with ecological sustainability (Eggers *et al.* 2017). Clear-cutting has been found to have negative ecological impacts on forest soil, biodiversity, and alteration of ecosystem processes but maximising economic interest (Felton *et al.* 2020; Hertog *et al.* 2022). Thus, there is a growing interest in Swedish forestry to develop silvicultural practices that maintain the ecological integrity of the forest while maximising its economic potential within this requirement (Erefur 2010; Hertog *et al.* 2022). Studies have suggested that gap-cutting can positively affect regeneration, biodiversity and ecosystem functioning (Coates & Burton, 1997; Drössler *et al.* 2017; Jokela *et al.* 2019). It is crucial to understand gap-cutting management and potential risks in a productive forest in southern Sweden. This information can inform forest management practices and promote sustainable stand development. Therefore, the study sought to assess the potential of gap-cutting management in Scots pine stands, aiming to provide insight into practical strategies for promoting forest productivity and sustainability while maximising other ecosystem services.

Our findings could inform forest management policies and practices in Sweden and help to ensure the long-term sustainability of the country's forest ecosystem.

In this study, the Heureka StandWise decision support system was used to simulate the stand development of new Scots pine stands in southern Sweden's forest. The reason for a simulation study instead of a field experimental study is that there is a lack of long-term empirical data on gap-cut management in southern Sweden, and it would be disastrous to shift to this management system without predicting how it will work in practice. Hence, Heureka StandWise was used to simulate and compare the development of Scots pine seedlings in gaps to maturity.

The specific objectives of this study are:

I. To compare the financial value of gap-cutting management with clear-cut management in Scot pine stands.
II. To compare Scots pine's growth in gap-cutting management with the clear-cut management system.
III. To assess the structural stand development in providing ecosystem services

Given the above, we Hypothesized that:

H1: Clear-cut management's financial value is higher than Gap-cutting management. This is based on the fact that harvesting with clear-cut removes all merchantable timber from the forest in one operation, while Gap harvest uses a step-wise harvest.

H2: The growth of Scot pine is higher in clear-cut management than in gap-cut management. This is based on the fact that the growth of seedlings in the gaps are reduced because of competition from neighbouring trees, and that genetically improved seedlings often are used on clear-cuts.

H3: Diameter distribution in gap-cutting is wider than after regeneration on clear-cuts. Gap-cutting creates an avenue for the mature stands to increase in size due to the gap created whereas the whole stand is regenerated in one-step in the clear-cutting system.

2. Materials and Methods

Study area and gap-cutting design

The data used in this study were obtained from four continuous cover forestry (CCF) long-term experiments in southern Sweden (Figure 1). The trial areas are divided into four treatments to study the production, natural regeneration, and growth of pine and fir species in CCF management (www.silvaboreal.com). Since the treatments were replicated three times in one experiment and two times in another experiment, a total of seven control plots were used in the simulation, and the site index ranged between T24 to T30.

The gap-cut design resembles the chequerboard design (Erefur 2010). There are four gaps per hectare and the gap shape in the first cutting was circular with a 25 m diameter, and the gap was extended by 1.5 times the initial radius, which is 18.75 m in 2 steps. The direction of the gap cut is designed diagonally from the southwest to the northeast (Figure 2). In the last harvest, the remaining trees between the gaps were removed. For the gap cut, the gap harvest was done in 5 year (hereafter Gap5) and 15 year (hereafter Gap15) intervals. About 20% of trees were harvested in the first three gap-cuttings, and the remaining 40% were removed in the last harvest of trees between the gaps. The extension of the gaps was therefore done before the mean height of regeneration was 2.5 m in Gap5, whereas, with Gap15, the mean height in the previous gap harvest would have attained 2.5m before gaps were extended. Therefore, Gap15 qualifies as a clearcut-free method according to the definitions by the Forest Agency whereas Gap5 do not.

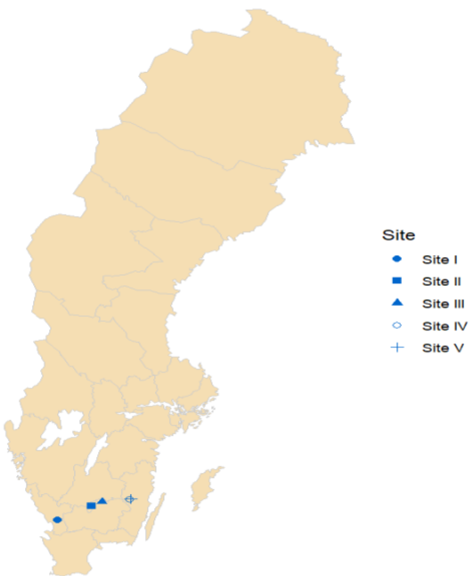

Figure 1. Study area map

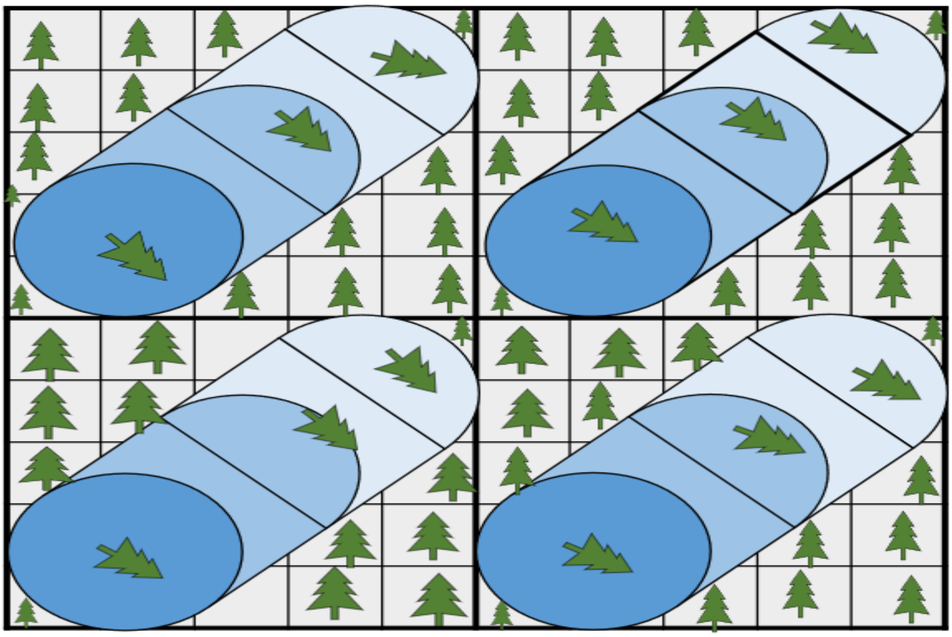

Figure 2.Gap-cut Design

2.1 Heureka Simulation

Heureka is a decision support system that is widely used in forestry management in Sweden. It is designed to assist forest managers in making informed forest management and planning decisions. The system uses a combination of models, data, and expert knowledge to predict how different forest management strategies will affect forest growth, timber production, and biodiversity (Wikström *et al.* 2011; Eggers & Öhman 2020). It allows decision-makers to evaluate the long-term consequences of different management strategies and explore the trade-offs between different objectives (Eggers *et al.* 2017). The functions of the Heureka system are delivered through models such as basal area growth models, ingrowth and mortality, and height-diameter models (Fahlvik *et al.* 2018; Wikström *et al.* 2011).

Simulation can be done on new and old stands (Lula *et al.* 2021). Moreover, to start with, the input data for the simulation consists of site characteristics, i.e., vegetation type, site index, latitude, altitude, soil properties, and tree characteristics such as height, diameter, and tree species. Hereafter, the simulation is done in 5 years-steps. Treatments such as commercial thinning, regeneration, and final harvest can be done, and the results can be viewed using tables or other visualisation types.

2.1.1 Simulation of the New Stands

The new Scots pine forest simulation was done with the Heureka StandWise with starting dominant heights >9.0 m (Table 1). Seven sites were simulated. One assumption used when simulating clear-cut and gap-cut management was that the site index for the clear-cut was four m higher than the gap-cut. The reason behind this assumption was that seedling growth in gap-cut would be reduced as a result of competition from trees at the edge of the gaps. In addition, genetically improved seedlings were used when planting on clearcuts whereas regeneration in gaps relied on natural regeneration from surrounding trees. This can also be justified by several researchers, such as Valkonen *et al.* (2002), who stipulated that neighbouring competition can significantly reduce the growth and survival of Scots pine seedlings.

The gap size and the cut frequency were replicated in four gaps per hectare (Table 2). Each gap with a predetermined gap size could also be viewed as an extension of the previous gap. In other words, gaps were extended after five and fifteen years of the last gap, and this is done in four steps. In contrast, the clear-cut simulation was done on one hectare with no cut dimension (Table 3). The three treatments were simulated from the first release to the final harvest. The Sodra thinning guideline was used to determine the basal area reduction and the year of thinning. Two commercial thinning was done, harvesting 35% and 25% of the basal area. In the first thinning, the simulation was performed when the dominant height was between 11 – 15 m, while the second thinning was done before 22 m. Final felling was simulated for different periods in order to determine the optimal rotation age for each stand based on Land expectation value calculations. The starting value for the new stand simulation was derived from diameter and height models developed by Fahlvik *et al.* (2018). Starting values were simulated for a stand with 10 m in top height. First, diameter distribution in 1-cm diameter classes at that time was simulated by estimating coefficients of the Weibull distribution model. Thereafter, coefficients for the Näslund height curve were estimated and each 1 cm diameter class were assigned a height. The total age at 10 m top height was estimated with site-index functions (Johansson *et al.* 2013).

Table 1. Initial starting values for the new stands (Gap cut and Clear cut) and old stands.

	Gap-cut				Clear-cut				*Old stand*			
Stand no.	Site Index (m)	Age (yrs)	Dominant Height (m)	Stem Density (tree/ha)	Site Index (m)	Age (yrs)	Dominant Height (m)	Stem Density (tree/ha)	Site Index (m)	*Age (yrs)*	*Dominant Height (m)*	*Stem Density (tree/ha)*
1	T 24	33	9,82	2000	T 28	26	9,9	1999	T 24	*106*	*24,59*	*368*
2	T 28	26	9,90	1999	T 32	20	9,9	2001	T 27	*86*	*24,35*	*396,3*
3	T 28	26	9,90	1999	T 32	20	9,9	2001	T 29	*91*	*28,16*	*431,7*
4	T 24	33	9,82	2000	T 28	26	9,90	1999	T 24	*121*	*26,45*	*1557*
5	T 26	29	9,86	1999	T 30	23	9,94	1999	T 30	*94*	*20,94*	*1154*
6	T 24	33	9,82	2000	T 28	26	9,90	1999	T 24	*95*	*21,23*	*1385*
7	T 24	33	9,82	2000	T 28	26	9,90	1999	T 24	*94*	*22,85*	*1544*

Table 2.Gap cut simulation table. showing the gap size and cut intervals in years

Treatment	Year	Dimension (m^2)	Area cut (ha)	Relative area
Gap cut	0	491	0.196	0,196
	5/15	469	0.188	0,188
	10/30	469	0.188	0,188
	15/45	1072	0.430	0,430

Table 3. Clear-cut simulation

Treatment	Year	Area cut (m^2)	Relative area
Clear cut	0	10000	1

2.1.2 Simulation of the Old Stands

The simulation of the old stands was done to get the values for the regeneration cycle in the new stands in the gap-cut treatments. This helps predict the Scots pine growth and development in gaps (Appendix). The harvested volume in the second, third, and fourth gap cuts was taken from periods 3, 6 and 9 for Gap15 and 1, 2 and 3 for Gap5. The first gap is where the stands were cut, where each gap cycle completes its full rotation length. i.e. merchantable harvest period. Lastly, the old stands simulation tables were also used to determine the site index the treatments fall into, i.e., clear cut is four indexes higher than gap cut (reasons explained above).

2.2 Analysed Variables After Final Felling

2.2.1 Estimation of Land Expectation Value

Land Expectation Value (LEV) is a financial tool used in forestry to evaluate the economics of a forest stand based on the future cash flows that can be generated from the land. LEV is used to determine the most profitable way to manage a forest. In addition, it can be used to determine the optimal rotation age, which is the age at which the forest stand should be harvested to maximise the net present value of the future revenue streams. The optimal rotation age depends on the growth rate of the trees, the price of the timber, the discount rate, and the cost of harvesting and transportation.
The basic formula for LEV is:

$$LEV = \frac{1 \times \rho^{u}}{(1 \times \rho^{u} - 1)} \times NPV \qquad (1)$$

Where LEV is the land expectation value, u is the length of the rotation period (years), ρ is the interest rate and NPV is the net present value of the costs and revenue streams from the first rotation.
In this LEV calculation, the interest rate used for the two management (i.e. clear-cut and gap-cut) was 3% and the estimated LEV is valued at SEK/ha.

2.2.2 Estimation of Mean Annual Increment (MAI)

Mean annual increment (MAI) is used to estimate the productivity and growth of forest stand over time. MAI is defined as the average volume or biomass increment of a stand of trees in a given year. It is calculated by dividing the total volume or biomass of the stand by the number of years of growth. The MAI for each treatment was estimated with equation 2.

$MAI_t = \frac{\mathbb{V}_1 + \sum \mathbb{V}_2}{t}$ (2)

Where V_1 is the standing volume ($m^3ha^{-1}yr^{-1}$) at a given time (t) and $\sum \mathbb{V}_2$ is the sum of the harvested volume from the previous year. Thus, the growth of the two management stands was obtained at different site indexes.

For calculating MAI for the gap-cutting treatments, the growth of the old stand in areas that were not cut needs to be included. Therefore, the formula for MAI was extended by:

$MAI_t = \frac{\mathbb{V}_1 + \sum \mathbb{V}_2 + \mathbb{V}_3}{t}$ (3)

Where V_3 is the growth of the old stand up until time t

2.3 Diameter Distribution

The diameter distribution of the Scots pine trees was computed from the simulated tables to determine the vertical stand structure for clear-cut and gap-cut. Each treatment consists of seven stands making twenty-one stands in total. For the gap cut, the diameter distribution was assessed in four periods (Table 2), of which the first period consists of all the diameter classes of Scots pine trees in the year LEV was maximised, then the second to fourth periods consist of all diameter sizes of trees from three periods at 5- and 15-years interval before the LEV was maximised. The proportion of the diameter classes was weighted per hectare and done per stand. In the clear-cut treatment, the diameter classes represented in each stand were only assessed at the year LEV was maximised, and their proportion per hectare was visualised in graphs. After that, the coefficient of variance was tested to assess the level of variation across the three treatments.

The coefficient of variance (CV) measures the relative variability that compares the standard deviation to the mean.

$$CV = \frac{standard\ deviation}{mean}$$

2.4 Statistical Analysis

The analysis of variance was used to test if the cutting treatments were significantly different in terms of financial value, structural variation, and the growth of Scots pine. The level of significance was 0,05. Differences among treatments were evaluated with Tukey's honestly significant difference (HSD) mean separation test when treatment effects were significant (*p*_0.05) in the analysis of variance.

3. Results

3.1 Financial Value of Clear-cut and Gap-cut Management

The difference in LEV between the three cutting treatments was statistically significant ($p<0.0001$; Table 4). However, the financial value from clear-cut treatment did not give a higher return on investment than gap-cut with five years cutting intervals, but Gap5 and Clear-cut had significantly higher LEV than Gap15 (Table 5). Across treatments, the highest LEV comes from stands 3 and 4 (Figure 3). Likewise, the financial value of the newly regenerated stands shows an increase in LEV with increasing site fertility. On average, the economic margin gap of clear-cut to Gap5 is 1,08, and to Gap15 is 1,44 (Figure 3). However, comparing LEVs of gap-cutting and clearcutting for only the new stands, the economical production of gap-cut out weights that of clear-cut (Figure 4). LEV was 6919, 5124 and 1524 SEK higher for gap cutting than clearcutting for the T28/T24, T30/T26 and T32/T28 comparisons, respectively (Figure 4).

Table 4. Analysis of variance for LEV of Clear cut and Gap cut. The level of significance is $p < 0.05$.

	Df	Sum Sq.	Mean Sq.	F value	Pr(>F)
Treatment	2	5.458e+09	2.729e+09	42.81	3.45e-06 ***
Stand	6	1.286e+10	2.143e+09	33.62	7.96e-07 ***
Residuals	12	7.650e+08	6.375e+07		

Table 5. Groups of mean at sig. Level = 0.05. This shows how significant each treatment is. "a" is significantly higher than "b". In this table, there is no significant difference between Clearcut and Gap5. Still, these treatments significantly differ from Gap15 in economic returns.

Treatment	Mean (Sek/ha)	G1	G2
Clear cut	121733.71	a	
Gap 5	111517.14	a	
Gap 15	83590.43		b

Figure 3. Land expectation value (sek/ha) for the treatments. Where cc is clear cut, gap 1 is the gap with 5 years interval, and gap 2 is the gap with 15 years interval. This illustrates how the treatments vary in economic value per stand.

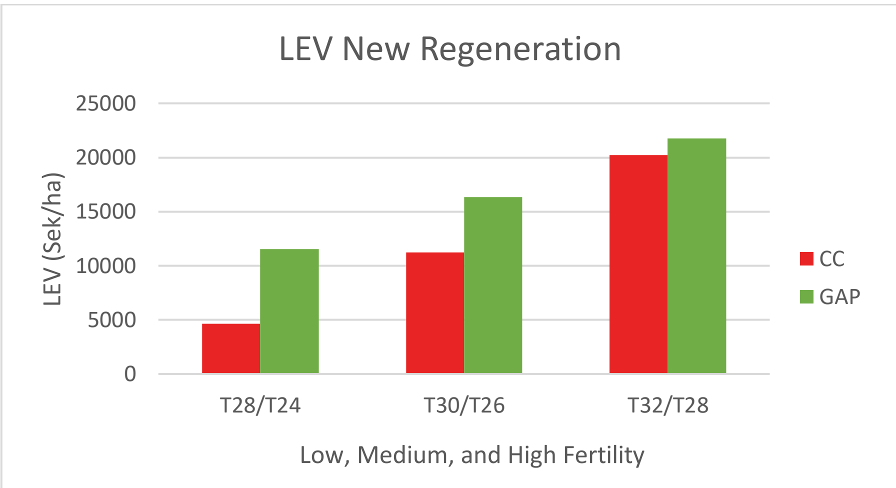

Figure 4. LEV of the new stands per site index. This illustrates the economic return of the newly regenerated Scot pine per site fertility level. Where T32 is more fertile than T24.

3.2 Growth Performance of Scots Pine in Clear-cut and Gap-cut Management

The analysis of variance performed on the mean annual increment of Scots pine shows that the growth performance in clear-cut differs significantly from the growth of Scots pine in gap-cut management (Table 6). Per annum clear-cut increases with 7.5 $m^3ha^{-1}yr^{-1}$ on average, whereas Gap15 and Gap5 are below 4.6 $m^3ha^{-1}yr^{-1}$ on average (Figure 5). Also, Figure 5 shows the group mean significant level. The growth output in each stand also differed significantly (Figure 6). Stands two and three produce the most with a yearly volume increment of 8.75 $m^3ha^{-1}yr^{-1}$ in the clear-cut.

Table 6. Analysis of Variance for MAI of Clear cut and Gap cut. The level of significance is $p < 0.05$

	Df	Sum Sq.	Mean Sq.	F value	Pr(>F)
Treatment	2	59.26	29.632	47.702	4.12e-15***
Stands	6	24.06	4.010	6.455	9.64e-06***
Residuals	96	59.63	0.621		

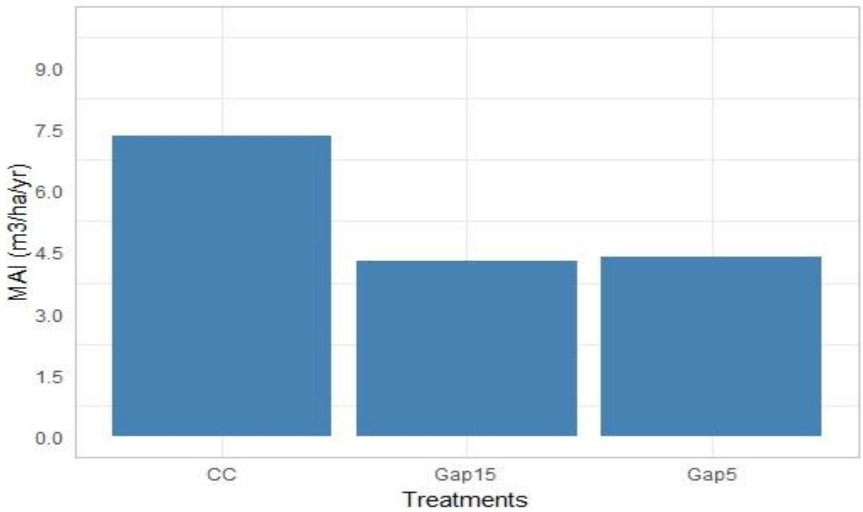

Figure 5. Illustrating the significant level of the treatments. This shows that clear-cut have higher MAI than gap-cut.

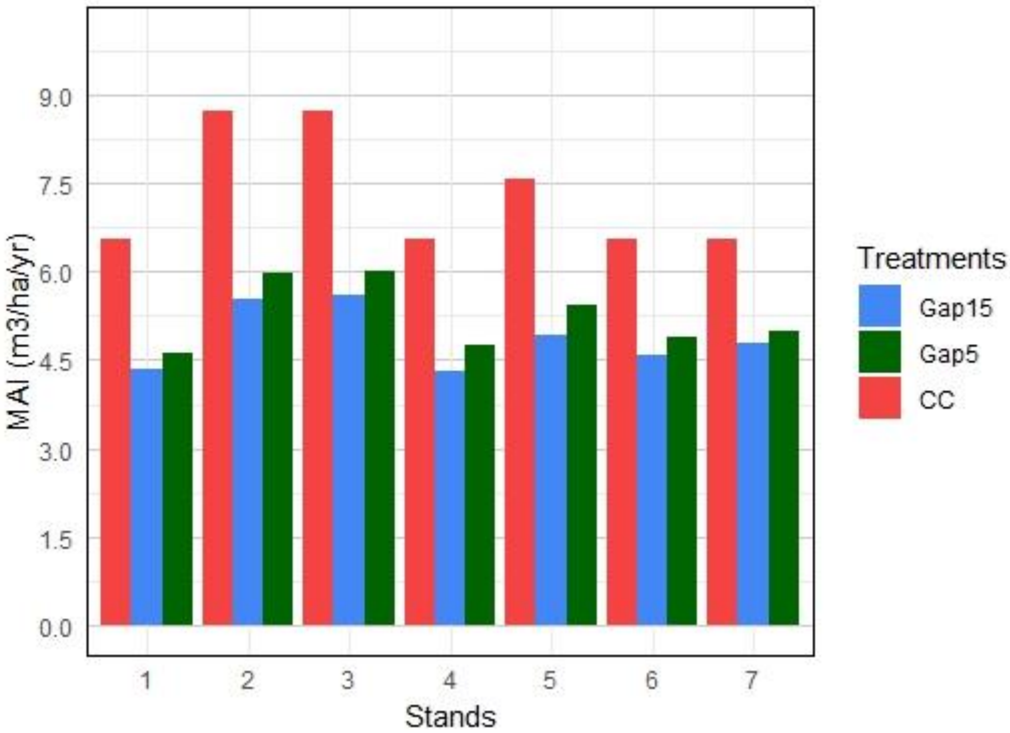

Figure 6. Mean Annual Increment ($m^3ha^{-1}yr^{-1}$) for Scot pine in Clear and Gap cut management.

3.3 Diameter Distribution

Statistically, the diameter class distribution in the three treatments differs significantly (p<0.0001; Table 7). There is a wider range of variation between clear-cut and gap-cut management. Gap15 has the highest variation with a mean value of 0.36 and clear-cut has the lowest diameter variation with a mean of 0.19 (Figure 7). Consequently, the proportion of diameter class to the biggest Scots pine sizes on all sites shows a very dense lower class (10% to 40%) in the Gap15. In contrast, Gap5 and Clear-cut have matching larger sizes of 80% to 100% across the sites, though in relatively low stem numbers (Figure 8).

Table 7. The coefficient of variance on diameter distribution in Gap-cut and clear-cut. The level of significance is $p < 0.05$

	Df	Sum Sq.	Mean Sq.	F value	Pr (>F)
Treatment	2	0.10486	0.05243	147.221	3.61e-09***
Stand	6	0.00052	0.00009	0.243	0.953
Residuals	12	0.00427	0.00036		

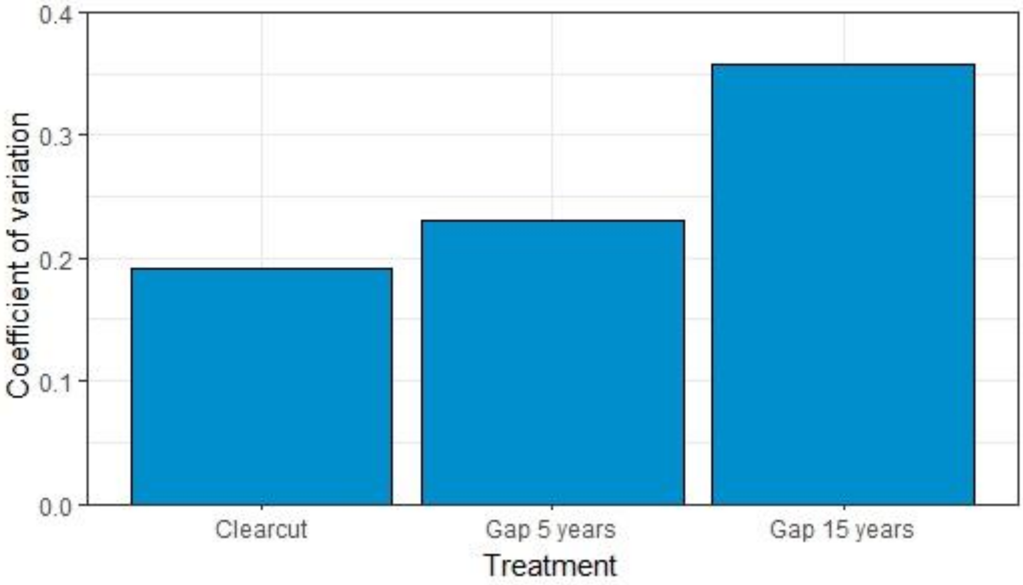

Figure 7. Diameter class distribution. This shows the level of variation in the diameter for each treatment.

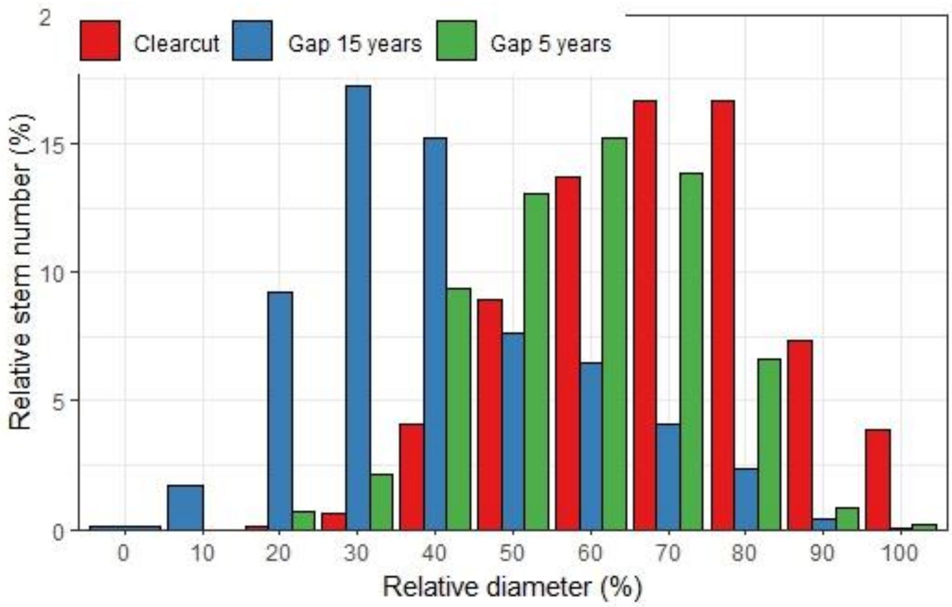

Figure 8. Relative diameter to the largest diameter on site. This shows the relative number of trees in 10% diameter classes in relation to the biggest tree on the site.

4. Discussion

4.1 Gap-cut management vs. clear-cut management

The results of this study indicated that clear-cut and Gap5 management do not differ significantly, while Gap5 and clear-cut differ significantly from Gap15. Therefore, the hypothesis that the financial value of clear-cut management differs significantly from gap-cut management is partially supported statistically (Table 4,5). Considering that a 3% interest rate was used for all the treatments, the explainable factors to the financial outcomes may include the length of time between harvesting in the gap (i.e. gap intervals), the site quality, and the percentage of timber harvested per cycle (Figure 3). Our analysis shows that stands on a higher site index yielded higher economic returns (Figure 3). However, these higher site indexes may also experience more competition from vegetation, which could be detrimental to the establishment of new stands through natural regeneration in the gap (Pasanen *et al.* 2016; Miina & Saksa, 2008). Nevertheless, our study could not test the assumption of vegetation competition and its effect on the LEV. Instead, the returns per site index (low, medium, and high fertility) were more economically profitable in gap-cut than in clear-cut (Figure 4). This economic margin gap could result from the kind of regenerating system and the cost of operating the management objectives. In the gap, the regeneration cost is 0 Sek/ha, which was not so in the clear-cut. The use of genetically improved seedlings and the cost of harvesting were accounted as a cash outflow, which must be subtracted from the incoming cash inflow in order to determine the efficiency of the management system. However, this study could have further proven the economic efficiency of gap-cut management if there were data to estimate the cost of harvesting in the gap with the percentage taken per harvest in southern Sweden. This could have highlighted the expenditure incurred and profits gained from the two management systems. A study by Knoke *et al.* (2023) found better economic returns in continuous cover forestry (partial gap harvest) than clear-cut, even though their economic model features planting of Norway spruce crop trees in clear-cut and in the gap, this factor in the establishment cost for the two-management system. Their results return an increase in land expectation value of gap management than clear-cut. From their approach, bias on improved seedlings was removed and this gave the two-management equal points to compete favourably. Likewise, Dash *et al.* (2019) reported that site quality impacted economic returns by 60% and only 7% of the planted improved seedlings impacted the financial returns in a *Pinus radiata* species while stem density significantly contributed to economic returns. These results consolidate and explain our result better that the site quality has more effect on the economic return as well as the improved seedlings but to a lesser extent and this explains why Gap5 could perform well as clear-cut statistically. Furthermore, Table 5 demonstrates that the length of time between harvest i.e. gap interval, impacts the financial value of gap-cut management. Notably, Gap5 outperforms Gap15 in terms of economic benefit, this valuable insight suggests that to optimize profits in gap-cut management, the interval should align with the period where the financial return is no more than 5 years. However, the cut frequency and the percentage of timber harvested in each stand in our study do not affect the stand's economic returns. Instead, the gap intervals do affect the returns (Table 5). Even though the gap-cut uses a step-wise harvest approach, the total area of the harvested site was equal to the total area in the clear-cut. This also suggests that the productivity of the Scots pine stands depends not only on how many times and proportion (Gap size) of timber is harvested but also on the site quality, gap intervals, and stem density. This consolidates Simonsen, (2013) and Hyytiäinen *et al.* 2006 findings. In addition, regeneration lag could not be attested in the gap-cut in comparison with the clear-cut. Nevertheless, some studies have shown that natural regeneration is more profitable than planting at a 3% interest rate (Simonsen, 2013; Hyytiäinen *et al.* 2006; Długosiewicz *et al.* 2019). However, other studies emphasized the success of regeneration through the reduction of edge competition, the density of seed trees per hectare, and ensuring a higher site index (Rautio *et al.* 2023; Długosiewicz *et al.* 2019; Valkonen *et al.* 2002). However, the profitability of forest management types may also be influenced by the market, climate, and government policies (Chudy *et al.* 2022; Dash *et al.* 2019).

Furthermore, our research reveals that clear-cut management is more advantageous for the growth performance of Scots pine in comparison to gap-cut management, and this supports our second hypothesis. Table 6 and Figure 5 depict that the estimated MAI of clear-cut management is higher than that of gap-cut management. This result is consistent with previous studies that have shown increased MAI via active regeneration methods such as planting and improved seedlings, rather than relying solely on natural regeneration (Jonsson et al. 2022; Lula et al. 2021). Figure 6 indicates that clear-cut management leads to higher yearly volume production due to genetically improved seedlings and site quality. Nevertheless, competing trees and browsing effects can negatively impact productivity in gap-cut management (Mercurio & Spinelli, 2012). Our study considered competition from neighbouring trees by reducing the site index for gap management. However, biotic stressors such as browsing and insect attacks can also affect overall volume production in gap-cut management, as noted by Nilsson *et al.* (2016) and Lula *et al.* (2021), which supports our findings.

Considering the risks of the two management systems as gap size influences the stand's structure is also essential. Studies have shown that a large gap size could expose the stands to wind damage (Panferov & Sogachev 2008). In this study, the canopy openings were done at a half-diameter length to the previous cut, which then aims to support the stand structure. Though the disturbances were not tested in this study, knowing the possible externalities is crucial. Also, consistent seed availability in the gaps is paramount for continuous timber production (Shepperd *et al.* 2006). The absence of natural regeneration of the desired seedlings in the gap could lead to the ingrowth of other species and could impact the management objectives (Hyytiäinen *et al.* 2006; Béland *et al.* 2000). However, this type of scenario is not common with clear-cut. In clear-cut, the stands are mostly artificially regenerated with genetically improved materials.

4.2 Possible ecosystem services with the stand structure

Stands managed with gap-cut show significantly higher structural variability than the clear-cut (Table 7, Figure 7). This implies that there is a wider variation in diameters between the two managements, hence, the third hypothesis was accepted. The stand structure and compositional variability are crucial to ecosystem functioning and service delivery (de Quesada & Kuuluvainen 2020). In this study, the diameter variation in gap-cut features a distribution of small to large tree sizes and is not negatively skewed like on the clear-cut (Figure 8). This structural distribution could facilitate the multi-functionality of the forest ecosystem, such as cultural and recreational services like hunting, berries picking, and regulatory services like carbon sequestration. The functionality of the forest ecosystem is often governed by the presence of old forest, deadwood, species composition, and intactness of forest structure (Başkent & Kašpar, 2023). In reference to this study, the stand structure of the treatments shown in Figure 8 is a testament to variation in the forest. More of the smallest diameters are seen in gaps, creating an extended period of rotation length where the presence of large trees can facilitate other ecosystem services, such as biodiversity, as time passes. Long rotation age leads to old forests, and the amount of harvested volume contributes to the intactness of forest structure. As such, the rotation age is longer in Gap5 and Gap15 than clear-cut, and the percentage of harvested volume per time in gap-cut also contributes to the intactness of the forest ecosystem structure compared to the clear-cut. In this study, the structural complexity is maintained through the percentage of harvested area per time, and this is an important factor that enhances the biodiversity of the Scots pine stands. However, maximizing the forest for timber means that the rotation age is shortened, and clear-cut management would be best for this type of choice. In general, structural variations lead to more ecosystem services and this study showed that Gap15 resulted in greater variation than the clear-cut system.

Bilberry's ingrowth is one of Sweden's recreational attractions (Felton *et al.* 2016). An abundance of Bilberries in stands is facilitated by low stem density, height, and diameter (Parlane *et al.* 2006). Bilberry requires sufficient light to germinate. Since there is a linear relationship between diameter and height (Fahlvik *et al.* 2018), the variability in diameter in the Gap15 may facilitate the development of Bilberry. Moreover, this is one of the ecosystem services collected wildly in Sweden for household consumption and large scale (Felton *et al.* 2016). In addition, prolonged rotation age in gap-cut results in the proliferation of Bilberries within the stands. However, clear-cut management has deleterious effects on Bilberry shoot proliferation and survival. This is due to little or no light radiation reaching the forest floor, bigger diameter intersecting incoming light, and short rotation age (Parlane *et al.* 2006).

Hunting is one of the cultural and recreational practices in southern Sweden. The importance of hunting is beneficial to both the forest owners and the hunters. This service provides food and recreational value where gross estimated annual values reported by Boman & Mattsson in 2012 was 3 billion SEK. Thus, it is an essential consideration in management goals. Considering that, the diameter structure in the gap-cut could enhance the breeding of large herbivores for hunting since small trees are present longer in gap-cutting. However, indulging large browsing animals in Scots pine stands could be detrimental to timber production and impede stand productivity. Hence, imbalances in managing browsers could lead to economic loss (Nilsson *et al.* 2016). In young stands with high numbers of naturally regenerated seedlings, pre-commercial thinning can be postponed to increase the chance of getting a sufficient number of undamaged seedlings (Fahlvik *et al.* 2018).
Furthermore, large Dbh has been posited to favour tree microhabitats (Martin *et al.* 2021; de Quesada & Kuuluvainen, 2020). Variations in diameter, height, and species composition create habitats for key micro and macro faunas, resulting in higher levels of biodiversity (de Quesada & Kuuluvainen 2020). In this study, having established the possibility of Bilberry in the gap-cut management, there are higher chances of species diversity in the gap-cut than in the clear-cut. This is supported by some findings, where under-story species composition in the gaps favours the development of pioneer species (Kern *et al.* 2013; Erefur, 2010; Burton *et al.* 2014), which could be attributed to the variation in the diameter and height of the species in the gap.

Lastly, some studies have posited the impact of large trees on carbon storage, an essential regulatory service to the environment (Fichtner *et al.* 2015). Carbon sequestered in these two management studies could be attributed to an increased growth rate (Figures 5 and 6). We could see that the amount of carbon accumulated per year in the clear-cut was higher than in the gap cut. However, tree growth is not the only metric to determine the capacity of the ecosystem to sequester carbon. The net primary productivity of the forest ecosystem is also a measure of the management system employed, i.e. how much carbon is stored through the regeneration rotation cycle and how much carbon is emitted through the harvesting method (Noormets & Nouvellon, 2015)—forest stores carbon in trees and soil pools. Management is crucial in keeping and maintaining the ecosystem as a carbon sink. Strukelj *et al.* (2015) reported that carbon pools in tree biomass result from tree growth and mortality, which are affected by harvesting intensity. The authors ' years of study in aspen-dominated stands in boreal forests found that clear-cut areas were a net carbon source while partially harvested areas were a net carbon sink. Also, Kishchuk *et al.* (2016) also reported differences in the total soil carbon between clearcut and partial harvest and forest cover types. Soil carbon pools in conifer forest cover decrease more with intensive harvesting than mixed or broadleave forest cover. And this could be worthy of noting when harvesting in conifer stands like Scots pine. However, their investigated conifer species were other kinds of Pinus. However, harvesting-induced soil carbon emission can be avoided or reduced to a minimal extent by harvesting during winter and extending the harvest rotation cycle (Mayer et al. 2020; Noormets & Nouvellon 2015). In addition, site productivity was another management implication highlighted by Kishchuk *et al.* (2016), as higher site quality influences the rate of stand recovery following intensive harvesting like clear-cut, which in turn impacts both the size of regeneration growth and recovery rate of the ecosystem soil carbon pools. Thus, in reference to our study, we could expect a higher emission of soil carbon following clearcut than a gap cut. Yoshida *et al.* (2017) opined that forest management did not reduce carbon accumulations in the ecosystem in their 30 years of carbon assessment in managed stands in relation to unmanaged stands. However, the possibility of extended rotation length and the proportion of timber harvested per gap and taking account of soil carbon pool goes in line with a study by Kishchuk *et al.* (2016), this suggests that there is a higher chance of gap management being a carbon sink per gap cycle than clear cut. Our study is limited to the available data for interpretation. However, this study indicates that there is a higher possibility of ecosystem services in gap-cut management compared to clear-cut management.

5. Conclusion

In conclusion, this study has shown the possibility of managing Scots pine with gap-cut and clear-cut at the stand level. Also, this study analyzed the stand productivity in growth and financial values of the two management types. As well as the ecosystem system services each management type can offer society other than timber in relation to diameter variation. Our simulation study has helped to predict the performance of a productive Scots pine forest, comparing gap-cut management with clear-cut management in southern Sweden. It is worth noting that diameter variation is not the only metric for assessing ecosystem services. However, its use is instrumental and could be used to assess sustainable forest management.

The gap-cut management design in our study tries to assess the arms of sustainable forest management which include social, economic and ecological factors. The economic demand is controlled by the amount of timber taken and the gap size. The demand for ecological stability is also governed by gap extensions and gap intervals. Having all in place, the gap-cut management was able to meet some regulatory services, provisioning services, supporting services, and cultural /recreational services. These are possible by the amount of timber taken per time, the gap size, and the rotation length. With all these measures, the economic returns in gap-cut of 5 years interval performs well as clear-cut management. It is important to note that economic returns from other ecosystem services from the gap cut are not included in the LEV. Other ecosystem services from the gap-cut management could be harnessed to strengthen the economic, ecological, and social values of forest management. However, as clear-cut management is geared towards economic gain, its ability to meet multifaceted services is challenged by the intensity of the operations. Thus, ensuring sustainable forest management through this gap-cut management design might be asymmetrical, as extent of the ecosystem services were not fully captured in our study.

The risks associated with the management types are also an essential consideration in this study. Extensive data are further needed to assess the structural stability of stands during natural disturbances when managed with a gap cut. Also, the timber quality of the regenerated trees and the operation cost of managing the stand with gap-cut are essential information needed before adopting this management system. Thus, this study will recommend research in that regard. This will help forest managers to do a cost and benefits analysis of the two management types before shifting entirely into practice.

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Popular science summary

Simulating the Right Path: Comparing Forest Management Practices for Maximizing Ecosystem Services

Forests are of such high worth that their value cannot be measured or quantified easily. They provide a wide range of ecosystem services essential for the well-being of humans and the environment. Some services are directly taken up by humans, which support day-to-day sustenance. On a larger scale, the forest provides raw materials that feed many global companies' production. Amidst these benefits, the forest also supports habitat preservation. The services the forest offers include but are not limited to timber provision for construction, furniture, and railway sleepers. Food provisions such as mushrooms and product provisions such as medicinal herbs. However, determining the most effective forest management practices for maximising these vital services is complex and multifaceted. With growing concerns about environmental sustainability in Swedish forestry, it is imperative to simulate and compare forest management practices in southern Sweden to identify the right path that optimises ecosystem services. By exploring clear-cut and gap-cut management approaches, we can make informed decisions that balance ecological conservation and human needs.

This study assessed two methods of managing forest ecosystems, clear-cutting and gap-cutting management. Clear-cutting forest management is a form of forest management practice that uniformly harvest all trees within a designated area simultaneously resulting in the removal of all trees in that designated area. In clear-cut management, planting seedlings in the harvested area is imperative to regenerate the forest immediately after harvest.

In contrast, gap-cutting management involves selectively removing specific groups or clusters of trees within a forest, creating openings known as gaps. In this system, gaps are regenerated naturally. This provides multiple benefits to the environment and the people.

However, most forest estates in Sweden are managed predominantly with clear-cutting management. The concern to this management has been the forest ecosystem's loss during harvesting. Hence, there is a need to create a forest management practice that promotes economic balance with social inclusion and ecological development. There is a saying that the fear of the unknown is an intense fear of an unfamiliar situation! This means that to shift from current forest management practice to a new one, ample knowledge of how it works, how to manage, what the benefits would be and the risks involved are needed. In practice, this isn't easy to achieve. But with a simulation tool like Heureka, there are no boundaries to the information we could get.

This study simulated three scenarios using the Heureka decision-supporting application tool. The aim was to find out the economic and growth performance of the trees if we managed the forest with gap-cutting with five or fifteen years intervals of harvesting in gaps. And what sort of ecosystem services we could get from such management. The results from gap-cutting were compared with clear-cut management. It is interesting to see that managing forest estates with a gap-cutting of five years harvesting intervals gave higher economic returns compared to the clear-cutting system. In addition, gap-cut supports ecosystem services, like berries picking and hunting services. Which is one of the cultural lifestyles in Sweden. However, managing the forest with fifteen years intervals, gap-cutting resulted in lower economic returns but not bad profits if I am to decide. But the beauty of this management strategy is that it provides a better harvesting rotation period which supports biodiversity. Hence, strengthening ecological and cultural preservation more than clear-cutting. The growth and development of the young trees in clear-cut were rapid, but young trees in gap-cuts are spontaneous. Quite intriguing to see!

The applicability of this study is limitless. The gap-cutting design could facilitate multiple ecosystem services that can provide local and international benefits, depending on the size of the forested area. Also, this is a good insight for forest managers. This study is a contribution to solving the fear of the unknown. With the knowledge of the economic performance and the growth of the trees, this study can help safeguard management strategy when shifting into gap-cutting management. And lastly, the information can help policymakers to adapt the obligations required of the forest owners to the growth performance and economic returns of gap-cutting management.

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Appendix 1

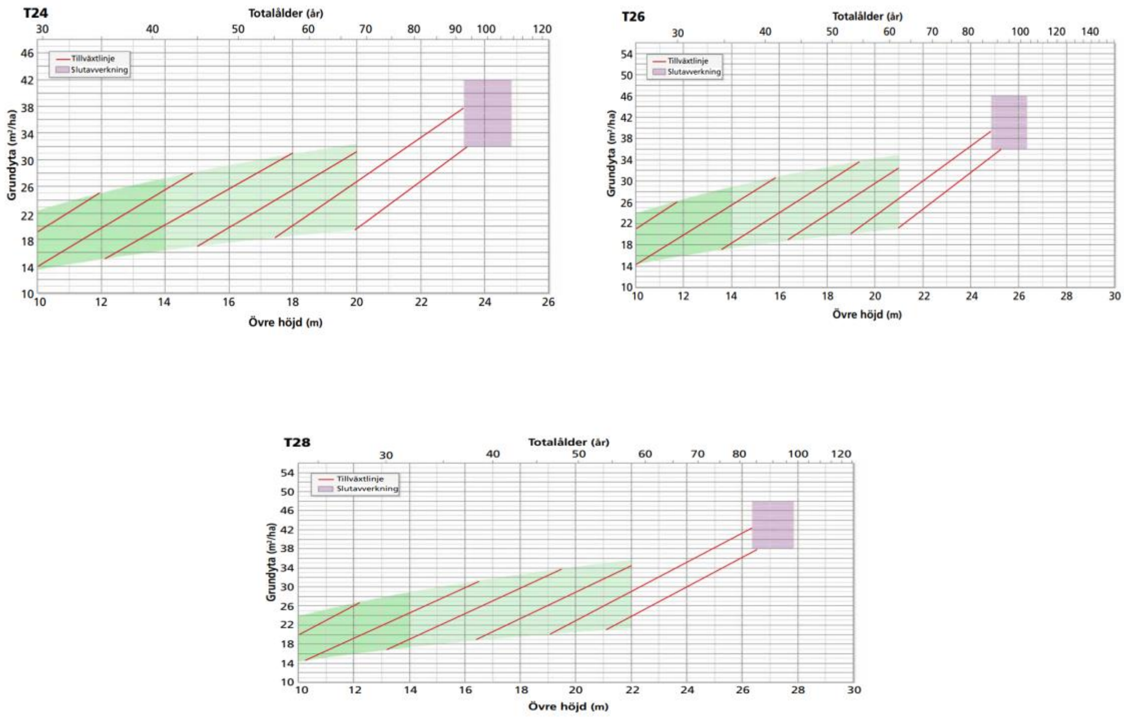

Figure 1. Thining grade

Treatments	stands	years	MAI	Treatment	stands	years	MAI	Treatments	stands	years	MAI	Treatments	stands	years	MAI
Gap15	1	15	3,024041	Gap15	3	15	4,309882	Gap15	5	15	3,613385	Gap15	7	15	4,792072
Gap15	1	30	2,946571	Gap15	3	30	3,939371	Gap15	5	30	3,44128	Gap15	7	30	4,34021
Gap15	1	45	3,141654	Gap15	3	45	4,02355	Gap15	5	45	3,633573	Gap15	7	45	4,222204
Gap15	1	78	3,942864	Gap15	3	71	5,126616	Gap15	5	69	4,492453	Gap15	7	78	4,563397
Gap15	1	93	4,199383	Gap15	3	86	5,413	Gap15	5	84	4,646903	Gap15	7	93	4,719829
Gap15	1	108	4,276754	Gap15	3	101	5,361893	Gap15	5	99	4,659521	Gap15	7	108	4,726734
Gap15	1	123	4,328248	Gap15	3	116	5,586383	Gap15	5	114	4,916761	Gap15	7	123	4,723571
Gap5	1	5	3,132412	Gap5	3	5	4,578982	Gap5	5	5	3,614602	Gap5	7	5	4,900443
Gap5	1	10	2,714602	Gap5	3	10	3,902268	Gap5	5	10	3,187887	Gap5	7	10	4,237141
Gap5	1	15	2,354517	Gap5	3	15	3,313035	Gap5	5	15	2,765321	Gap5	7	15	3,631564
Gap5	1	78	3,471072	Gap5	3	71	5,602109	Gap5	5	69	5,433941	Gap5	7	78	4,992778
Gap5	1	83	4,372314	Gap5	3	76	5,819668	Gap5	5	74	5,442538	Gap5	7	83	4,999057
Gap5	1	88	4,471503	Gap5	3	81	5,911948	Gap5	5	79	5,37005	Gap5	7	88	4,916555
Gap5	1	93	4,60326	Gap5	3	86	6,008087	Gap5	5	84	5,219998	Gap5	7	93	4,790037
CC	1	71	6,56	CC	3	55	8,73	CC	5	68	7,57	CC	7	71	6,56
Gap15	2	15	3,988422	Gap15	4	15	3,024041	Gap15	6	15	3,988422				
Gap15	2	30	3,720594	Gap15	4	30	2,888523	Gap15	6	30	3,744893				
Gap15	2	45	3,885638	Gap15	4	45	3,063256	Gap15	6	45	3,801506				
Gap15	2	71	5,039208	Gap15	4	78	3,897634	Gap15	6	78	4,320687				
Gap15	2	86	5,340837	Gap15	4	93	4,161448	Gap15	6	93	4,516266				
Gap15	2	101	5,300447	Gap15	4	108	4,244087	Gap15	6	108	4,551443				
Gap15	2	116	5,532883	Gap15	4	123	4,299565	Gap15	6	123	4,569657				
Gap5	2	5	4,096792	Gap5	4	5	2,971681	Gap5	6	5	3,936062				
Gap5	2	10	3,723617	Gap5	4	10	2,634237	Gap5	6	10	3,464712				
Gap5	2	15	3,170114	Gap5	4	15	2,32476	Gap5	6	15	3,021331				
Gap5	2	71	5,571914	Gap5	4	78	4,734028	Gap5	6	78	4,875425				
Gap5	2	76	5,79146	Gap5	4	83	4,758583	Gap5	6	83	4,888774				
Gap5	2	81	5,885482	Gap5	4	88	4,693804	Gap5	6	88	4,812538				
Gap5	2	86	5,983159	Gap5	4	93	4,579262	Gap5	6	93	4,691613				
CC	2	55	8,73	CC	4	71	6,56	CC	6	71	6,56				

Figure 2. Supplementary table showing the growth of the whole stands for a complete rotation circle of the new stands in clear-cut and gap-cut management.

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