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From clearcutting to continuous cover forestry: impacts on investment profitability, harvest, and carbon dynamics in Poland.

Rafal Chudy, [a,b*] Frederick Cubbage, [c] Kathleen McGinley, [d] Jacek Siry, [e] Karolina Chudy [b]

a: Norwegian Institute for Nature Research (NINA), Oslo, Norway.
b: Forest Business Analytics, Nowe Miasto nad Pilica, Poland.
c: North Carolina State University, Department of Forestry and Environmental Resources, Raleigh, NC, USA.
d: United States Department of Agriculture (USDA) Forest Service, International Institute of Tropical Forestry, San Juan, Puerto Rico.
e: University of Georgia, Warnell School of Forestry and Natural Resources, Athens, GA, USA
[*]Corresponding author: E-mail: rafal.chudy@nina.no

ABSTRACT

Improved forest management (IFM), particularly the transition of even-aged forests to continuous cover forestry (CCF), is gaining attention as a management approach that may contribute to climate change mitigation by enhancing forest carbon sequestration and maintaining soil carbon storage. CCF aims to maintain continuous tree cover over time by using selective harvesting and natural regeneration instead of clear-cutting (CC), and is promoted as a forest management method that enhances productivity, ecological, and social benefits. Using a Scots pine stand management in Poland, we evaluated the profitability, harvest rates, and carbon fluxes of CCF compared to traditional CC. We used discounted cash flow models to assess the potential benefits of transitioning even-aged Scots pine stands to a CCF regime. At the assumed 5% discount rate, CC management had higher Land Expectation Values (LEVs), while CCF had higher internal rates of return (IRR) for lower land acquisition prices of 8,000 EUR or less. For land prices ranging from 9,000 to 11,000 EUR, IRRs varied considerably depending on the age at which the stand was transitioned to CCF. Purchasing older forests, which then produced earlier harvest revenues, was more profitable. CC management consistently produced more wood per hectare than CCF, but since CCF had lower input costs, the costs per tonne of CO_{2e} were similar between the two management regimes, as were the wood production costs. Our findings highlight important trade-offs, suggesting that while CCF may not always maximize wood yields, it can offer competitive financial performance under favorable land prices while simultaneously supporting climate mitigation objectives.

Keywords

clearcut management, continuous cover forestry (CCF), discounted cash flow (DCF) analysis, improved forest management (IFM), Poland, Scots pine

Citation

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INTRODUCTION

Improved forest management (IFM) encompasses a range of silvicultural management actions that incorporate above- and below-ground biomass carbon (C) components, as well soil C stocks (Kaarakka et al. 2021) and is among the key methods that may contribute to climate change mitigation by increasing forest carbon sequestration rates and maintaining higher carbon storage in soils compared to clearcuts (Ameray et al. 2021; Haya et al. 2023). Among the many forms of IFM, continuous cover forestry (CCF) is again gaining special attention (Pommerening and Murphy 2004) as it promotes timber production through "selective cutting", maintaining forest cover (Trentanovi et al. 2023). CCF popularity has waxed and waned in successive cycles under many names, such as uneven-aged silviculture, selection systems, partial cutting, and retention cuts. Often, this method is discussed as an alternative to clearcutting (CC)[1], where the forest stand is harvested in a single entry or operation, leaving a treeless open area (Trentanovi et al. 2023). CC, in consequence, may result in negative outcomes, including biodiversity loss and other ecological impacts (Fedrowitz et al. 2014; Česonienė et al. 2019; Norkute et al. 2025), as well as decreases in aesthetic and recreational values for society (Koivula et al. 2020). From a profitability standpoint, CCF can yield similar or even superior outcomes compared to traditional CC (e.g., Kaimre, Kängsepp and Sirgmets 2024; Ahtikoski et al., 2025).

Tahvonen (2009) demonstrated that both CC and CCF systems could represent locally optimal solutions, offering similar economic returns. The study further indicated that changes in factors such as discount rates, wood prices, or planting costs could lead to a shift in the optimal management strategy from even-aged to uneven-aged approaches. Additionally, Peura et al. (2018) found that CCF outperformed CC in several aspects, including timber net present value, carbon sequestration, bilberry production, scenic beauty, and the number of large trees. They concluded that CCF can be an essential part of the solution towards more sustainable forestry.

Uneven-aged management through CCF has been demonstrated to match or even slightly surpass the wood flow from even-aged CC forest management approaches (e.g., Stål et al. 2024), while also providing higher ecological benefits, such as continuity of habitats, ecosystem services, and

[1] For example, in Polish forestry practices, clearcutting is limited to areas no larger than 6 hectares. This approach contrasts with gap management, which involves creating single or multi-stage openings smaller than 0.5 hectares (50 ares) (State Forests 2023).

biodiversity (e.g., Peura et al. 2018; Skogsstyrelsen 2025). However, economic assessments of CCF's performance are mixed and depend on various factors. Substantial research has been conducted on silviculture and management of uneven-aged Scots pine (*Pinus sylvestris L.*) stands in Europe. For instance, Gallo et al. (2020) compared the structure and production of Scots pine stands managed under different silvicultural systems in Czechia and Spain. They found that transitioning from even-aged to uneven-aged forest does not negatively influence stocking and wood production and provides higher diversity and structural complexity benefits than regular stands.

On the other hand, some case studies have shown that uneven-aged management may be competitive with existing even-aged management (e.g., Pukkala et al. 2010). Nevertheless, according to (Kuuluvainen et al. 2012), out of 14 reviewed studies, seven analyzed economic performance, and among them, two demonstrated the superiority of even-aged management over uneven-aged management; two demonstrated opposite results; and the remaining three depended on climatic zone and other variables such as the interest rate and the initial stocking of the stand. The authors noted that different economic contexts and growth models may explain discrepancies between studies' results.

Dynamic vegetation models that estimate forest carbon sink potential typically exclude economic variables such as management costs and timber/wood prices. As a result, the forest management strategies incorporated into these models are externally defined/exogenous and do not respond to economic feedbacks (e.g., Lindeskog et al. 2021). Although these models can answer the questions related to changes in environmental drivers induced by changes in forest management regimes (Oberpriller et al. 2022), they omit the socio-economic drivers and their impact on forest management practices. Consequently, the scenarios analyzed may neglect impacts on forest carbon and harvest levels induced by owners' management choices linked to financial and economic criteria.

With approximately 60% of its forests dominated by Scots pine (*Pinus sylvestris L.*) (State Forests 2024), Poland offers a robust and representative European case study for examining the effects of uneven-aged management through the CCF method on investment profitability, harvest rates, and carbon fluxes compared to traditional clearcutting regimes. The research methods and findings presented in this study offer a framework that may be applicable to other species and transferable to different national contexts.

Several studies have been conducted in Poland regarding uneven-aged pine management. For example, Andrzejczyk (2003) discussed the origin, structure, and silviculture behind uneven-aged Scots pine stands. Czacharowski and Drozdowski (2021) reviewed various methods of managing Scots pine stands across Europe and concluded that, in the context of both climate and social change, there is a need to explore alternative management approaches that fully utilize natural regeneration while limiting the negative effects of clearcutting on the forest landscape, for example, by retaining seed or residual trees and patches of old-growth. Despite a growing body of research on CCF, the economic viability of management alternatives to clearcutting remains understudied for Scots pine in the context of Poland. Exceptions include a study by (Chudy et al. 2022), who used a discounted cash flow models to evaluate the profitability of artificial and natural regeneration in Scots pine stands in Poland.

OBJECTIVE

Building from previous studies of forest management in Europe and the growing interest in improved forest management approaches such as CCF, this research investigates the comparative outcomes of timber yield and forest carbon dynamics under two management regimes: traditional even-aged Scots pine stands continued to be managed under CC, and an alternative transition of the same stand to CCF. We estimated financial returns and costs for a variety of timber production rates and costs associated with land acquisition and transition from even-aged/CC to uneven-aged/CCF Scots pine management. We compared these different scenarios to determine which system and rotation strategies yielded higher wood volumes or greater carbon storage. The results of these analyses offer insights into the relative advantages and disadvantages of CCF compared to CC, in terms of potential returns for forest investors and contributions to forest carbon sequestration as a climate change mitigation strategy.

MATERIAL AND METHODS

Performing an analysis of CCF and CC forest management methods first required building representative forest stand models and management scenarios for each system. Then, a transition from the typical CC forest stand common in Poland to the CCF method was modeled. Next, growth and yield were estimated, along with management costs and stand returns for the two management approaches. Finally, the results were compared to evaluate differences between the systems.

Hypothetical forest and growth and yield assumptions

For this analysis, we developed a general model for a hypothetical 1-hectare, single-species Scots pine forest in Central Poland. The model was based on an existing pine stand that was 38 years old at the time of inventory, established on a site classified as productivity class III according to the site productivity index[2], with a stocking rate[3] of 0.9, and a total yield of 160 m^3/ha. This forest represents a typical planted pine stand in Central Poland and was considered as well-suited for applying CCF and CC regimes. Since our analysis started with a forest stand at the age of 50, we needed to update the initial stand information with available growth and yield information. For this purpose, we used the Szymkiewicz growth and yield table for even-aged Scots pine stands growing on the III productivity site index as well (Szymkiewicz 2001).

To our knowledge, growth and yield models for continuous cover forestry have not yet been developed in Poland. Some studies reported that individual tree growth is lower in continuous cover forestry compared to rotation forestry (clearcutting). For instance, Bianchi et al. (2020) analyzed the growth difference between CCF and clearcuting regimes for Norway spruce; they suggested the lower growth at the stand level observed in continuous cover forestry after selection cuttings was mainly due to the greater removal of big and dominant trees.

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[2] Productivity classes (bonitet classes) in Polish forestry define the potential productive capacity of a forest site for a given species. The bonitet class is determined separately for primary forest-forming species based on the age and height of the stand. They range from Class Ia (highest productivity, optimal conditions for rapid growth) to Class V (very low productivity, challenging conditions with slow growth), guiding the selection of silvicultural practices suitable for each site. The third bonitet represents moderate productivity. These sites have average soil quality and climate, and trees grow at a moderate rate. Forest management is aimed at maintaining stability and optimizing growth despite the less-than-ideal conditions. (refer to e.g., (Jaworski, 2011).

[3] Tree cover rate of a single-species and single-age stand with a volume of large timber is determined from the ratio of the estimated volume per 1 ha (yield) to the volume of timber in the table - for the same tree species, with the same site index and the same age - included in the tables as a total volume of large timber in the main and secondary stands.

For our hypothetical Scots pine stand, we assumed the same growth rates for the CCF and the clearcutting regime. The reason is that the cuts of CCF in single-species stand can vary from single-big tree removals up to larger areas (gaps) removals to convert such stands to multi-age species stands, and therefore, the effect of adjacent trees competing for resources with new seedlings is not well known. Also, we wanted to keep the growth rates at the same level, focusing in our modelling exercises on volumes removed and economic parameters such as acquisition and management costs.

While the harvest thinnings were not so far apart, the harvest methods were different. Thinning under a clearcutting regime focuses on maximizing timber production and enhancing the growth of the remaining trees to maximize yields for the final harvest. In contrast, thinning in CCF emphasizes the selective harvesting of trees as they reach their target diameters, aiming to harvest trees at their economic optimum. This approach prioritizes the removal of lower-quality stems in earlier thinnings, thereby improving the overall quality, value, and growth of the remaining stand. However, our model was unable to differentiate these thinning approaches, as it relied on the percentage of total volume harvested within the stand rather than implementing stem-by-stem management or retaining specific groups of trees within the stand.

Silvicultural management costs and wood prices

Table 1 presents the costs of site preparation and planting (only applicable to the clearcutting regime), periodic stand treatments, harvest, and management costs (both regimes). The costs are expressed per hectare or cubic meter (m^3). The costs presented in Table 1 were updated to represent average market values between 2022 and 2023, and the data were obtained through a literature review and expert consultation with the local forest manager.

Table 1. Costs of site preparation and planting (only clearcutting regime), periodic stand treatments, harvest and management costs (both regimes).

Unit Prices per Activity		
Site Preparation (total):	**183 EUR**	**/ha**
a) Plough/Shear	183 EUR	/ha
Planting (total):	**819 EUR**	**/ha**
a) Seedlings	345 EUR	/ha
b) Plant distribution (transport)	323 EUR	/ha
c) Natural regeneration costs	0 EUR	/ha
d) Replant	151 EUR	/ha
Periodic Stand Treatments (as applicable)	**890 EUR**	**/ha**
a) Protection from deer-browsing	560 EUR	/ha
b) Early cleaning (CW, soil treatment)	330 EUR	/ha
Management costs (total)	**40 EUR**	**/ha**
Disease Control & Prevention	3 EUR	/ha
Roads	2 EUR	/ha
Fire Control	1 EUR	/ha
Administration	25 EUR	/ha
Property Tax	9 EUR	/ha

Roundwood nominal prices were obtained from the Forest and Wood Portal (State Forests 2023), representing the average wood prices at the roadside in Poland sold by State Forests to retail and corporate buyers under limited and unlimited auctions. We calculated the average wood prices between 1Q 2022 and 2Q 2023 in Polish zloty (PLN) per m^3 (PLN/m^3), which were later converted to euros (EUR) per m^3 (EUR/m^3) using the EUR/PLN conversion rate of 4.64 from Yahoo Finance. The prices for the following wood assortments were included in the model: pulpwood, sawlogs, and fuelwood, with values of 62, 89, and 20 EUR/m^3, respectively. We assumed the same wood prices at the roadside for both management regimes.

Forestland acquisition price

To develop a CCF forest management stand, we assumed the acquisition of an existing even-aged forest that would be transitioned to CCF. This was also compared with the continuation of the same forest stand under the CC forest management regime. Forest acquisition prices in central Poland (lodzkie voivodship) in 2022 were between 2,400 EUR/ha and 13,500 EUR/ha, with an average of 7,500 EUR/ha (Chudy 2023).

In the case of our defined middle-aged Scots pine stand in Poland, we assumed acquisition prices were above the average values, and we modelled scenarios with acquisition prices ranging from 7,000 to 11,000 EUR/ha (with 1,000 EUR/ha increments). We also assumed that the owner acquired the forestland and kept it without selling it at the typical 110-year rotation age (no disposition). This assumption follows economic reasoning that discounting disposition revenue after 100 years does not affect the capital budgeting indicators reported in the paper.

Silvicultural management regimes

The silvicultural management regime for CCF is presented in Table 2 and also illustrated in Appendix B.

Table 2. The CCF silvicultural regime.

Activity	Age	Volume reduction (%)	Sawlogs (%)	Pulpwood (%)	Firewood (%)
Early cleaning	10	-	-	-	-
Late cleaning	20	-	-	-	-
CCF I	50	33	0	80	20
Thinning I	60	20	0	80	20
Thinning II	70	20	0	80	20
CCF II	80	33	10	80	10
Thinning III	95	20	10	80	10
CCF III	110	100	50	30	20

Source: Based on personal communication with Andrzejczyk (2022).

In the CCF regime, three regeneration cuts were applied at ages 50 and 80, and the final cut was at age 110. Each cut resulted in a 33% volume reduction. In addition, three thinnings were introduced between these periods at 60, 70, and 95, each with 20% volume reduction intensity. We assumed that the owner wanted to avoid the depreciation of the wood quality after age 110.

Therefore, under the CCF regime at age 110, everything is removed from what was left in the final cohort after two regeneration cuts, allowing a smooth transition from one system to another without penalizing the owner by leaving mature and marketable wood standing. Table 2 also shows the volume proportion of wood assortments produced under each cut. These proportions were based on the study of Mandziuk and Parzych (2019), adjusted with the expertise of a local forester concerning the proportion of fuelwood.

Regarding the CC model, we assumed it will follow standard practice in Poland, which includes four periodic thinnings every 10 years between the ages of 50 and 80, and one additional thinning between the ages of 80 and the final clearcut in year 110. The difference between the two regimes in the timing of harvests was modest but led the CCF model to better conform to the improved forest management paradigm (both CC and CCF models are presented in Appendix B).

We assumed that revenues from small-diameter wood sales cover operation costs for early and late cleanings. Finally, the regeneration costs (site preparation and planting) were only applied to the CC regime, while we assumed natural regeneration for the CCF model.

Discounted Cash Flow (DCF) model

To evaluate forest investment opportunities under two different forest management regimes (CCF vs. CC), the DCF model has been used to calculate the internal rate of return (IRR), net present value (NPV), and Land Expectation Value (LEV). This framework has been applied in previous studies investigating plantation forestry investments worldwide (Cubbage et al. 2007; Cubbage et al. 2010; Cubbage et al. 2014; Zhang et al. 2019; Kanieski da Silva et al. 2020; Cubbage et al. 2022), different regeneration methods or variations of input costs and timber prices, and their impacts on investment profitability (Chudy et al. 2020; Chudy et al. 2022), or the performance of private equity timberland funds (Chudy et al. 2021).

The NPV was calculated by using the following formula:

$$NPV = \sum_{n=0}^{N} \frac{CF_n}{(1+IRR)^n}$$

where: CF_0 – initial investment, CF_1, CF_2…CF_N – net cash flows, NPV – net present value of the discounted costs and discounted benefits, IRR – internal rate of return, index n = 1, 2, 3, …N.

The IRR was computed by setting the net present value of all cash flows in each forest investment scenario to zero. We used the Excel IRR function to calculate the IRR. Due to multiple roots that may arise if net cash flows change in sign, the IRR function may not be solved, even if the initial values in the net cash flows are positive. This would be an issue in our research as regeneration cuts applied at the age of 50 or 80 make the first net cash flows positive. In such cases, even the iteratively calculated IRR, which involves comparing discounted costs and discounted revenues with different discount rates until they are equal, and thus NPV = 0, would be problematic and likely unsolvable. We overcame this issue by introducing the acquisition cost at the beginning of each cash flow stream, making the IRR function solvable in all scenarios.

Although we can compare the NPV of different management forestry regimes unless they are equal in their rotation ages, we also calculated and reported LEV, assuming these regimes are repeated in perpetuity.[4] This used the following formula:

$$LEV = NPV + \frac{NPV}{(1+r)^d - 1}$$

where,
r - discount rate (5%), and
d – rotation age (i.e., 110 years).

Tonnes "Merchantable" CO_{2e} per ha

In our calculations for Scots pine, we used a basic wood density[5] of 450 kg/m³, defined as the ratio of the dry weight of wood to the volume of green wood (Jelonek et al. 2010 Table 2). Although we acknowledge the ongoing debate regarding variations in carbon content across wood species (Lamlom and Savidge 2003; Martin et al. 2018), we adopted the commonly used estimate that carbon constitutes approximately 50% of the dry biomass, which we considered sufficient for carbon accounting purposes (Matthews 1993) in our hypothetical exercise. Thus, we calculated

[4] LEV does require an identical set of cash flows repeated in perpetuity to be valid. This then indicates that we assume that we were reproducing the set of activities from age 38 to 110 every time, which would imply on a new or adjacent stand. This was a strong assumption just for mathematical calculation of the LEV under this novel form of management and models. In practice, one should start a whole new stand, and then calculate the NPV of that new stand from 0 to 110, and then calculate that LEV and add to the first NPV. This was too cumbersome, and the use LEV calculation for identical rotations of greater than 100 years old would make a minute addition to the total stand value.
[5] Wood density is measured as basic density (oven-dry weight per cubic meter) or specific gravity (ratio of oven-dry weight to the weight of the same volume of water, which is 1,000 kg/m³). For example, if 1 m³ of green wood weighs 400 kg when oven-dry, it has a basic density of 400 kg/m³ and a specific gravity of 0.40.

the carbon content of Scots pine as 225 kg/m³ by multiplying the wood density (450 kg/m³) by 0.5. Next, we calculated the weight of carbon dioxide (CO2) content of wood per every kilogram of carbon, which is not the same. The ratio of CO_2 to carbon weight is 3.67; thus, 1 tonne of dry wood sequesters about 0.5 tonnes of carbon and 1.83 tonnes of CO_2. In our calculations, we multiplied 225 kilograms of carbon per cubic meter (kg/m³) by 3.67 and obtained the value of 825.75 CO_2/m³. Furthermore, we calculated metric tonnes of CO_2 per cubic meter by dividing 825.75 by 1,000. This allowed us to calculate the amount of tonnes of "Merchantable" CO_2 equivalent (CO_2e) per hectare of forest – that was a result of the multiplication of total wood produced per hectare and metric tonnes of CO_2 per m³. Our calculations did not account for soil carbon. For instance, a study by Roth et al. (2026) found that CCF and CC forestry had no different effect on total soil C stocks.

*Tonnes "Merchantable" CO_2e/ha = TWP * Metric tonnes CO_2/m³*

where,

TWP – total wood produced in the 100-year rotation (m³)

Metric tonnes CO_2 per m³ = Dry Weight per m³ (450 kg for Scots pine) * proportion of carbon in dry weight (0.5) = carbon weight per kg (225 kg) * kg CO_2 per kg carbon (3.67) = 825.75 kg / 1,000 = 0.83

Cost of tonne of CO_{2e} (EUR/tonne)

$$Cost\ of\ Tonne\ of\ CO2e\ (EUR/tonne)\ =\ \frac{TDC}{Tonnes\ "Merchantable"\ CO2e\ per\ ha}$$

, where

TDC – total discounted cost

Cost of Wood at 5% Discount Rate (EUR/m³)

$$CW = \frac{TDC}{TWP}$$

where,
CW – cost of wood at 5% discount rate (EUR/m³),
TWP – total wood produced in the 100-year rotation (m³)

RESULTS

The results of the analyses include information on the two forest management regimes of even-aged CC forestry and transition to CCF uneven-aged stand. Table 3 presents only the differences between clearcutting and CCF regimes for the capital budgeting criteria (NPV, LEV, and IRR) at a 5% discount rate, considering variations in initial forest stand age and acquisition prices. This allows a focused discussion of the main results of our study. For reference, Table 1 in Appendix A provides all the values of NPV, LEV, and IRR for both management regimes at the 5% discount rate, changing initial forest stand age, and different acquisition prices.

Table 3. The difference in capital budgeting criteria (NPV, LEV and IRR) between and clearcutting (CC) and continuous cover forestry (CCF) regimes for forest stands having different initial age at the beginning of the modelling exercise and for different acquisition prices, at a 5% discount rate.

Initial stand age	NPV	LEV	IRR
	Acquisition price 7,000 EUR		
50	**- 537**	**- 542**	**-0.6%**
55	**774**	**780**	**0.6%**
60	**652**	**657**	**0.5%**
65	**494**	**498**	**0.3%**
70	**354**	**356**	**-0.2%**
75	0	0	**-0.5%**
80	**- 307**	**- 309**	**-7.4%**
AVERAGE	**204**	**206**	**-1.1%**
	Acquisition price 8,000 EUR		
50	**- 537**	**- 542**	**-0.3%**
55	**774**	**780**	**0.6%**
60	**652**	**657**	**0.5%**
65	**494**	**498**	**0.4%**
70	**354**	**356**	**0.1%**
75	0	0	**-0.2%**
80	**- 307**	**- 309**	**-2.7%**
AVERAGE	**204**	**206**	**-0.2%**
	Acquisition price 9,000 EUR		
50	**- 537**	**- 542**	**-0.1%**
55	**774**	**780**	**0.6%**
60	**652**	**657**	**0.6%**
65	**494**	**498**	**0.4%**
70	**354**	**356**	**0.2%**
75	0	0	0.0%
80	**- 307**	**- 309**	**-1.3%**
AVERAGE	**204**	**206**	**0.1%**

Note: Green values indicate cases where the CC regime yields higher NPV and LEV, while blue values indicate cases where the CCF method results in higher values.

First, the differences in NPV and IRR between the two methods are the same regardless of the land acquisition values. A closer look at full values (refer to Table 1 in Appendix A) shows that all values for the selected budgeting criteria decrease with increasing forestland acquisition prices. For instance, for acquisition prices within the range of 7,000 and 11,000 EUR/hectare, the average NPV/ha values are between 1,109 and -2,700 for CCF and 1,314 and -2,496 EUR for CC management regime. For LEV/ha calculated as NPV repeated infinitely, the ranges are 1,118 and -2,721 and 1,324 and -2,515, respectively. Based on these two criteria, CC regime brings higher profitability measured by NPV and LEV values.

For the IRR criterion, the situation looks very similar, with a tendency to favour a continuous cover forestry management regime. If we look at the full values (refer to Table 1 in Appendix A) for CCF, the values with increasing acquisition price are within the range of 7.1 and 3.4%, and for clearcutting, 6.1 and 0.3%.

A closer examination of initial age variation reveals that, in general, a higher initial stand age results in higher NPV, LEV, and IRR values. However, this trend is influenced by the application of various cuttings over time, which adds complexity to the overall picture. We can see that regeneration cuttings in the CCF system at the ages of 50 and 80, which reduce the stand volume by 33% each, produce higher NPV, LEV, and IRR values than under a clearcutting regime (Table 3 and Table 1 in Appendix A). This also applies to the ages of 70 and 75 (five and ten years before regeneration cut, respectively), which in most cases result in higher values than the CC regime. Therefore, regeneration cuts under CCF produce higher positive cash flows upfront and reduce the effect of negative cash flows (most notably acquisition and fixed management costs) and lead to better financial results.

Table 4 shows the differences between CCF and CC regimes for carbon and wood production and their cost. Regarding total wood produced, we can see that the CC regime produced more cubic meters of wood over the 100-year rotation. Depending on the initial stand age at which both regimes were applied, the difference ranged from 28 to 233 m^3 in favor of CC management. Consequently, the same is observed for the tonnes of "merchantable" CO_2 equivalent per hectare, as the relation between carbon is proportional to the amount of wood produced in each regime.

However, when the total discounted costs of each management system are considered, the results for costs of CO_2e and wood are higher at the age of 50, 75 and 80 years for CC system than CCF.

At age 50, the total wood produced under both systems is marginal (28 m3 difference), and the higher discounted regeneration cost for CC makes this regime more expensive. For the initial years of 75 and 80, in addition to the difference in the amount of wood produced under both systems, there is an additional reason related to the closer date of clearcutting (110 years) and consequently higher discounted costs of artificial regeneration that occur 35 and 30 years from the introduction of this regime.

In other initial years, i.e., 55, 60, 65, and 70, the CCF system produces higher costs of tonne of CO_2e and wood. Therefore, it may be concluded that CCF has the potential to deliver wood and improved forest management carbon credits if the tradeoffs of the amount of wood produced under both systems and the upcoming regeneration costs in the CC regimes are taken into account.

Table 4 shows wood and carbon production costs without forestland acquisition. If the forestland acquisition is considered, the cost per tonne of CO_{2e} will increase by 7-10 EUR/tonne and 11-14 EUR/tonne for acquisition prices of 7,000 EUR and 11,000 EUR, respectively. For wood, this will be 6-8 EUR/m^3 and 9-12 EUR/m^3. These production costs for wood and carbon may seem low compared to existing prices on the wood and carbon markets. While the production costs of wood and carbon may appear low in comparison to current market prices, it is imperative to bear in mind that forestry is a venture characterized by long-term investment. The seemingly advantageous cost structure should not overshadow the fact that cultivating and harvesting trees entail extended periods before realizing substantial returns.

Table 4. Wood and the merchantable CO_{2e} per ha amount produced for CC and CCF management regimes, together with their costs.

	Total Wood Produced (m^3)			Tonnes "Merchantable" CO_{2e} per ha			Cost of Tonne of CO_{2e} (EUR/tonne)			Cost of Wood at 5% Discount Rate (EUR/m^3)		
Initial stand age	CC	CCF	Diff	CC	CCF	Diff	CC	CCF	Diff	CC	CCF	Diff
50	1,273	1,245	(28)	1,051	1,028	(23)	0.80	0.77	(0.03)	0.66	0.63	(0.026)
55	1,230	996	(233)	1,016	823	(193)	0.84	0.96	0.12	0.69	0.79	0.097
60	1,283	1,103	(180)	1,060	911	(149)	0.82	0.87	0.04	0.68	0.71	0.036
65	1,236	1,075	(161)	1,021	888	(133)	0.88	0.89	0.01	0.72	0.73	0.010
70	1,264	1,058	(207)	1,044	873	(171)	0.89	0.90	0.02	0.73	0.75	0.015
75	1,212	1,039	(174)	1,001	858	(143)	0.96	0.92	(0.04)	0.79	0.76	(0.034)
80	1,213	1,012	(202)	1,002	835	(167)	1.01	0.94	(0.06)	0.83	0.78	(0.052)

DISCUSSION AND CONCLUSIONS

Clearcutting remains the predominant logging method in many regions of the world, particularly in North America and Europe, primarily due to economic advantages such as lower costs, higher timber yield, and easier regeneration with economically suitable tree species (Keenan and Kimmins 2011; Rosenvald and Lõhmus 2008). There is growing interest among researchers, forest managers, and policymakers in identifying forest management alternatives that contribute to climate change mitigation and biodiversity conservation (e.g., European Commission 2021).

IFM is one of the three principal methods promoted for enhanced carbon sequestration and storage in native and non-native forests worldwide, along with afforestation and forest retention. IFM can be designed to increase carbon storage in trees and wood products while delivering additional ecological, economic, and social co-benefits. The approach aims to enhance the management of natural stands to produce and store at least as much—or preferably more—forest carbon than would be achieved under conventional CC management practices. The baseline it is compared with is usually some level of natural forest growth rates. CCF is one form of IFM and has been highlighted by numerous studies for its substantial forest carbon and biodiversity benefits (Tahvonen and Rämö 2016; Peura et al. 2018; Pukkala 2018; Parkatti et al. 2019; Ersson 2020; Fagerberg 2022; Granhus et al. 2024). Although many of these studies were conducted across different countries, climate conditions, and species, making direct comparisons challenging, their general findings align with ours, suggesting that CCF is a viable alternative to even-aged CC management that forest managers should consider alongside rotation forestry, provided certain conditions are met, and assumptions hold true.

CCF can provide timber production rates, present values, forest carbon, and wood costs that are similar to those of even-aged management, depending on growth, yield, costs, and returns for individual forest sites and selected management regimes. There is no consistent advantage of either CCF or CC management across all cases; therefore, individual analyses of forest stands are necessary to determine the optimal management approach. However, the discounted forest carbon production costs are consistently quite similar for CCF versus CC regimes for all stand regimes we analyzed, indicating that forest management regime selection could be based on maximizing LEV or, indeed, on anticipated IFM wildlife, biodiversity, or social benefits.

Caveats

Acknowledging our models' limitations, multiple assumptions were required to analyze CCF with our representative Scots pine system in Poland. We assumed that one would acquire an existing planted stand at age 38 for both CCF and CC regimes, but manage it differently under each regime, with the CCF system conducting partial harvests every 30 years in addition to regular thinnings in between, and the CC stand being regularly thinned with the same intensity. Their yields, management costs, and timber product mixes differed during their rotation periods. We used a 5% discount rate, which is quite typical in forestry analyses. Different rates may favor one regime more or less (refer, e.g., to Tahvonen and Rämö 2016; Kaimre et al. 2024).

Our models reflect current input costs, timber prices, and yields, incorporating reasonable assumptions. Chudy et al. (2020) used a Monte Carlo simulation framework to test various ranges of input parameters in single-hectare financial models, identifying key factors influencing IRRs across several global timber plantation investment opportunities. Their findings showed that, for pine stands in Poland, IRRs were most affected by growth rates, management costs, and log prices—specifically pine pulpwood prices. The influence of these factors underscores the importance of accurate growth and yield models, not only in traditional CC forestry but also in alternative management regimes such as CCF.

Assumptions about growth and yield models play a crucial role in CCF findings and can significantly influence the results. For instance, Parkatti et al. (2019) noted that the characteristics of the optimal solutions for continuous cover forestry strongly depend on the ecological model used. We found similar caveats for our economic models for CCF, which was affected by the limited availability of growth and yield models suitable for uneven-aged management, which was also pointed out in the study of Kuuluvainen et al. (2012). Since Kuuluvainen's study was published over a decade ago, the situation appears to have changed little, and accurate growth and yield models for selective cutting remain scarce and in high demand.

The ingrowth issue has been considered the most challenging component of uneven-aged forest management (Kuuluvainen et al. 2012), and it is also central in retaining structural diversity. In Poland's case, there appears to be no single growth-and-yield model for a selective cutting regime. Future research should evaluate the applicability of identical growth and yield models to both CCF and CC regimes. Models that accurately simulate growth and yield under uneven-aged management for Scots pine and other important timber species will support informed decision-making. Nevertheless, given the relatively small differences between these two management systems observed in our case study (see Table 3), the lower growth rates typically associated with CCF systems are likely to reduce the profitability of such stand development compared to CC. This effect is further amplified if the forest owner chooses a more marked transition to a CCF regime and decides not to remove the final standing cohort, thereby foregoing revenues from mature, high-quality timber.

Additionally, beyond financial returns, CCF can provide increased social-ecological co-benefits such as enhanced habitat conservation or biodiversity protection that may be taken into consideration in management decisions (Larsen et al. 2022; Skogsstyrelsen 2025). The desire to industrialize production forestry through the establishment of single-species plantations has often overlooked variations in soil types. In contrast, individual tree or stem-by-stem management considers site-specific and habitat variations within sub-compartments, offering a more tailored approach (Susse et al. 2011). Our model was unable to differentiate between these thinning approaches because it relied solely on the percentage of total stand volume harvested, without incorporating stem-by-stem management or retention of specific tree groups.

We assumed identical nominal roadside wood prices for both management regimes, which also implies equal harvesting and logging costs across methods. However, one of the main concerns when shifting from CC to CCF is the potentially higher harvesting costs (see e.g., to Tahvonen and Rämö, 2016; Eyvindson et al., 2021). These arise from restrictions on equipment use, the need to move machinery more frequently between blocks, and the inability to harvest a large stand in a single operation with associated skidder and landing infrastructure (including tail holds), without having to maintain these structures throughout the rotation cycle. To address this limitation, future research should apply the model to real case studies that incorporate single-tree modeling, explicit harvest selection criteria, and the associated costs of both regimes.

Applications

Verification of certain forest management principles, including the assumptions about volume cuts in our models and the potential practical application of CCF in Polish conditions, is necessary. For example, the results of Parkatti et al. (2019) demonstrated that optimal continuous cover solutions for Scots pine in Finland often resulted in very low stand densities. Moreover, many economically optimal solutions were found to conflict with the provisions of the revised Finnish Forest Act of 2014.

Our results suggest that the profitability, carbon sequestered and stored, as well as harvested wood volumes, depend on the stand's initial age and the management regimes applied. Therefore, generalizing our hypothetical single-stand model to the landscape level (regional or national) is challenging. Other complexities like age class distribution, various land ownership categories, and preferences of forest owners may significantly shape the outcomes of such forest economic modelling exercises. As is common with all forest management analyses and decisions, the selection of a management regime should be carefully considered at the stand level by forest owners, taking into account many variables.

Our study suggests that CCF may be a profitable IFM investment, but not necessarily the most beneficial for climate mitigation practices because it has similar forest yields to CC forestry and thus lacks carbon additionality. However, this is actually a misleading criticism with IFM/CCF. We found that CCF was quite similar to afforestation in its forest carbon production, as well as investment returns and wood costs. This implies that it is equally valuable for forest carbon production in planted stands, only using a perceived preferred, more diverse forest management approach. Furthermore, CCF often starts as an IFM practice in existing native and natural forest stands and then improves them. This is a potential benefit that IFM brings to the fore—increasing forest carbon production in existing natural stands, which comprise more than 90% of the world's forests.

Thus, when CCF or IFM improves carbon additionality, it can then enter the forest owner's cash flow revenue stream. If CCF allows natural forests to grow more profitably, where poorly managed forests once existed, even at slightly lower rates than planted forests, it can help keep working forests. It can also achieve the universal forest benefits of substituting more carbon-intensive materials (concrete, steel, etc.) in the economy; this management regime may bring other ecosystem services (refer to, e.g., Peura et al. (2018).

As pointed out by Fagerberg (2022) with regard to Fennoscandia, continuous cover forestry or the so-called individual tree selection method is only practiced to a limited extent, partly because of a scarcity of knowledge and skills among all stakeholders, but also due to the shortage of scientific guidelines for how optimized tree selections are performed in practice. Without proper expertise, there is a risk that silvicultural management may degrade the forest, for example, through the repeated removal of the 'best' trees in each cycle. It seems the same holds for Poland, where the CCF method is practiced as smaller scale by individual forest owners (e.g., Andrzejczyk 2006) using wood for their own purpose (e.g., firewood, fencing) and CCF method in Scots pine has not been recognized yet by the biggest industrial actor – State Forests, which could lead to the improved cost efficiency and thus contribute to the stability of the State Forests (Chudy et al. 2016).

Government subsidies for private forest owners in Poland, provided under the European Union's Common Agricultural Policy, have mainly focused on afforestation of agricultural land, increasing biodiversity by adding extra tree or shrub layers in stands aged 30–60 years, and encouraging precommercial thinning in younger stands (around 11–30 years old[6]). Promoting continuous forest cover instead of CC has not been a key priority yet. Because of this, it may take some time before the CCF method becomes commonly used in Poland. Initially, its application may be limited to public forests, where clearcutting can reduce aesthetic and recreational values, and the CCF approach offers a way to address these concerns.

We believe that Chudy et al. (2022) and our research may contribute to a better understanding among forest owners and managers in Poland of alternative forest management regimes that, in addition to silvicultural aspects, also consider economic and financial factors. In addition, this modeling approach can be applied in other countries to compare CCF and even aged planted forests.

CONFLICTS OF INTEREST

The authors confirm there are no conflicts of interest.

[6] Refer to: Zwiększenie bioróżnorodności lasów prywatnych kampania 2024 roku: https://www.gov.pl/web/arimr/zwiekszenie-bioroznorodnosci-lasow-prywatnych-kampania-2024-roku

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APPENDIX A

Table 1A. Capital budgeting criteria (NPV, LEV, and IRR) for CCF and clearcutting (CC) for forest stands having different initial ages at the beginning of the modelling exercise and for different acquisition prices, at a 5% discount rate.

	NPV		LEV		IRR	
	CCF	CC	CCF	CC	CCF	CC
Initial stand age	**Forestland acquisition price 7,000 EUR**					
50	679	141	684	142	5.7%	5.1%
55	- 1,060	-286	-1,068	-288	4.2%	4.8%
60	507	1,159	510	1,168	5.5%	6.0%
65	93	587	93	591	5.1%	5.4%
70	1,888	2,242	1,903	2,259	7.2%	7.0%
75	1,712	1,712	1,725	1,726	6.6%	6.1%
80	3,947	3,640	3,977	3,668	15.7%	8.3%
AVERAGE	*1,109*	*1,314*	*1,118*	*1,324*	*7.1%*	*6.1%*
	Forestland acquisition price 8,000 EUR					
50	- 274	- 811	- 276	- 817	4.8%	4.5%
55	- 2,012	- 1,238	- 2,028	- 1,248	3.6%	4.3%
60	- 446	207	- 449	208	4.6%	5.1%
65	- 860	- 366	- 866	- 368	4.4%	4.8%
70	936	1,290	943	1,300	5.9%	6.0%
75	760	760	766	766	5.6%	5.5%
80	2,995	2,688	3,018	2,708	9.8%	7.1%
AVERAGE	*157*	*361*	*158*	*364*	*5.5%*	*5.3%*
	Forestland acquisition price 9,000 EUR					
50	- 1,226	- 1,763	- 1,235	- 1,777	4.06%	3.94%
55	- 2,965	- 2,190	- 2,987	- 2,207	3.17%	3.82%
60	- 1,398	- 746	- 1,409	- 752	3.97%	4.5%
65	- 1,812	- 1,318	- 1,826	- 1,328	3.84%	4.3%
70	- 17	337	- 17	340	5.0%	5.2%
75	- 193	- 192	- 194	- 194	4.9%	4.9%
80	2,042	1,735	2,058	1,749	7.5%	6.2%
AVERAGE	*- 795*	*- 591*	*- 801*	*- 596*	*4.63%*	*4.70%*
	Forestland acquisition price 10,000 EUR					
50	- 2,178	- 2,716	- 2,195	- 2,737	3.53%	3.52%
55	- 3,917	- 3,143	- 3,947	- 3,167	2.79%	3.44%
60	- 2,351	- 1,698	- 2,369	- 1,711	3.44%	4.03%
65	- 2,765	- 2,270	- 2,786	- 2,288	3.38%	3.86%
70	- 969	- 615	- 976	- 620	4.27%	4.63%
75	- 1,145	- 1,145	- 1,154	- 1,153	4.23%	4.41%
80	1,090	783	1,098	789	6.13%	5.50%
AVERAGE	*- 1,748*	*- 1,543*	*- 1,761*	*- 1,555*	*3.97%*	*4.20%*
	Forestland acquisition price 11,000 EUR					
50	- 3,131	- 3,668	- 3,155	- 3,696	3.1%	-9.6%
55	- 4,869	- 4,095	- 4,907	- 4,127	2.5%	-8.4%
60	- 3,303	- 2,651	- 3,328	- 2,671	3.0%	3.6%
65	- 3,717	- 3,223	- 3,745	- 3,247	3.0%	3.5%
70	- 1,921	- 1,567	- 1,936	- 1,580	3.7%	4.14%
75	- 2,097	- 2,097	- 2,113	- 2,113	3.7%	3.99%
80	138	- 169	139	- 171	5.12%	4.90%
AVERAGE	*- 2,700*	*- 2,496*	*- 2,721*	*- 2,515*	*3.4%*	*0.3%*

APPENDIX B

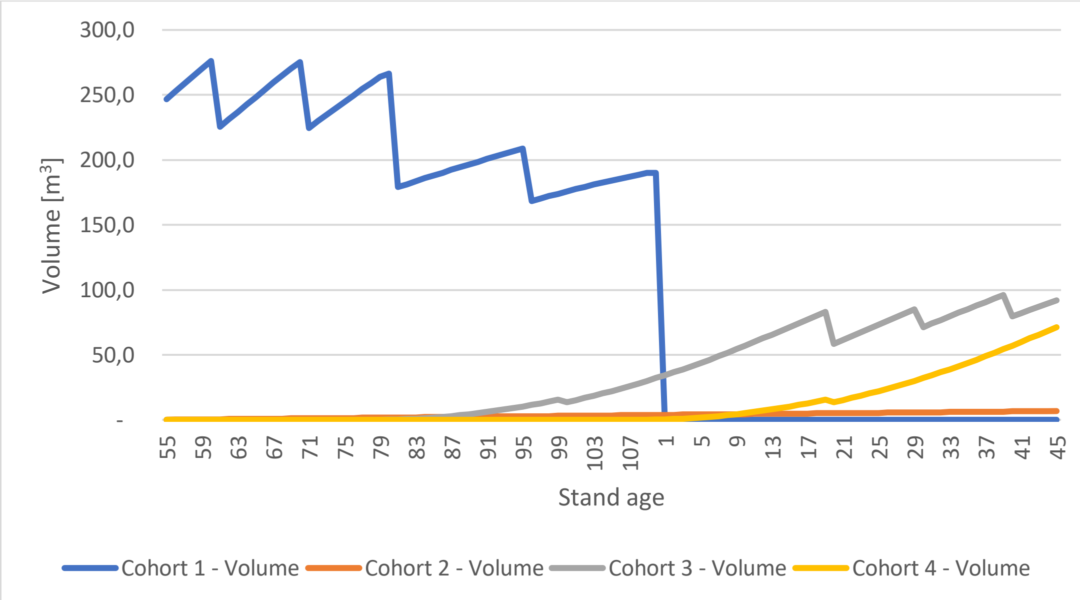

Figure 1B. The cohort volume development of the CCF system. Note: We initiated the exercise at the age of 50 to demonstrate the first regeneration cut at this age, followed by two thinnings and the next regeneration cut at 80, and the final cut at 110, when two new cohorts are established and the third one begins. In our modeling exercise, we began at the age of 50, with the regeneration cut implemented immediately after forest acquisition.

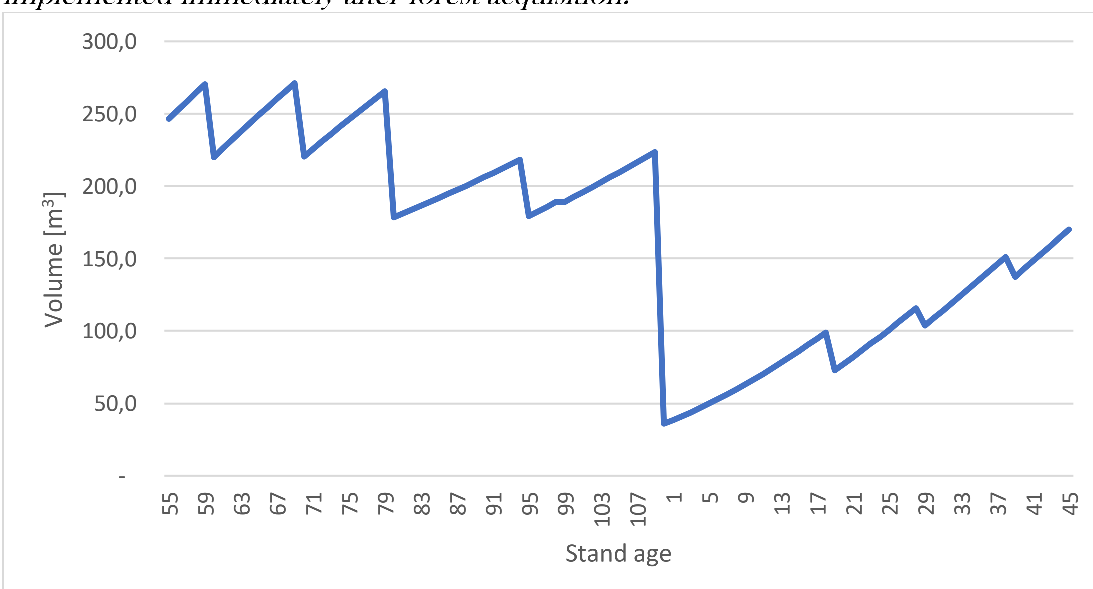

Figure 2B. The total net volume development for the CCF regime.

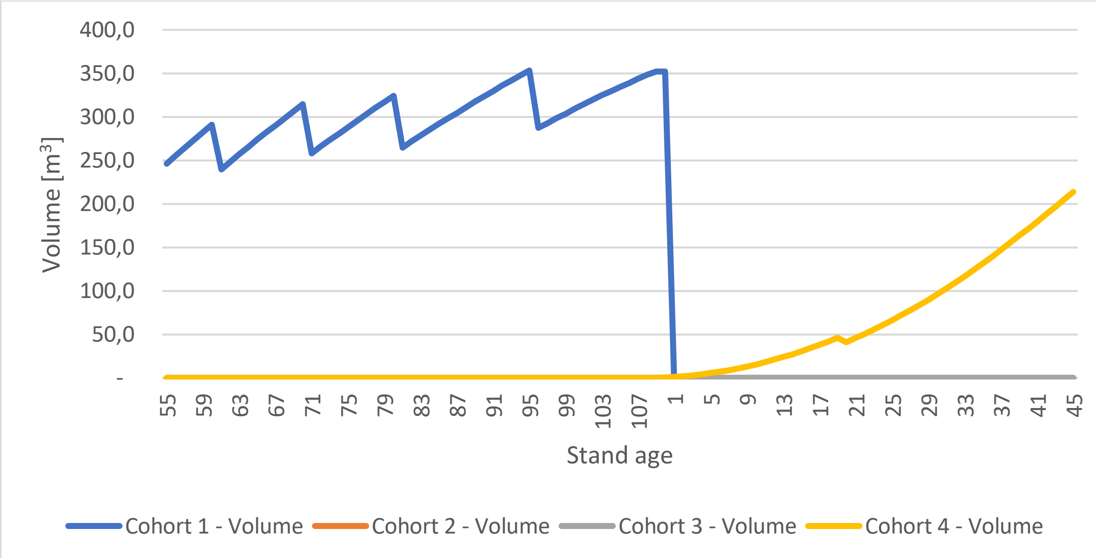

Figure 3B. The two-cohort volume development under the CC system.

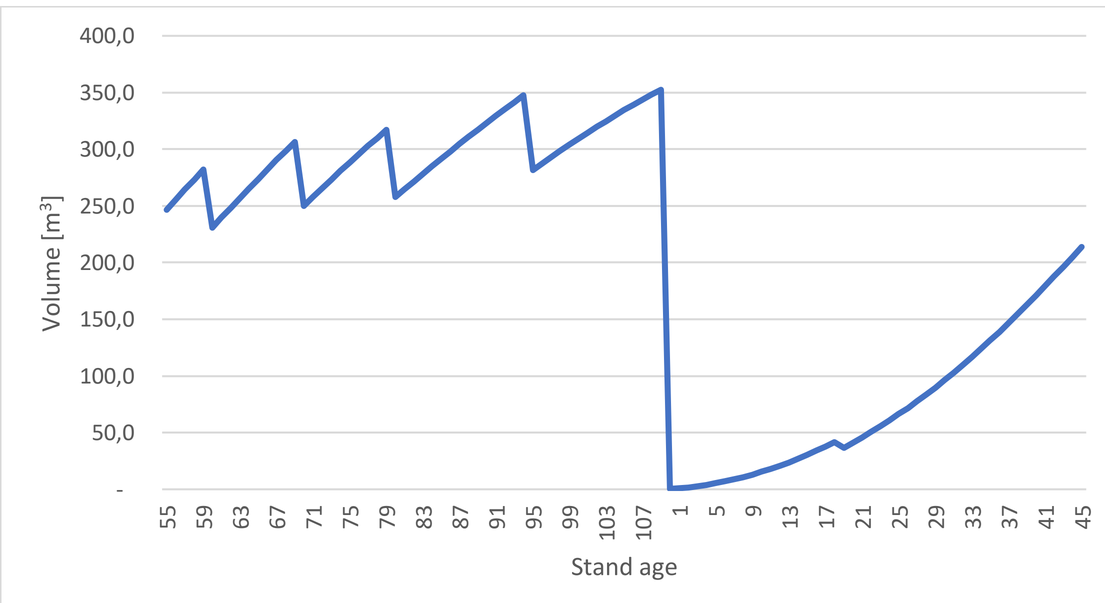

Figure 4B. The total net volume development for the CC system.