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Potential consequences of a rapid transition from rotation forestry to continous cover forestry in Sweden

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ABSTRACT
In the EU Forest Strategy for 2030 continuous cover forestry (CCF) is promoted, while rotation forestry (RF) is recommended only if required by forest health or environmental reasons. RF is the current practice on about two thirds of the EU forests. The envisioned shift toward CCF will have significant implications for Europe's forests and the industries. Using Sweden as a case, we simulated two scenarios: RF as a continued practice and a rapid transition to CCF. The results show that RF would ensure an even wood flow and slightly increasing harvest levels over the 50 years period. In contrast, the annual harvest in CCF exhibited significant variation, ranging from 50% to 108% of the RF harvest in the same year. This variation in harvest outcomes for CCF can be largely attributed to both economic and legal constraints during the transition from RF to CCF. As a result, the growing stock in CCF increased, allowing the forest to serve as a significant carbon sink. During the transition period, the ratio of pulpwood to sawlogs fluctuated for CCF, while it remained stable for RF. Consequently, the volume of sawlogs harvested under CCF was 86% of that harvested under RF.

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Continuous cover forestry; closer to nature; EU forest strategy; forest management; rotation forestry; transition

Introduction

The fundamental objective of forestry has been, and still is, the production of wood-based materials and bioenergy. Today current legislation in many forested countries also mandates that forest management consider the viability of the ecosystem, with the broader goal of providing a wide range of forest ecosystem services beyond what a natural, unmanaged forest can offer. A managed forest is expected to fulfill societal needs in a sustainable manner, drawing from established practices and a science-based understanding of forest dynamics. This also means that the future of forestry must be adaptable to ongoing environmental changes and rapidly evolving societal demands.

In Europe, the new EU Forest Strategy for 2030 outlines policy objectives for European forests to enable a diverse array of services and products from the forest (Anon 2021a). In addition to specifying the desired goals, the Strategy provides guidelines on how forests in Member States should be managed to achieve these objectives. One significant recommendation is that clear-cutting, as part of rotation forestry (RF), should be avoided and employed only when fully justified, such as for reasons related to forest health or for environmental reasons (Anon 2021a). Consequently, the Strategy strongly advocates an alternative to RF known as continuous cover forestry (CCF), often described as "closer-to-nature forestry". The claimed benefits include higher carbon stocks in the forest, a greater proportion of timber (saw logs) and enhanced forest biodiversity.

In the Strategy this assumption is backed by scientific references and several non-governmental interest organizations supporting CCF practices (Anon 2021a). The assumption is also supported in some scientific literature reporting on model based studies suggesting that CCF can be a cost-efficient tool for enhancing forest ecosystem services and biodiversity (Knoke 2012; Peura et al. 2018; Eyvindson et al. 2021; Mason et al. 2022). On the other hand, there are studies suggesting that RF with appropriate considerations to particular forest biodiversity can also be a cost-efficient method to combine high forest productivity with sufficient biodiversity (Fedrowitz et al. 2014; Gustafsson et al. 2020). Although, there are modeling studies suggesting that the economic return from CCF can be as high as from RF, since costly regenereration practices can be avoided in CCF relying on natural regeneration (Knoke 2012; Tahvonen and Ramo 2016), most studies report lower forest growth from CCF than RF (Hannerz et al. 2017 Lundqvist 2017; Ekholm et al. 2023;). Recent generations of forest owners seem to have found RF to be the best system to achieve their goals as approximately two thirds of forests in Europe are managed with RF (ForestEurope 2020; Mason et al. 2022). The call for a rapid transition to CCF will most likely change this but may also lead to unforeseen effects on forests

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productivity and yield due to the transition itself (Hanewinkel 2001).

In Sweden, RF has been practiced in parallell with CCF at least since the early 1800s (Lundmark et al. 2013; Lundmark et al. 2017). In 1923, the first national forest inventory was initiated, and the forest was classified into productive (≈23 million hectares) and unproductive land (≈5 million hectares), where forest production was assessed to exceed or fall below one cubic meter per hectare per year, respectively. Until 1947, clear-cutting was not allowed in certain parts of Sweden to avoid regeneration difficulties (Enander 2007). In mid 1900s research and practical experience made it possible to safely regenerate all forest land by means of planting or direct seeding. Since the 1950s, RF has become the completely dominant silvicultural system. The key factor behind this was the updated assessment, indicating that RF had become the most efficient method for timber and pulpwood production, while also offering excellent predictability for future harvests (Lundmark et al. 2013). Since the 1990s, conservation efforts have increased, and approximately 4 million hectares of productive forest land have been excluded from wood supply through voluntary and formal set-asides. The remainder of Sweden's productive forest land available for wood supply (≈19 million hectares) is now characterized by predominantly even-aged stands, an even age-class distribution (Figure 1) and management plans for RF. A recent survey conducted by the Swedish Forest Agency shows that just under 800,000 hectares, less than 5% of the forest area available for wood supply, are currently managed with some form of forestry that does not involve a clear-cutting phase (Anon 2024).

With Sweden as a case, the aim of this study was to analyze potential forest harvests and key attributes of future forests following a rapid transition from the prevailing silvicultural system, RF, to CCF over a 50-year period. To conduct this analysis, we simulated two nationwide scenarios. The fundamental assumptions underlying these scenario simulations were that 100% of growth (calculated as annual net growth = gross growth − the portion of mortality that is not harvested) should be harvested annually, where ver possible. Although storm-felled trees are categorized as mortality, they are generally still viable and are mostly harvested, meaning their contribution to the deadwood pool is much smaller than the total mortality. The assumption with a high and even flow of timber constitutes the core principles of forest management in countries with well-developed forest industry structures, such as Sweden, relying on a consistent and sustained flow of wood from the forests to the industry while maintaining high efficiency in harvesting operations and other silvicultural measures. We hypothesized (1) that a rapid conversion to CCF would mean a greater proportion of saw timber in the felling but also (2) that there was a risk of difficulties in maintaining an even timber flow as a result of the starting situation where the forest is characterized by even-aged stands and an even distribution of age classes.

Materials and methods

In this section, we will introduce the model employed in our study, the national forest analysis tool Heureka RegWise. Subsequently, we will outline the scenarios utilized in our analysis: RF and CCF, each projected over a 50-year period starting from 2018. Finally, we will detail the assumptions made for each scenario. Our modeling is based on data from a forest impact assessment conducted by the Swedish Forest Agency in 2022 (Eriksson 2022a; Eriksson 2022b). The modeling data is derived from the National Forest Inventory (NFI) in Sweden, covering the years 2016–2020, encompassing approximately 30,000 samples from productive forested lands. The NFI procedure is comprehensively described in (Fridman et al. 2014). At an overall level, the state of Sweden's forest is described in official statistics for Sweden on an annual basis (Roberge et al. 2023).

Heureka RegWise

The Heureka system (https://www.heurekaslu.se/wiki/Download_and_install) is an advanced forest decision support system developed by the Swedish University of Agricultural Sciences (SLU). Heureka offers a range of models and applications for forest planning at various levels, including regional, estate, and stand-level planning. In the context of our current study, Heureka RegWise is the specific application used. This application is designed for long-term analysis at regional or national scales and relies on a simulation-based approach. The core of Heureka RegWise is the projection of individual tree development over time, driven by empirical growth models primarily derived from data gathered through the NFI. The growth models are applicable to all Swedish tree species, including mixed species stands, and are used to provide reliable growth predictions for up to 100 years (Fahlvik et al. 2014). In addition to growth models, the system incorporates models for natural mortality (Fridman and Ståhl 2001; Siipilehto et al. 2020) and the establishment of naturally regenerated seedlings within forest stands (Wikberg 2004). Wind is a major natural disturbance factor in forestry (Persson 1975). Historical time series of storms per region can be repeated during simulations in Heureka. The effect of storm events is calculated using both empirical and mechanical models (Lagergren et al. 2012.) Users have the flexibility to define various settings for forest management activities such as final felling, regeneration, thinning, fertilization, CCF, and nature conservation. In the RF scenario, logistic regression functions are used to calculate the probability of thinning and final felling based on information from permanent NFI plots where these activities have been conducted. For every fifth year during the simulations, a probability of final felling is calculated for each NFI-plot that have passed lowest allowed age for final felling. The functions for calculating the probability is based on NFI data, meaning that the circumstances on the plot is used as independent variables and performed final felling as dependent variable, using logistic regression. For instance, the probability for final felling will increase with increasing age. The plots are then ranked according to the calculated probability, and the plots are harvested going from high to low ranking. For the CCF scenario, functions governing the proportional volume growth determine the probability of harvesting (Holm and Lundstrom 2000). This means that prioritization takes place according to relative

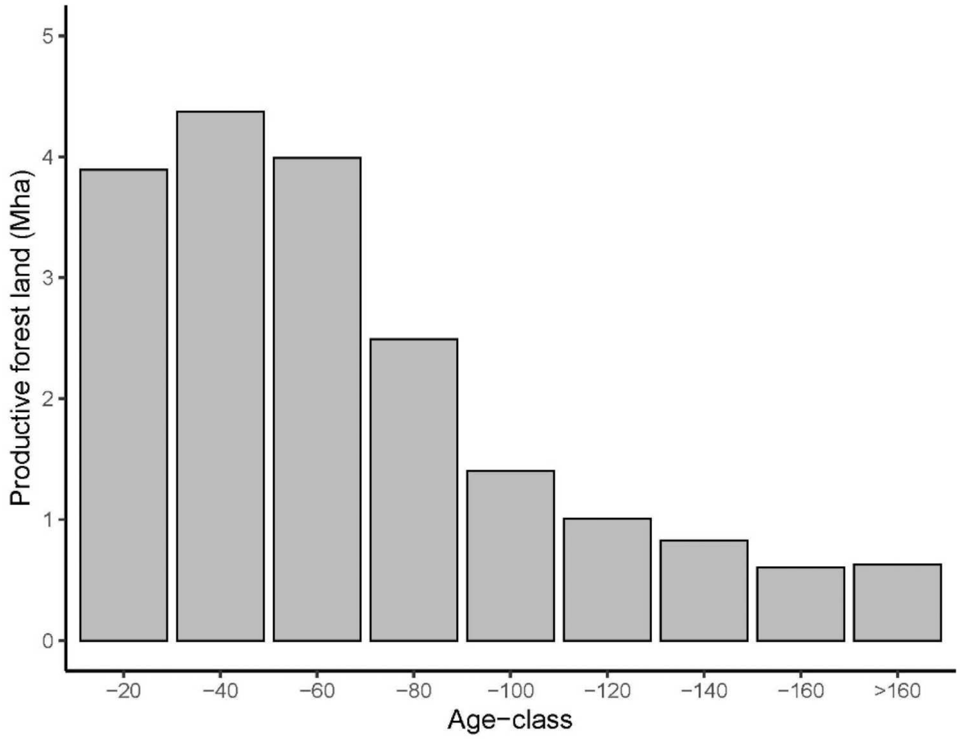

Figure 1. Age-class distribution of Sweden's 18.9 million hectares of productive forest land (annual growth >1 m^3 ha^{-1} $yr^{-1)}$ available for wood supply. The age-class ditribution is weighted against the basal area giving higher significance to larger trees. Rotation length depends on site fertility varying from 45 years for the most fertile sites to 120 + years for the lower site productivity. When combining the age classes of forests with av even age-class distribution across various site qualities into a single diagram, the distribution of forest in the younger age classes tends to be relatively uniform. However, fewer stands persist in the older age classes. This is because only the slower-growing trees on less fertile soils remain in the oldest age categories, as trees on more fertile soils reach maturity and are harvested sooner.

growth rate of stem volume where high standing stock and low stem growth give high priority. For both scenarios, if the desired volume is reached, harvesting stops, and the routine is repeated in the next five-year period. Heureka RegWise incorporates an integrated climate model, enabling users to select from different climate scenarios. For our simulations, we opted for the Max Planck Institute's MPI-ESM model, MPI 4.5, which replicates a climate scenario in which radiative forcing stabilizes at 4.5 W/m2 before the year 2100. The effect of climate change on forest growth is based on the process-based model BIOMASS (Mcmurtrie et al. 1990), which has been tailored and validated to suit Swedish conditions (Bergh et al. 1998; Freeman and Linder 2001 Bergh et al. 2003;). Heureka RegWise can be used to simulate scenarios on large geographical areas to answer questions of "what if" character. For example, the effects of various forest management strategies, e.g. RF or CCF, on the output of harvested wood in different assortments and several other ecosystem services. Moreover, users can define the harvest intensity within the Heureka system to suit their specific needs and objectives.

Scenarios

The two scenarios, RF and CCF, were applied to the 18.9 million ha in Sweden available for wood supply, i.e. formal and voluntary set-aside areas were excluded. This exclusion was based on geographical data on both types of set-asides, as provided by the most recent forest impact analysis (Eriksson 2022a; Eriksson 2022b). In this study, our objective was to achieve 100% harvest of the net growth in non-set-aside areas, ensuring the standing volume remained ideally stable over time. In both scenarios, the removal of trees through thinning in individual stands was subject to regulatory restrictions outlined by the Swedish Forest Agency (Anon 2022). This meant that post-thinning standing volume was not allowed to drop below a specified threshold determined by the mean height of the trees. To simulate current biodiversity considerations, we retained trees within each harvesting area, adhering to riparian forest buffer zones along water bodies as stipulated by forest certification standards in Sweden. Moreover, in the RF scenario, clear-cutting was only permitted once stands had reached a certain age, thereby ensuring optimal utilization of the forest's productive capacity. This age, referred to as the minimum final felling age, varied between 45 and 100 years for stands dominated by conifers, depending on site conditions and tree species, as dictated by §10 in the Swedish Forestry Act. Where the available forest volume for harvest fell short at a particular time step during the simulations, the target of achieving 100% harvesting of growth was not met, and a lower level of harvest was implemented for that specific five-year period.

Rotation forestry (RF)

In a landscape managed under the principle of RF, the landscape will be divided into forest stands, for more efficient management. A forest stand is often uniform, and the geographical demarcation is usually adapted to the conditions of the site. In Sweden, the size of a stand that is notified for final harvesting ranges from 2 to 5 hectares (https://www.skogsstyrelsen.se/globalassets/statistik/statistikfaktablad/jo0314-statistikfaktablad-avverkningsanmalningar-2022-korr20230221.pdf). Within a stand, the trees typically share the same age, and the management practices applied are consistent, guided by the same set of procedures such as planting and thinning. When RF maintains a stable age-class distribution over time, it ensures a uniform area available for harvesting each year, resulting in a steady wood flow for the industry.

The Swedish Forestry Agency, in collaboration with the Swedish university of agricultural sciences (SLU) and on behalf of the Swedish government, conducted a comprehensive forestry impact analysis known as SKA 22 (Eriksson 2022a). This analysis encompasses an evaluation of future requirements for forest raw materials, biodiversity preservation, and other benefits that forests can offer. It also includes forecasts of the forest's trajectory under six different scenarios. In our study, we adopted the scenario representing the continuation of current management practices as our RF scenario. Following final harvests, stands were regenerated through artificial means, involving planting, seeding, or natural regeneration with seed trees. Artificially regenerated stands were planted (or seeded) with seedlings from tree breeding programs. Throughout the simulation, these trees were intermixed with naturally regenerated trees using algorithms constructed from available NFI data. Additionally, one or two thinning operations were simulated in each stand to foster the growth of the most viable trees before the final harvest. With these conditions, the harvest yield typically consists of approximately 70% from final felling and 30% from thinning (Roberge et al. 2023).

Continuous cover forestry (CCF)

CCF represents a forest management approach in which the forest canopy remains intact through selective harvesting, avoiding clear-cutting practices. Various definitions of CCF exist in the literature (Puettmann et al. 2015). In this study, we use the term CCF for a management approach that avoids clear felling and planting by utilizing thinning from above and by promoting natural regeneration. These choices aim to sustain an uninterrupted tree canopy and gradually transition even-aged stands into uneven-aged forest structures. In the CCF scenario, we assumed a swift transition from RF to CCF in Sweden. Similar to the RF scenario, our target was to harvest 100% of the annual growth. Trees were selectively harvested through thinning operations, and clear-cutting was strictly prohibited. Within the thinning routines of Heureka, users have the flexibility to harvest individual trees and express preferred species and dimensions. In our case, the simulation settings primarily emphasized thinning from above. New trees were regenerated through natural regeneration, involving the establishment of seedlings in the gaps created by the removal of individual trees. To ensure that thinning operations remained economically viable while preventing stands from becoming overly sparse, we established specific criteria's. In CCF, as well as in RF when it comes to thinning, the harvest volume had to exceed 20% of the standing tree volume but could not exceed 40%, all while complying with the regulations outlined in the Swedish forestry act. To allow the forest to recover in terms of volume before the next harvest cycle, our model incorporated waiting periods of at least 10 years in southern Sweden, 15 years in central Sweden, and 20 years in northern Sweden. This approach was designed to ensure that a reasonable economy was obtained in the thinning operations. Thinning operations were permissible across all age classes within established stands (mean height > 7 m), regardless of stand structure and tree species composition.

Results

Growing Stock

In the simulation of the RF scenario, which represents current clear-cutting practices, close to the entire growth was harvested consistently over the 50-year analysis period. This approach resulted in a relatively stable standing stock throughout the period (Figure 2a), with only a slight increase to 2.2 billion cubic meters on the land available for wood supply. In contrast, the CCF scenario, where continuous cover forestry was implemented, saw a 47% increase in the growing stock over the initial 50 years (Figure 2a). This increase was more substantial, with the growing stock reaching 3.1 billion cubic meters, contributing to a significant carbon sink during this period in the CCF scenario.

Growth

In the RF scenario, a consistent and sustained growth increment was observed throughout the entire simulation period. This resulted in a slight increase in both the absolute and relative growth rates, with a net growth rate 15% higher than at the beginning of the study period (Figure 2b). By the end of the 50-year period, the relative growth rate (RGR) in the RF scenario had risen to 4.7%.

In contrast, the CCF scenario displayed a different growth trajectory. Initially, there was an increase in both absolute and relative growth rates, but this was followed by a decline as the period progressed. By the end of the simulation, the absolute growth rate in the CCF scenario was 9% lower than in the RF scenario. This downward trend was also reflected in the relative growth rate, which decreased over time. Starting at around 4,3% for both scenarios at the beginning of the simulation, the RGR in the CCF scenario dropped to 3.1% by the end of the period (Figure 2c).

Harvested volumes (all assortment)

The enhanced growth in the RF scenario facilitated a steady and increasing flow of harvested wood from the forest (Figure 2d). In contrast, the CCF scenario displayed considerable fluctuations in harvested volumes between five-year

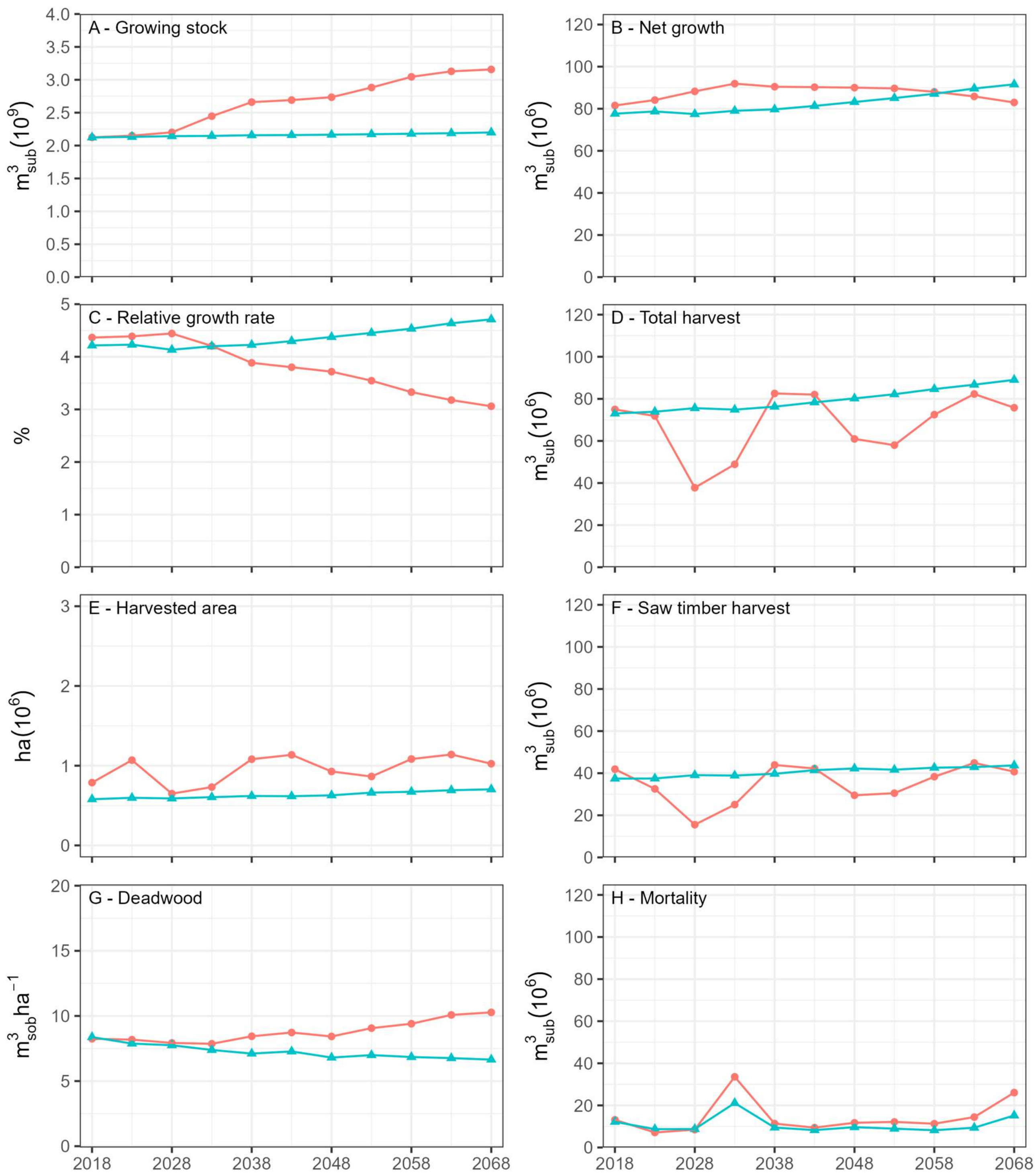

Figure 2. Results for the simulations of Swedens productive forest (the forestland available for wood supply excluding formal and voluntary set-aside areas, and retention patches) between 2018 and 2068. Blue line plus triangles refers to RF and red line plus dots refers to CCF. (a) growing stock refers to the state in 2018, 2023 … , (b) annual net growth expressed as gross growth – the portion of mortality that is not harvested, referring to 2018–2023, 2023–2028 … , (c) RGR, growth in relation to the growing stock, growth 2018–2023/state 2018 … , (d) annual total harvest, living and storm-felled trees, sawlogs + pulpwood in m^3 solid volume under bark, (e) annual harvested area, hectare, (f) annual saw timber volume, referring to 2018–2023 … , (g) deadwood per hectare, refers to the state in 2018, 2023 … and (h) annual mortality, refers to 2018–2023 … ., includes all mortality, including storm damage. Note different scales on y-axis.

periods, ranging from 50% to 108% with an average of 85%, in comparison to the RF scenario (Figure 2d). For the CCF scenario, the area that could be harvested varied significantly due to the restrictions and assumptions made in the analysis. On average, the area impacted by timber harvesting was 51% higher for CCF compared to RF (Figure 2e).

Saw timber

The CCF scenario exhibited a similar fluctuation in saw-log yield as observed for total harvesting. In contrast, the saw timber flow in the RF scenario was stable and gradually increasing in absolute terms. Throughout the entire period, the proportion of sawlogs remained approximately the same for both scenarios, with 51% for RF and 52% for CCF. During the simulation period, the saw timber flow from CCF ranged from 40% to 112% of that in RF, with an average of 86% (Figure 2f).

Deadwood

The amount of deadwood on the forest area available for woodsupply decreased slightly over time in the RF scenario, while it increased significantly in the CCF scenario. Toward the end of the period, the average amount of deadwood per hectare was 10,3 m3 in CCF compared to 6,6 m3 for RF (Figure 2g).

Mortality and storm related damages

Mortality in the forest area available for wood supply consisted of two primary causes: storms and other factors. Based on historical storm data, two severe storms were simulated during the period, occurring in 2033 and 2068. These events led to increased mortality in both scenarios, with a more pronounced effect in the CCF scenario (Figure 2h). Additionally, CCF showed a slight increasing trend in mortality during the latter part of the analyzed period. On average, mortality accounted for 16% of the growth in the CCF scenario and 13% in the RF scenario.

Both scenarios were based on the same forest condition with a relatively even age-class distribution at the start of the simulation (Figure 1). For RF, it was roughly maintained throughout the period with some tendency to steere toward more younger forests (<100 years) and less old forest (>100 years) (Figure 3). In the CCF scenario, forests experienced ageing, marked by a substantial rise in mature and old forests, coupled with a significant decline in young and middle-aged forests. Windthrow events simulated in the model, however, create some young age classes also in the CCF scenario (Figure 3).

Discussion

The choice of a silvicultural system in a country is historically shaped by natural conditions, socio-economic factors, actors, values, and scientific knowledge. Transitioning from selection to rotation forestry is relatively straightforward. This can be done by clear-cutting an area equal to total area for each site quality class divided by the rotation length for the corresponding site class. However, shifting in the opposite direction can involve a more lengthy and intricate process. Not least, when converting an even-aged forest landscape to uneven-aged forests, forest owners and policymakers require tools to facilitate the transformation and anticipate its economic and ecological implications.

The rapid conversion from RF to CCF, for the whole of Sweden, favored some of the goals set up by the new EU forest strategy for 2030 (Anon 2021a). The CCF scenario showed an increase in growing stock (increased carbon storage) and consequently an increased forest carbon sink for the first 50 years (Figure 2 panel a). There was an increase in older trees (Figure 3), and the amount of deadwood also increased due to higher mortality; part of the mortality was harvested, while some was left in the forest, contributing to actual deadwood accumulation (Figure 2 panel g), which both favor the EU biodiversity strategy for 2030 (Anon 2021b) connected to the EU forest strategy 2030. At the same time, the EU forest strategy aims to promote long-lived products for a sustainable forest bioeconomy. We hypothesized that a rapid conversion to CCF would mean a greater proportion of saw timber in the felling, which would also contribute to this goal. This was however not achived in the CCF scenario where lower volumes of saw logs was able to be harvested in comparison with the RF scenario (Figure 2 panel f), although the proportion of saw logs of the total round wood volume was in average slighty higher during the simulated period (52% vs 51%). This phenomenon can be attributed to the nature of older age classes in the forest that are being converted to CCF, where large diameter trees are located. In this context, full harvesting of these older age classes was not possible; instead, they must undergo thinning. As a result, a large part of the mature trees must be preserved and await the next thinning cycles. Following thinning, stands must grow for 10–30 years before substantial economic extraction within legal boundaries is feasible. Another consequence will be that the area of thinning operations in younger forests must increase to approach the goal of harvesting the entire or close to the annual growth. Coupled with the prevalence of young forests in the landscape under transition, this explains periodic shortages of harvestable trees in the CCF scenario, in the first 50 years (Figure 2 panels d and f). This results in an immediate reduction in saw timber volumes to the market proportional to the reduction in total harvested volume compared to RF, contrary to the common belief that CCF yields a higher timber share which would indicate potentially higher saw timber volumes (Hanewinkel 2001).

The 15% reduction in harvested volumes for CCF compared to RF is supported by a recent study in Finland where they also found a 15% reduction in harvested volume for the CCF scenario compared to RF (Peura et al. 2018). It is clear that more frequent thinning intervals would lead to reduced variation in the timber flow for CCF, but at the same time the costs per harvested cubic meter increase. For Sweden to maintain a more even supply of round wood during the transition, the restrictions that the current Forest Act places on forest management need to be changed and other financial incentives than revenues from harvesting are needed if thinning is to be done more often to reduce volatility in harvest levels. It should also be noted that the Swedish Forestry Act is tailored to RF and is designed to ensure high timber production, which can be a limiting factor for the application of CCF with the aim of maintaining a consistent timber flow. Nonetheless, given current Swedish forestry legislation, our assumptions regarding thinning intervals are considered reasonable.

A prominent feature of CCF was the much larger forest area affected by harvesting on an annual basis compared with RF (Figure 2e). With current round wood prices, this

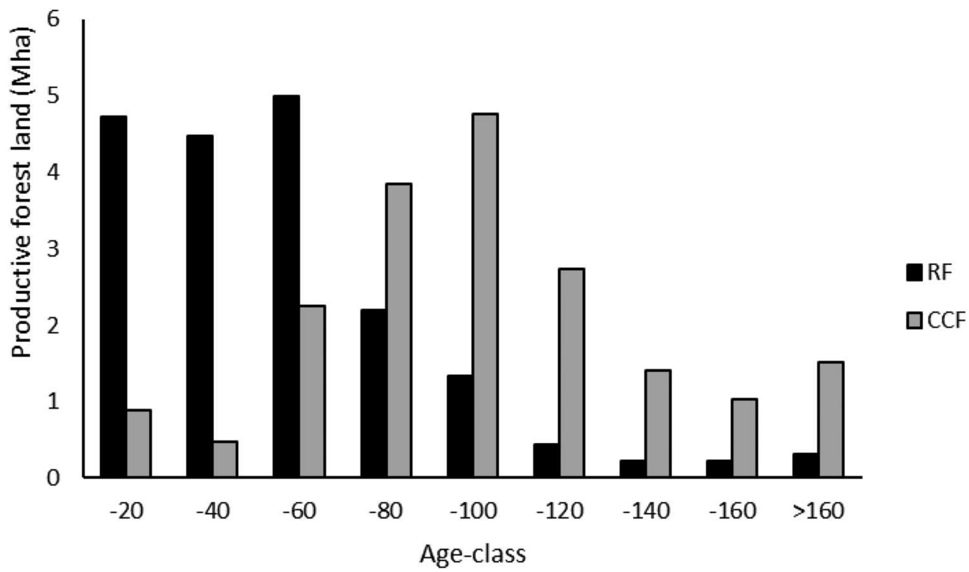

Figure 3. Age-class distribution for the two scenarios RF and CCF at the end of the study period (2068). The age-class ditribution is weighted against the basal area giving higher significance to larger trees.

posses large challenges for the economy of the forestry sector since large emphasis is beeing placed on cost minimization to obtain a financial return, especially in the northern parts of Sweden. CCF demands an increased number of harvesters and forwarders togheter with an increased hauling distance and more frequent harvesting operations per cubic meter of wood, both for the within forest operations and transportations to the industry. In turn, this will be associated with increased costs and CO_2-emissions. Add to that, an increased soil compactation and disturbance due the more frequent occuring effect of heavy machines when harvesting is conducted more often (Labelle et al. 2022). On the other hand, CCF, which is primarily based on natural regeneration, generally incurs no costs associated with the regeneration process, such as planting, sowing, and soil scarification, which can significantly affect soil disturbance. However, in cases where storm damage occurs on smaller areas, soil scarification and planting may still be necessary, meaning that the absence of these costs is not absolute. Optimum trade-off between even timber flow and costs has been outside the scope of this study but is something that needs to be studied more.

A swift transition from RF to CCF at the landscape level leads to volatile harvest levels (Figure 2d,f). This means that our findings are consistent with the predictions made by hypothesis 2. Initially, there was a increased growth due to increased standing stock and maintained relative growth rate in the CCF scenario but the latter part of the period showed a trend of reduced growth both in absolute and relative terms (Figure 2 b,c). The growth reduction could be explained by ageing forests (Figure 3; Pilli et al. 2022) when full harvesting of these older age classes was not allowed. For the RF scenario there was a steady increase of growth possibly explained by the use of genetically improved planting material which is expected to boost growth by 10-25% (Jansson et al. 2017). The pronounced shift toward older trees in the CCF scenario can be explained by the initial conditions of the CCF simulation, which was characterized by a uniform age-class distribution (Figure 1). Since there are no final fellings in the CCF scenario, except following severe storms, there is no inflow of young stands during the simulation period, leading to an increasing proportion of older stands, as shown in Figure 3. The young age classes of even-aged stands must mature before thinning can begin, resulting in a shift toward older age classes by the end of the study period. Consequently, a significant portion of the trees in the age-class distribution at the end of the period already existed in the initial conditions.

In both scenarios, thinning was regulated by the Swedish Forest Agency (Anon 2022), requiring that post-thinning standing volume not drop below a threshold determined by the mean tree height. This kept the stands relatively dense, even at older ages, which inhibited the development of new tree ingrowth. As a result, naturally regenerated trees were quite old when they reached a size sufficient to impact the basal area-weighted mean age of the stand. In the CCF scenario, the presence of younger trees in Figure 3 is mainly due to storm events that created larger gaps in the forest, allowing for some natural or artificial regeneration.

Conversion scenarios, as explored in various studies using growth models, frequently indicate lower growth rates during the conversion period (Hanewinkel and Pretzsch 2000; Brunner et al. 2006; Hilmers et al. 2020; Reventlow et al. 2021). This decline in growth is attributed to a reduced stand density necessary to initiate recruitment. Our results showed an initial increase in growth followed by a decrease in the CCF scenario. This pattern may have been influenced by the fact that we did not allow for more intensive thinning, which could have helped ensure the establishment of new seedlings. If more aggressive thinning practices had been permitted, our results for CCF might have been different. However, implementing such practices would require exemptions from current forestry legislation. The precise reduction in stand growth remains uncertain in conversion scenarios due to the inadequacy of growth models designed for these specific stand structures (Brunner et al. 2006; Drössler et al. 2014; Lundqvist 2017) or the utilization of rudimentary assumptions concerning the establishment and growth of seedlings and saplings (Hanewinkel and Pretzsch 2000; Drössler et al. 2014; Lundqvist 2017; Hilmers et al. 2020; Reventlow et al. 2021). Some scenario studies provide insufficient details about the conversion method, making it challenging to adapt prescriptions to different forest types (Hanewinkel and Pretzsch 2000; Drössler et al. 2014; Lundqvist 2017; Hilmers et al. 2020; Reventlow et al. 2021). Needless to say, more studies are needed.

Our analysis is based on empirical growth models in the Heureka system, which have demonstrated reliable predictions for up to 100 years for RF in Sweden (Fahlvik et al. 2014). There are however indications that current growth function may underestimate long-term growth in uneven-aged forestry, potentially introducing bias into the simulation and optimization results (Fagerberg et al. 2022). Furthermore, there are modeling complexities related to new tree ingrowth and their growth responses on canopy realese which is influenced by tree age and size variables (Elfving 2003 Wikberg 2004;). For example, the suppression that occurs on hight development of regenerated trees in CCF because of competition does not fully stop with canopy realese, resulting in old low productive trees, the productivity is thus projected as declining. These are reasons why we choose to present results only from the first 50 years of the simulation, even though the standard practice is to run it for 100 years. The results of our study show that net growth is maintained in both scenarios, although absolute and relative growth rate declines in the later part of the period for CCF. In the CCF scenario net growth is maintained as the timber stock increases due to the fact that the entire growth cannot be harvested. This highlights the importance of long-term analyzes when discussing silvicultural systems. Therefore, what happens beyond 50 years following a large-scale transition from RF to CCF needs to be further investigated. One can question what might happen in the longer term, beyond the 50-year period, considering the declining growth trend observed in the CCF scenario. At the end of the studied period net growth was 9% lower in CCF than in RF. Field-based studies show a 10-30% reduction in net growth for CCF compared to RF (Lundqvist 2017 Hynynen et al. 2019;). However, it contrasts with some simulation studies indicating similar or slightly reduced growth in CCF compared to RF, although these often focus on stand-scale scenarios with short thinning intervals and stand structures and tree species more suitable for CCF (Tahvonen et al. 2010; Rämö and Tahvonen 2014; Tahvonen and Ramo 2016; Lundqvist 2017; Kellomäki et al. 2019 Parkatti and Tahvonen 2020;).

Our national-scale approach using existing forests of all age classes and tree species is essential for understanding the effects of a rapid shift from RF to CCF. Emperical studies conducted in Fennoscandia in Norway spruce dominating stands suggests that CCF typically yields lower growth (Hannerz et al. 2017; Lundqvist 2017 Ekholm et al. 2023;). Our study includes all Swedish productive forests available for wood supply, regardless of composition and age structure. This might not be realistic when it comes to regeneration, depending on site conditons and tree species which differs a lot from north to south and with increasing alltitude. CCF is highly dependent on successfull regeneration through natural processes (Erefur et al. 2008) which has been shown to be succesfull in southern Sweden while on northern latitudes natural regeneration has shown to be poor whitout natural disturbances (Lundqvist 2017). The difficulty of Scots pine in establishing new seedlings when overshadowed by larger trees can lead to long-term production losses. Additionally, this can cause a shift in species composition, favoring the more shade-tolerant Norway spruce. Scots pine seedlings also face significant belowground competition for water and nutrients, further hindering their establishment and growth (Häggström et al. 2024). Given these factors, one can expect greater production losses in forests dominated by Scots pine compared to those dominated by Norway spruce in Fennoscandia. Scots pine and Norway spruce are the most common tree species in Sweden, each accounting for approximately 40% of the total timber volume (Roberge et al. 2023). This may result in an overestimation of regeneration, leading to an inaccurate assessment of the growing stock and overall growth in the Continuous Cover Forestry (CCF) scenario.

Mortality rates increased in the CCF scenario as a result of reduced harvested volumes, higher growing stock, and increased average age. The amount of storm related mortality was also higher in the CCF scenario. CCF introduced thinning-related factors that can amplify storm damage risk. Severeal studies indicates that trees remaining after a thinning are more sucepitble to wind damage because of a lack of stability due missing root anchoring from adjecent removed trees and that they are tall and thin because of hight competition (Burton and Smith 1972; Lohmander and Helles 1987). Potterf et al. (2022) interpreted the wind damage risk under management scenarios RF, CCF and a combination of the two on a landscape level. They found that there was an increasing storm damage probability in CCF scenario due to taller trees and higher thinning frequency. Furthermore, because of the continuous cover of forest the light conditions closer to the forest floor will favor the secondary species Norway spruce characterized by shallow root systems which will further increase the storm damage probability (Felton et al. 2016). As shown in several earlier studies the risk of wind damage increases by increased standing volume (e.g. Persson 1975; Valinger and Fridman 2011). This could also explain why mortality was higher in CCF scenario since standing stock became so much higher than in RF scenario, especially in the later part of the studied period. However, mortality functions or storm damage in Heureka are not adapted to CCF, but builds upon empirical data from RF. Since empirical mortality data from CCF is largely lacking, mortality rates in the CCF scenario is also uncertain.

Conclusion

While CCF may work well in isolated stands with suitable tree species and site conditions, a swift transition from RF to CCF at the country level leads to volatile harvest levels and reduction in harvested volumes and amounts of timber suitable for long-lived products. RF would ensure a consistent wood flow with gradual increases in harvest levels over the 50-year period analyzed. Conversely, CCF would lead to substantial fluctuations in harvest levels, resulting in a total harvest equivalent to 85% of the RF scenario. Contrary to the expectation of increased saw-log volume in CCF, our results suggest that the harvested saw-log volume under this scenario was 86% of the RF scenario. For countries heavily reliant on a robust forest industry, maintaining a high and steady timber flow is of paramount importance. The primary concern with a rapid conversion from RF to CCF is then the inability to meet this crucial condition. Fluctuating supply could lead to more volatile prices, creating market uncertainty and complicating long-term planning for industry as well as for land-owners.

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