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Production losses during the transition from even-aged management to gap cutting in Norway spruce and Scots Pine stands in Southern Sweden

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ABSTRACT
Knowledge on continuous cover forestry (CCF) in Sweden is limited, as even-aged silviculture has dominated in the Swedish forestry since the mid-twentieth century. This study examines production losses during the transition from even-aged management to gap cutting at the stand level. Simulations were conducted using the forest simulator LandSim for Norway spruce and Scots pine across various productivity levels in southern Sweden. Up to 36 conversion schedules were modeled per species and productivity class. Production losses, compared to the mean annual increment (MAI) under even-aged management, ranged from 16 to 320 m^3 ha^{-1} or 2.7 to 32.7 MAI equivalents. Trade-offs between several aspects of the target stand structure after transition and the transition period production were found. Late conversions, starting at the reference final felling age, generally, decreased production more than the early transition options. A sensitivity analysis of reduced growth in the gaps suggests that production losses due to suboptimal timing of harvests are likely to be the main component of the total production losses during the transition period, even for longer conversion schedules.

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KEYWORDS
Gap cutting; CCF; conversion; transition period; simulation

Introduction

EU policy developments and domestic debate are driving growing interest in Continuous Cover Forestry (CCF) in Sweden. For example, the New EU Forest Strategy for 2030 encourages greater use of CCF over clear-cutting (European Commission 2021). Nationally, the 2020 update to Sweden's Forest Stewardship Council (FSC) standard requires that at least 5% of the productive forest area on each property be managed using some form of CCF (Forest Stewardship Council 2019). This trend is largely fueled by public concerns over biodiversity loss and the perceived depletion of nature associated with clear-cutting. However, scientific evidence on the specific biodiversity benefits of replacing clear-cutting by selective cuttings remains inconclusive. While CCF is likely beneficial for species dependent on closed-canopy forests (Savilaakso et al. 2021), its widespread application could reduce open habitats and potentially have negative effects on beta- and gamma-diversity (Schall et al. 2018).

CCF in the current international usage typically denotes selective cutting-based silviculture. In Central Europe, variants of selection systems have been practiced for a long time, denoted as "jardinage" in French and "Plenterwald" in German (Pommerening and Murphy 2004). The "Dauerwald" concept introduced by Möller (Möller 1922) laid an important foundation from which more recent ideas such as "close-to-nature" silviculture could be drawn. A shared feature of various CCF definitions appears to be a strong focus on features of the remaining forest rather than on the amounts or features of outputs from forest management. The Swedish Forest Agency's (SFA) definition of CCF published a few years ago includes selection systems, gap cutting and shelterwood systems (Appelqvist et al. 2021). While the shelterwood system is relatively common in the practical management of Scots pine (Pinus sylvestris) and is part of a sufficient number of silvicultural experiments (e.g., Lula et al. 2021), the uncertainty concerning the potential of selection and gap cutting management is great.

Quick and conclusive answers concerning the productive performance of the systems, especially during the transition period, are unattainable due to the lack of data and the consequently poor adequacy of existing growth models and stand simulators. In a recent comparison of simulated and observed short-term growth from a set of selection cutting experiments Grzeszkiewicz et al. (2025) found underestimation of basal area growth by the growth models in the Heureka system (Lämås et al. 2023). No evaluation of long-term predictions of forest growth under CCF by the Heureka system is as yet available due to the scarcity of reference data. The evidence from the scarce experiments in the Nordic region and some tentative modeling studies appears to suggest that the long-term production of uneven-aged Norway Spruce (Picea abies) stands managed by selective cuttings may be about 80% of the even-aged system Ekholm et al. (2023).

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This study aims at expanding our knowledge on the conversion process from even-aged management to uneven-aged gap cutting management. Gap cutting occupies an intermediate position between individual tree selection systems and shelterwood systems in the SFA definition of CCF. Gap-sizes and shapes vary in the global silvicultural practice, with one to two tree length often used as an approximate diameter for gaps (Nyland 2003). According to the SFA definition, an opening is considered a clear-cut if it exceeds 0.25 ha (Appelqvist et al. 2021). Currently, gap-cutting is used as seldom as individual tree selection, the average clear-cut size in Sweden in 2019 being approximately 3.6 ha, with clear cuts in the South being generally smaller than in the North (Svensson and Vargas 2024; Swedish Forest Industries 2025). This, and the small number of silvicultural experiments on these systems, results in a lack of data on regeneration and growth hindering their systematic analysis and comparison to clear-cutting under various conditions.

The comparison of production under a gap cutting system to that of a clear-cut system will naturally depend on regeneration and early growth in the gaps. Natural regeneration, often practiced in gap cutting systems, tends to be slower and to result in more variable outcomes than artificial regeneration (Valkonen and Siitonen 2016). Additionally, overshadowing from gap edges is bound to have some hampering effect on early tree growth in gaps, with the impact closely related to gap size (Coates and Burton 1997). On the other hand, some moderation of frost damage can also be expected. Furthermore, a positive release effect on the growth of edge trees surrounding a gap might to some extent compensate for the slower early growth inside the gap. Depending on the balance of these factors, the production in a gap cutting system is likely to be less than or equal to that of a clear-cut system with the same tree species and rotation period. Unfortunately, the scarcity of data and the consequent limitation of the existing models make it impossible at the present stage to include these aspects in a simulation study.

Before a multi-age cohort structure is established, however, a stand must undergo a conversion process from an even-aged state. Alternatively, it can be established on bare land by stepwise regeneration in patches. Both approaches incur production losses: the former, due to untimely harvest of parts of the original stand while the latter, due to delayed regeneration of parts of the stand. These production losses occur independently of how the gap-cutting system in equilibrium performs in comparison to even-aged management (the occurrence of such losses was obvious already to forestry classics e.g. Heyer (1883, p. 267)). For forest owners considering changing the sylvicultural system, these transition costs may be nearly as significant as the expected long-term performance of the new system, as they can impact the forest property for an extended period, often beyond the typical ownership duration. Additionally, at an aggregate level, production losses will sooner or later translate into harvest reductions which may affect the forest industry and the national climate change mitigation efforts.

In the present study, an even-aged growth model was applied to estimate the harvest-inoptimality related transition period losses as defined above. The estimates were obtained for Norway spruce and Scots pine stands across a range of productivity levels in Southern Sweden and a large number of gap cutting schemes. The tested gap cutting schemes varied in the number of age cohorts, cutting intervals, and the stand age at the start of conversion. Production of stands in transition was compared to that of even-aged stands. To contextualize the estimated losses due to harvest timing, a sensitivity analysis was performed considering various levels of potential growth reduction in the gaps. The actual level of growth in gaps, subject to the factors enumerated above, remains an open question. The comparison is limited to physical production without financial variables.

Material and methods

Model

The simulation tool employed in this study is a version of the forest simulator LandSim (Pang et al. 2017; 2019) with novel functionality for gap cutting and updated growth parameters. LandSim projects forest growth for 25×25 m cells over geographically referenced grids, which can be visualized as raster maps. The growth is projected in a relatively coarse manner involving only a few variables, which facilitates applications over large geographic areas without reductions in spatial resolution.

Originally, the tool was developed as a spatial extension of the area-based matrix model of forest growth, SMAC (Sallnäs, 1990), the predecessor model of EFISCEN (Verkerk et al. 2016) and EFDM (Vauhkonen et al. 2019). The spatialization of the model involved a change in the modus of growth projections from deterministic fractioning of aggregated area assigned to a specific state to stochastic state transitions of elementary forest units with spatial references. Such modifications allowed for retaining the parameters of the original non-spatial model including the transition probabilities.

The area-based growth model integrated in LandSim uses a discrete state-space defined by four dimensions: productivity, species, age, and volume. The productivity class set consists of six classes based on potential site productivity ("bonitet" in Swedish) understood as the maximum Mean Annual Increment (MAI) which can be achieved under optimal management for either pine or spruce. The species class set includes spruce-, pine- or broadleaves-dominated stand classes based on the volume proportion of each species or species group. The age class set consists of 45 classes of five-year length, which limits the maximum modeled age to 225 years. The volume class set consists of 10 volume classes, with specific definitions for each productivity class corresponding to their respective growth patterns. The growth model parameters, the transition probabilities, for the present version of LandSim have been derived from the EFDM implementation for Sweden (Vauhkonen et al. 2019). Volume growth resulting from transitions in the state-space includes ordinary (non-catastrophic) mortality implicitly. Before simulation, the initial forest description is classified according to the class limits (Appendix 1). After simulation, volume outputs are converted back to exact values based on class midpoints.

Regeneration and establishment in the simulator are managed by a specialized routine controlled by user-defined parameters. Key parameters include the probabilities of three different regeneration qualities, which influence the speed of establishment and potential deviations in species composition from the primary regeneration species. The specific impacts of these regeneration qualities can be customized by the user.

In this study, the regeneration settings included a five-year period in which the land remains bare after felling, followed by a 10-year phase during which the cell reaches the first volume class. This results in a total of 15 years from the final harvest of a cell to the point at which it re-enters the growth model for established forest, then with age class 2 (10 years) and volume class 1. The exact volume figures depend on the productivity class. These outcomes are comparable to the outcomes of default regeneration settings in the Heureka system (Lämås et al. 2023).

Precommercial thinning (PCT) is not explicitly modeled in the tool. Instead, the growth model accounts for the combined effects of the extent and intensity of PCT conducted in Swedish forests through growth parameter estimates, specifically the transition probabilities. However, this approach assumes that wood harvested during PCT is not extracted, which can be a limitation, though it was not a critical factor in this study.

Thinning can be explicitly modeled by decreasing the volume of a cell by one or two classes. In this analysis, thinning was not applied to avoid potential conflicts between thinning schedules and gap-cutting regimes. Final felling is modeled by resetting the volume and the age classes of a cell to zero.

Removals in felling are accounted for in standing volume units without calculating actual extractable volumes considering losses, log types, or changes in volume units.

Stand types

The analysis focused on spruce- and pine-dominated forests and included the most appropriate species-site combinations (from production point of view) for southern and southern-central Sweden. Pine stands were evaluated in site productivity classes 2, 3 and 4 and spruce stands in site productivity classes 4, 5, and 6. In each simulation, stands were initiated from bare land condition using the simulators' regeneration routines. In order to reduce the stochasticity of stand growth to negligible levels, stands were represented by 10 000 cells each, which corresponds to 62.5 ha with the currently applied cell size of 25 × 25 m.

MAI estimates for even-aged management

Maximum MAI for even-aged management was used as the reference for determining production losses during the transition period. It was estimated by simulating stand growth from a bare land condition, without thinnings, for a period of 150 years and finding the highest MAI and the corresponding rotation length for each of the studied stand types. The chosen time period was sufficient for reaching MAI culmination in all studied species and productivity combinations.

Gap-cutting

The basis for gap cutting simulation in LandSim is the felling of individual cells or groups of cells within a stand. Specified portions of the stand are felled at specified time intervals to form age cohorts. Furthermore, the conversion process can start at different ages of the original stand. Different gap cutting schemes could be formed by varying these aspects. Table 1 details relevant parameters of the process as well as a few variables relevant for assessing ecological and aesthetic impacts.

The conversion to a specific gap cutting scheme is fully determined by four parameters: Target Rotation Length (TRL), Time Between Cuttings (TBC), Number of Age Cohorts (NAC) and Conversion Timing (CT), for which different input values were applied. In addition, three important variables, resulting from the above parameters, were identified: Harvesting Cycle (HC), Minimum Age of the Oldest Cohort (MAOC), and Percentage of the stand Felled (PF).

When TBC equals TRL divided by NAC, harvesting proceeds over consecutive harvesting cycles without disrupting the regular sequence of cuttings. However, if TBC is shorter than TRL divided by NAC, the interval between the last cutting of a cycle and the first cutting of the next cycle deviates from TBC.

CT determines the timing of the first HC, which is the transition period, in relation to the final felling age of the original stand. MAOC is the age of the remaining oldest cohort after each cut when there is an equidistant succession of age

Table 1. Conversion parameters and features.

Parameter (p) or variable (v)	Abbreviation	Description	Values
Target rotation length for gaps (p)	TRL	Target rotation length for gaps after conversion	Equal to the rotation length of the even-aged reference MAI
Number of age cohorts (p)	NAC	Number of age cohorts in the stand after conversion	2, 3, 4, 5
Time between gap-cuttings (p)	TBC	Time interval between two consecutive gap-cuttings within a harvesting cycle	10, 15, 20
Conversion timing (p)	CT	The timing of the transition period in relation to the reference final felling age	CT = 0, 0.5, 1 end year = TRL + CT*HC start year = end year − HC
Harvesting cycle (v)	HC	The shortest duration in which the entire stand is harvested	HC = (NAC-1)* TBC
Minimum age of the oldest cohort (v)	MAOC	The minimum age of the oldest cohort at any given time	MAOC = HC
Percentage of the stand felled (v)	PF	Proportion of the stand area harvested in each cut	PF = 1 / NAC

cohorts. If there are longer intervals between cuttings of consecutive HC than between cuttings within a HC, then MAOC is determined by the age of the remaining oldest cohort after the last cutting of each HC.

Parameter input values

The target rotation length for trees after the transition period significantly affects the long-term production level of the entire stand. Since the same growth models were used for both gaps and the calculation of reference MAI under even-aged management, the rotation length for trees established in gaps was set equal to the even-aged reference rotation length. The number of age cohorts to be established during the transition ranged from two to five. More than five cohorts were deemed impractical given the rotation lengths and the intervals between cuttings, which were set at 10, 15, and 20 years. Intervals of 5 years were considered too short, as regeneration is unlikely to advance enough in that time to create meaningful differences between consecutive cohorts, while also increasing operational costs.

Three conversion timing options were considered:

1. **Early Conversion:** The transition has to be completed by the reference final felling age.
2. **Medium Conversion:** The conversion starts half of a harvesting cycle length before the reference final felling age, with split values rounded to full 5-year intervals.
3. **Late Conversion:** The transition begins at the reference final felling age.

These parameters resulted in 216 possible combinations. After excluding 36 combinations in which the intervals between the last cutting of a harvesting cycle and the first cutting of the next harvesting cycle were shorter than the interval between consecutive cuttings within the cycles, a total of 180 combinations were used for the simulations.

Production losses during the transition period

To determine production losses, the MAI at the end of the transition period was compared to the even-aged reference MAI for the specific stand type. The end of the transition period is defined as the point when the first full harvesting cycle is completed. At that time, an age-class structure is established, which then recurs at regular intervals. The cumulative production loss was expressed in cubic meters and as MAI equivalents, calculated by dividing by the even-aged reference MAI. MAI equivalents were used to enhance comparability and detect differences not only in absolute but also in relative losses across productivity classes.

Sensitivity analyses to potential growth reduction in the gaps

Additional calculations were conducted to estimate the impact of permanent productivity reductions due to gap cutting on production during the transition period.

Table 2. Productivity reductions in sensitivity analyses.

			Reduction by 1 prod. class		Reduction by 2 prod. classes	
Species	Prod. class	MAI under EA	MAI under GC	Reduction %	MAI under GC	Reduction %
Spruce	6	14.9	12.2	18	9.8	34
	5	12.2	9.8	20	7.0	43
	4	9.8	7	29	5.9	40
Pine	4	8.2	5.8	29	5.1	38
	3	5.8	5.1	12	2.6	55
	2	5.1	2.6	49	n.a.	n.a.

Note: MAI: mean annual increment, m^3/ha*year; EA: even aged management; GC: gap cutting.

Specifically, the productivity class of each harvested portion of the original stand was reduced by one and by two units, resulting in a MAI reduction of 12% to 55%, depending on species and productivity class (see Table 2).

Due to simulation constraints in LandSim – where standing volume is only accounted for once a cell becomes "established forest" at 10–20 years age – only conversion schedules with a transition phase of 30 years or more were considered. Additionally, productivity class 2 was excluded when the reduction involved dropping by two units.

To account for the variations in growth reduction percentages caused by productivity class changes, the cases were grouped into four categories based on actual growth reduction: "20%" (18% and 20%), "30%" (29% and 34%), "40%" (38%, 40%, and 43%), and "50%" (49% and 55%). The scenario with a 12% reduction was excluded from the analysis.

Results

Production losses due to harvest inoptimality during the transition period varied widely dependent on conversion parameters and site productivity, ranging from 16 m^3/ha (2.7 MAI) to 320 m^3/ha (32.7 MAI). The length of the harvesting cycle, which also determines the transition period length and the minimum age of the oldest cohort in the stand, proved to be the most influential factor. Losses increased as the harvesting cycle lengthened, both in absolute terms and relative to MAI (Figure 1). The increase was less pronounced between the harvesting cycles of 40 and 60 years. Reducing the intervals between cuttings with unchanged harvesting cycle length, which results in more age cohorts, led to slightly higher losses. This difference is more marked in absolute values than in MAI equivalents. For instance, a 40-year harvesting cycle with 10-year intervals between cuttings resulted in a significantly higher maximum loss compared to 20-year intervals within the same cycle length.

Conversion timing also had a substantial impact on the losses (Figures 2 and 3). Starting the conversion half of the harvesting cycle before the reference final felling age of the original stand was the least costly option, except for spruce in the highest productivity class. On such spruce sites, the cheapest option was staring the conversion at the final felling age, which is likely due to shorter rotations and harvesting cycles combined with the stands' growth pattern.

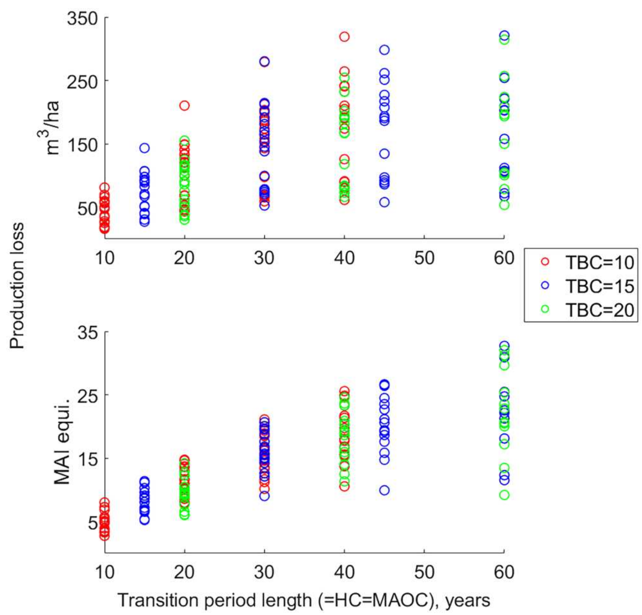

Figure 1. Production losses during the transition in m^3/ha over transition period (harvesting cycle) length, which also represents the minimum age of the oldest cohort (MAOC), and time between cuttings (TBC).

The early conversion option, which implies finishing the conversion by final felling age, generally resulted in losses between the medium and the late option. With decreasing productivity, the difference between the early and the medium timing was smaller. Pine in productivity class 3 deviated from the overall pattern with regard to both conversion timing and the overall loss level, suggesting this might be an artifact of the growth model.

Production losses in absolute values increased with site productivity, as shown in Figure 4. For longer harvesting cycles, the increase was larger than for shorter cycles. Observations for 60- and 45-year harvesting cycles were limited to productivity classes 2–4 and 2–5, respectively, because such harvesting cycle are too long in comparison with the shorter rotation lengths applied for higher productivity classes. In terms of MAI no clear trend could be observed.

A direct comparison between the two species was possible only on productivity class 4, showing similar mean values and a larger spread of losses for spruce.

Impact of reduced growth in gaps on production during the transition period

In addition to suboptimal harvest timing of parts of the original stand, slower regeneration and reduced growth in the gaps also can contribute to production losses during the transition period as well as after it. Dependent on the size of these growth-related losses, the harvest inoptimality-related losses may appear as more or less substantial or even negligible.

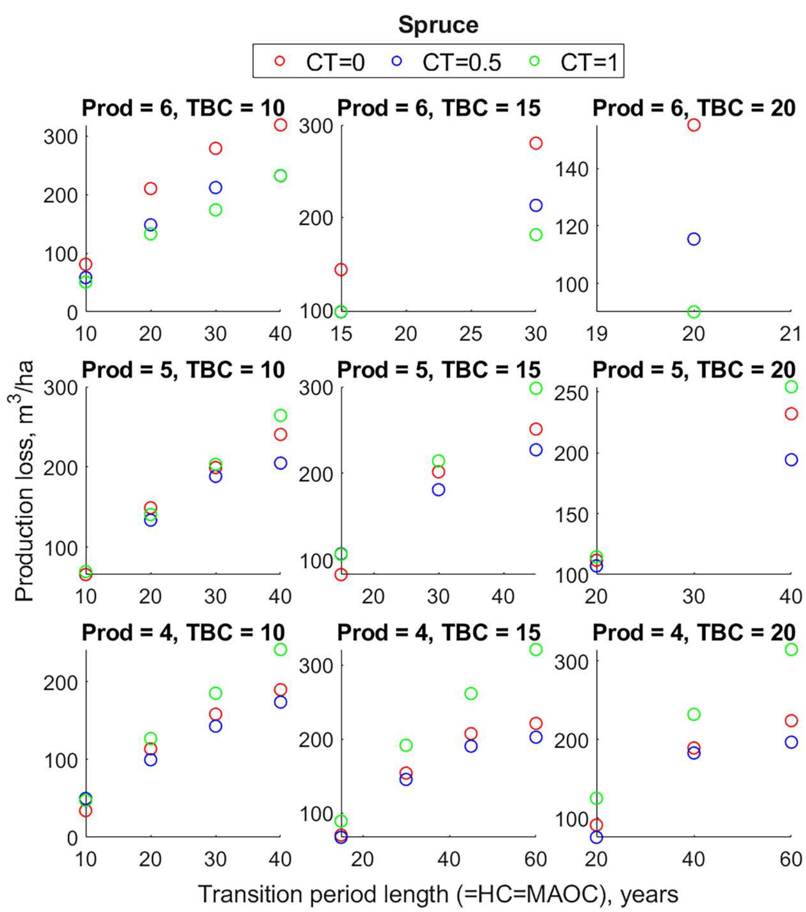

Figure 2. Production losses during the transition in m^3/ha over transition period (harvesting cycle) length, which also represents the minimum age of the oldest cohort (MAOC), productivity class, time between cuttings (TBC) and conversion timing (CT) in spruce stands.

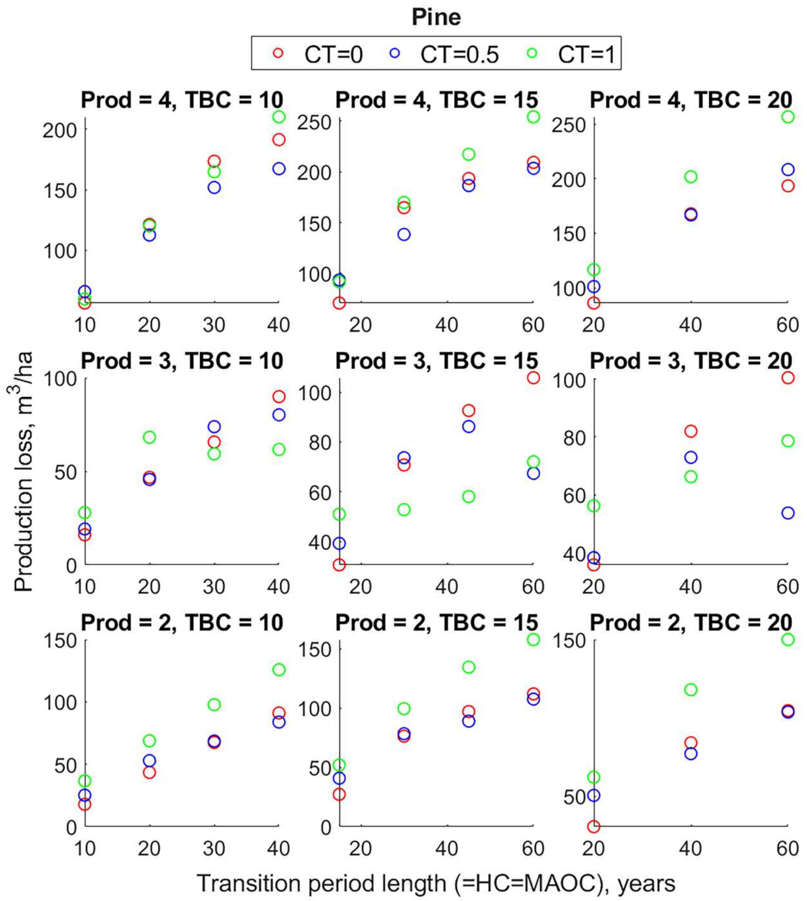

Figure 3. Production losses during the transition in m^3/ha over transition period (harvesting cycle, HC) length, which also represents the minimum age of the oldest cohort (MAOC), productivity class, time between cuttings (TBC) and conversion timing (CT) in pine stands.

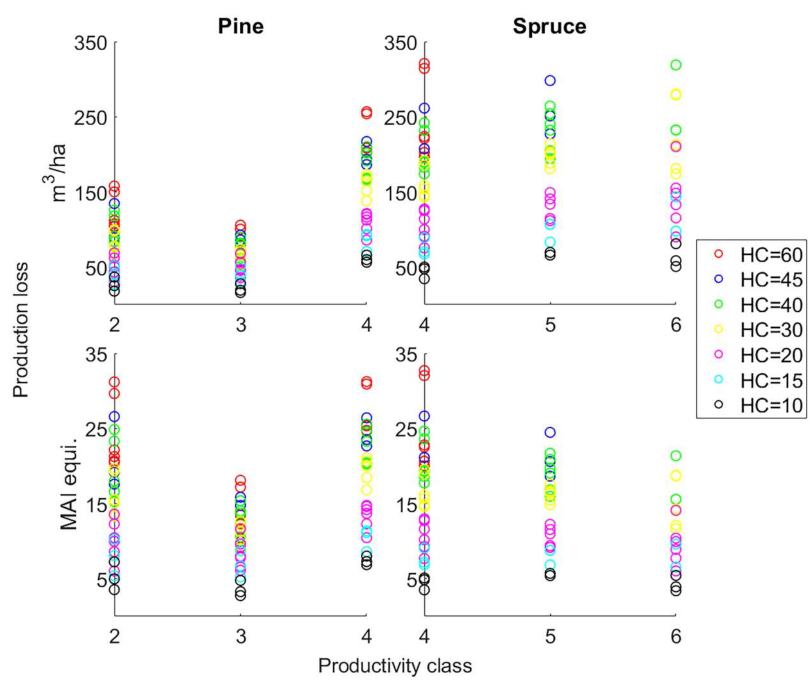

Figure 4. Production losses during the transition in m^3/ha and MAI equivalents over productivity classes, transition period length (harvesting cycle, HC) and species.

This was investigated through additional simulations with reduced productivity in the gaps. The proportion of the growth-related losses in the the total transition period losses increased with both the length of the transition period and the level of growth reduction (Figure 5). Longer intervals between cuttings within the same transition

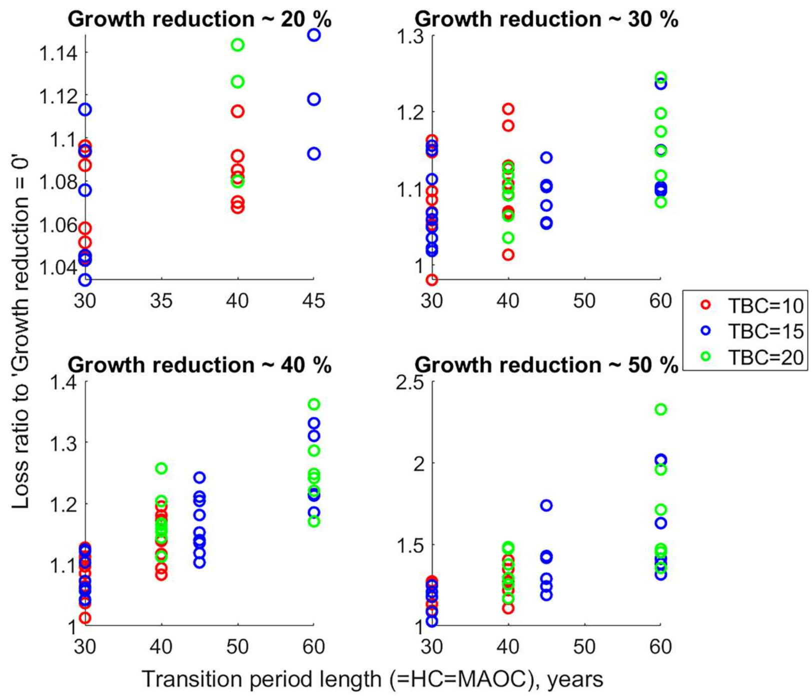

Figure 5. The ratio between production losses during the transition with and without growth reduction over transition period length (harvesting cycle, HC), minimum age of the oldest cohort (MAOC), and time between cuttings (TBC).

period (resulting in fewer future age cohorts), in most cases, slightly amplified the growth-related losses. This trend is the opposite of how the harvest inoptimality-related losses responded to changes in cutting intervals. For a 20% reduction in growth, the total losses increased by up to 15%. In some cases with a 50% growth reduction and a 60-year transition period, the total losses doubled. Overall, these findings indicate that in nearly all scenarios, the harvest inoptimality-related losses constitute the larger portion of the total production losses up to the end of the transition period.

Having assumed certain levels of permanent growth reduction in the gaps, we also can explore the pattern of accumulation of the production losses beyond the transition period. In Figure 6, the cumulative production loss is plotted over time for different levels of growth reduction in two cases, one with a longer and one with a shorter transition phase. The figure makes it obvious that even with the higher levels of assumed productivity reduction (40 and 43%) a substantial time is required, about 40 years in the more productive and about 70 years in the less productive case, after the end of the transition phase, to double the amount of the transition period losses, which further underlines the non-negligible size of the harvest inoptimality-related losses vis-à-vis the potential growth-related losses in the future.

Discussion

This study primarily examines the harvest inoptimality-related transition losses when converting from even-aged management to gap cutting. Gap cutting is a way to mitigate some of the negative social and ecological aspects of the current clear-cutting practices, and as such should be of interest to forest managers. Besides providing quantitative estimates, the study establishes the relationships between the target properties of the stand structure and the production losses of the transition period. Some of the relationships imply trade-offs between the transition period production and

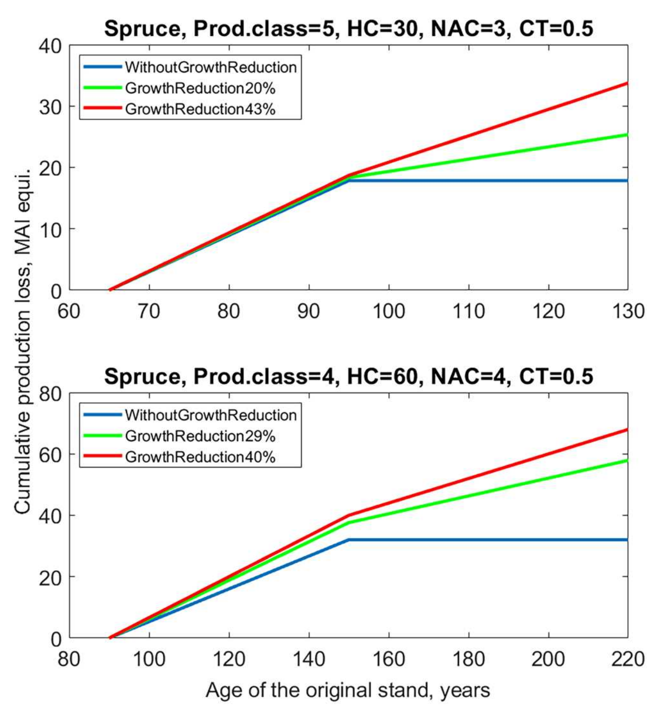

Figure 6. Cumulative production loss in MAI equivalents over time, productivity class, harvesting cycle (HC), number of age cohorts (NAC) and conversion timing (CT).

creating ecologically or otherwise desirable stand structures characterized by low proportion of stand area cleared at any one time and a permanently high age of the oldest cohort in the stand.

The approach used by the study is conceptually simple yet robust. It consists in applying an empirical even-aged growth model at a sub-stand level. This method enables the examination of a wide range of gap-cutting schemes, varying in cutting intervals and targets for the number of age cohorts to be established (30 per species-productivity combination, totaling 180). This is unusual as most tools, when used without access to the source code, offer far less flexibility in defining management programs (e.g. Reventlow et al. (2021) examined three conversion strategies starting at two ages). In addition, this study deliberately isolates harvest inoptimality-related losses from the uncertain growth-related losses. To achieve this, it assumes that the tree growth in the individual gaps follows the same pattern as in stands under standard even-aged management – except in the sensitivity analysis. This approach prioritizes a clear and well-supported answer to a specific question over speculative modeling of long-term consequences of conversion for which the available empirical models are insufficient.

Unfortunately, and as a consequence of the above, the findings of the study provide only a partial answer to the pressing practical question: how would the shift to gap-cutting affect production in the long-term? A full answer to this question remains elusive due to insufficient data on gap-size effects on growth across the diverse conditions in Sweden. The evidence to date is mostly limited to measurements from a few recently established experiments. Thus, early measurement from "checkerboard" felling experiments in Vindeln Experimental Forests north of Umeå, using 0.25- and 0.5-hectare gaps and artificial regeneration, show that seedling and retained tree growth varied depending on location in the gaps and retained patches, respectively (Erefur 2010; Borgstrand 2014). Sufficient natural regeneration and no edge effects were found in a similar experiment near Gällivare, further north, 10 years after harvest (Ackemo 2018). A survey of natural regeneration in a gap- and selective cutting experiment in Rogberga in Southern Sweden found abundant regeneration of spruce and birch in 10-, 20- and 30-meter large gaps 10 years after cutting (Svensson and Vargas 2024). However, long-term growth estimates in these stands are not yet possible.

Neither does international literature provide a conclusive answer, although regeneration outcomes in gaps appear generally positive. For example, Valkonen and Siitonen (2016) report from a gap cutting experiment in Norway spruce in northern Finland that 75% of naturally regenerated and 100% of planted patches had acceptable seedling density 11–13 seasons after cutting. The tree growth was somewhat slower in the smaller patches, but the overall regeneration result in the experiment was comparable with that of average clear-cuts. Similarly, Downey et al. (2018) observed promising natural regeneration of Norway sprue in gaps in a forest in southern Finland, though they advise against using gaps of more than 40 m in diameter. Hallikainen et al. (2019) reported equally successful Scots Pine regeneration from an experiment in northern Finland, with less than 10% of the plots lacking pine seedlings, though birch was present. In British Columbia, Coates and Burton (1997) found that growth increased with gap sizes up to 1000 square meters, beyond which there was little difference. The authors note that although smaller gaps promote natural regeneration, growth of young trees may be slower due to the hampering effects of the surrounding stand and that this could be an argument for using larger gaps and artificial regeneration.

To put the production loss estimates obtained in this study into perspective, and at least partially reduce the uncertainty concerning the accumulation of potential growth-related losses, a sensitivity analysis was performed considering various levels of growth reduction in the gaps. The analysis showed that under tested assumptions including up to 50% growth reduction and a transition period of up to 60 years, the harvest inoptimality-related losses, in most cases, by far exceeded the growth-related production losses during the transition period. Additionally, the results suggest that approximate adjustment factors could be applied to add the reduced growth effects to the harvest-inoptimality related losses during the transition period.

No economic analysis was carried out in the present study due to the limitation of the model. Several important differences to the present analysis in physical units could be anticipated. First, discounting of revenues from timber sales at a positive interest rate would likely favor earlier conversion. However, when comparing the options of starting the conversion of an older stand immediately versus clear-cutting followed by the conversion in the next generation, discounting would likely favor clear-cutting. Second, operation costs, both concerning harvesting and concerning planting (if planting in gaps is required), can be expected to be higher in the gap cutting alternatives. For example, Eliasson (2018) found that harvesting and forwarding costs were 15% higher in "checkerboard" cutting compared to a standard clear-cut. Moreover, these higher costs are not limited to the transition period; they would also apply to all future cuttings.

An option not considered in this analysis is the creation of mixed species even-aged stands prior to conversion, choosing species in a way that would match the conversion schedule. For instance, if a portion of a stand is scheduled for the first conversion cut at age 30, it could be more efficient to plant that portion with a species like birch instead of spruce. To be sure, several factors must be considered besides just the growth pattern of the species, such as the ease of changing back to the target species (consider, for instance, sprouting). Nevertheless, this strategy could enhance the economic performance of early conversion.

A further limitation of this study is that no effects of the silvicultural system change on the biotic or abiotic damages to the stands was considered. It can be surmised that the risk of wind damage would increase during the transition, particularly in its early stages. Another source of damage under gap cutting management could be the harvesting operations themselves. However, there is no specific reason to believe that during the transition period, especially in the early stages when there are no or few young trees, such damage would be more significant than in regular thinning operations.

In summary, the growth-related production losses and the damage to the remaining trees can only add to the harvest-inoptimality-related production losses, representing the minimum potential losses during the transition period – the optimistic scenario. The economic effects of factors like discount rates, operational costs, and regeneration costs create complex trade-offs. Thus, the conversion to a natural regeneration-based gap system could be economically beneficial despite inferior production capacity in physical terms. For instance, Reventlow et al. (2021) report positive economic outcomes at a 3% interest rate for some conversion scenarios using gap cutting in Norway spruce.

Beyond the production losses, converting to gap cutting at a landscape scale, depending on the cutting schedule, may result in a temporary increase in the growing stock during the transition period compared to continued even-aged management. However, the extent of this increase cannot be determined from the results of this study, as it depends also on the initial forest composition across the landscape. Additionally, the timing of the conversion plays a crucial role in influencing the production losses. At the landscape scale, there will likely be trade-offs between minimizing the losses and the speed at which the entire landscape is converted. To reduce the losses, it may be preferable to delay the conversion in older stands until the next generation after clear-cutting. Economic criteria might further support such strategy.

The top priority for future research on gap cutting is undoubtedly to strengthen the empirical foundation for model development by establishing new experiments and resurveying the existing ones. However, certain questions can already be explored within the current modeling framework. Conversion to gap cutting at the landscape scale and its impact on the landscape spatial pattern could be one of such questions. Another could be an economic evaluation of the time shifts in harvests during the conversion. Additionally, more complex conversion strategies – such as those involving temporary mixtures – could be analyzed in terms of both physical production and economic outcomes.

Conclusions

Harvest inoptimality-related production losses during the transition period can reach as much as 30 MAI equivalents when aiming to establish a stand structure with many cohorts separated by longer age intervals. In absolute terms, the losses increase with site productivity. There is a trade-off between the harvesting cycle, which is also the transition period length, and the transition period production. A structure with the same overall harvesting cycle length but fewer cohorts and longer intervals between cuttings tends to incur slightly lower transition period losses. This also translates into a trade-off between transition period production and the age of the oldest cohort in the stand, as well as the proportion of the stand cleared, at any one time after the conversion end. It is usually best to start the conversion half of the harvesting cycle length before the normal final felling age, and starting too early is less costly than starting too late. If regeneration and early growth in gaps fall short compared to the normal clear-cut regeneration, it further increases the losses. Nevertheless, even with significant reductions of the future growth in the gaps, production losses due to harvest inoptimality during the transition period remain a substantial component of the total cumulative production losses for several decades after the conversion.

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Appendix 1

Productivity, volume and species class definitions.

Table A1. Lower limits of productivity classes, m^3/ha*year.

Productivity class	1	2	3	4	5	6
Productivity, m^3/ha*year	0	2.5	5	7.5	10	12

Table A2. Lower limits of volume classes (m^3) for different productivity classes.

	Productivity class					
Volume class	1	2	3	4	5	6
1	0	0	0	0	0	0
2	18	35	40	53	81	76
3	45	83	98	129	191	182
4	79	143	173	227	325	314
5	117	206	256	335	464	453
6	155	268	341	443	598	589
7	191	325	421	546	719	714
8	224	375	496	639	824	825
9	253	418	563	722	913	921
10	319	511	714	907	1099	1124

"Spruce", in the context of the used model, refers to the class of plots (stands) in which the volume of conifers exceeds 70% of the total volume and the volume of Norway spruce is higher than the volume of Scots pine. "Pine" refers to the class of plots (stands) in which the volume of conifers exceeds 70% of the total volume and the volume of Scots pine is higher than the volume of Norway spruce.