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Abandoning conversion from even-aged to uneven-aged forest stands – the effects on production and economic returns

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ABSTRACT
There is growing interest in continuous cover forestry in Sweden. The historical domination of even-aged forest management means there is a need to focus on methods for transforming even-aged to uneven-aged stands. Practical conversion management today is highly adaptive, and the possibility of failures, such as persistent lack of tree recruitment, must be allowed for. We used simulations to evaluate various scenarios in which conversion management is introduced at different development stages in even-aged stands and then abandoned in favour of clear-felling. A shift towards an inverse J-shaped diameter distribution at the end of the simulations was most evident in northern Sweden and with an early introduction of conversion forestry. The largest losses were incurred in a scenario where the conversion management started with removing larger trees at pre-commercial thinning: it reduced the volume of production by up to 25% and, if clear-felled, resulted in a lower land expectation value than conventional management. Earlier decision to abandon conversion management reduced the losses, but the effect of timing was minor. In summary, the results indicate that conversion management could be started and abandoned without any major economic loss during the timeframe of a normal rotation.

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Introduction

In Sweden, there is growing interest in methods for continuous cover forestry (CCF). There are several drivers of this interest. At the political level, a new EU forest strategy for 2030 was announced by the European Commission in July 2021 (EC 2021). This strategy promotes uneven-aged forest management and a reduction in the use of clear-cutting, which is challenging given that only a quarter of Europe's forests are currently uneven-aged (Forest Europe 2020). At a national level, Sweden has set a political goal to increase the area of forest managed through CCF, and the Swedish Forest Agency has carried out several projects to gather, synthesize and communicate information and knowledge about CCF (c.f. Cedergren 2008; Appelqvist et al. 2021). Another driver is the voluntary market-based FSC certification: the new standard (FSC 2020) states that 5 per cent of forest land should be managed with special consideration to other values such as recreation, non-wood forest products and reindeer husbandry. This implies using some variant of CCF. Yet another driver is various environmental NGOs and environmental and forestry commentators putting a great effort in popularizing and advocating for CCF in the public debate, praising its potential benefits for biodiversity and ecosystem services. The small, non-industrial forest owners, who own about half the productive forest land in Sweden, appear to have been particularly receptive of these influences.

As forest management in Sweden and the rest of Europe has historically been dominated by even-aged management, the interest in shifting towards CCF has put a focus on methods for transforming even-aged into uneven-aged stands (Pommerening and Murphy 2004). In 88–94% of forests in Sweden over 80% of the standing volume is of one 20-year age class, with the remaining 6–12% indicating some degree of layering (Lundström 2008). Mason et al. (2022) have identified a lack of experience in transforming even-aged forests into more diverse structures as a major obstacle to wider adoption of CCF in Europe. Strategies for transforming even-aged stands into less regular structures have mainly been tested and discussed (O'Hara 2001; Schütz 2001) with respect to older even-aged stands and using methods such as thinning from above or target diameter harvesting (Sterba and Zingg 2001; Hilmers et al. 2020). These studies indicate the need for long-term engagement by forest managers to complete the transformation.

Sufficient recruitment has been pointed out as an important prerequisite for successful conversion (Hanewinkel and Pretzsch 2000). Currently, knowledge on recruitment processes in selection forests in Swedish conditions is scarce due to a low number of existing experiments and the scarcity of selection management in practice. Preliminary data from two conversion experiments in southern Sweden showed very low recruitment in conversion plots (Goude et al.

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2022). However, size stratification can also significantly contribute to a multi-layered structure. Lundqvist et al. (2019) reported on four full-storied Scotch pine (*Pinus sylvestris*) stands that developed from as few as two age-cohorts. In a modelling exercise, Drössler et al. (2014) used data from three experiments established in young forests to promote development towards multi-layer structure in first thinning as a starting point for simulations of stand structure development. Their simulations of stand structure development indicated that a multi-layered structure could be obtained in the boreal stands of central Sweden within 50 years, but not at the more southerly experimental sites. The projected stem wood production during the 50-year transition period was a third lower than would be achieved through conventional thinning regimes.

Economic assessments of the transformation of forest stands towards uneven-aged structure have yielded varying conclusions, depending on the starting point for the transformation and the interest rates applied. Price (2003) simulated the transformation of Welsh forests and found that it reduced profits except at low interest rates. This was mainly due to sub-optimal felling ages during the transformation. Vítková et al. (2021) compared simulations of transformation initiated at the thinning stage (52 years) and in a more mature stand (95 years). They found that only the transformation of the younger stand was economically promising, and only at interest rates over 2 per cent. Juutinen et al. (2018) simulated conversion from even-aged to uneven-aged Norway spruce stands in Finland. They found that uneven-aged forestry could be more profitable than even-aged forestry if interest rates were high, and if the initial state was a mature even-aged stand with a wide distribution of diameters. Even-aged forestry was in general more profitable if the initial state was bare land or a young forest. Note that none of these studies evaluated a case where the conversion management fails to produce structures capable of sustaining reasonable volume growth under continued application of selection fellings within reasonable time.

With only a few experiments and limited data available in northern Europe, there is a lack of reliable models and, consequently, silvicultural guidance for successful conversion of even-aged to uneven-aged forest. In this context, practical conversion management must be adaptive and allow for potential failures. It is easy to conceive that the longer there is no emergent multilayered/uneven-aged structure in response to conversion management, the higher will be the relative production and economic cost of ever completing the transformation. At some point, it might be not worthwhile to continue, even if, potentially, the multilayered/uneven-aged structure still could be achieved at some distant point in the future. Such development constitutes an abandoned conversion attempt, i.e. a period of management aiming at stand structure transformation and yet concluded by a clear-cut. We believe that managers who are inclined to engage in conversion management despite the uncertainty of success would benefit from this knowledge. Simulation tools could be one alternative to elaborate conversion forestry and the consequences on stand development and economy. There is still a need to develop and evaluate growth models for long-term simulations of conversion forestry and growth dynamics in uneven-aged stands. However, the available models allow us to explore the potential of promoting size stratification among the trees of the original stand at thinnings during the time span of conventional rotation in a clear-cutting system (ca. 100 years).

In this study, we used field data from 24 young stands to simulate alternative starting and abandonment time points for conversion management into multi-layered/ uneven-aged stands. The main aim was to assess the effects on production and economic returns if conversion management is initiated and later abandoned. We tested conversion management aiming both at size stratification among the existing trees, especially through pre-commercial thinning (PCT) design, and at creating conditions for the ingrowth of new trees by selection cuttings focused on the removal of largest trees.

Material and methods

Simulations of scenarios were carried out with Heureka PlanWise, part of the Swedish forest planning system Heureka (Wikström et al. 2011). Heureka PlanWise is a system with optimization functionality, which first simulates a number of treatment alternatives per stand and then selects the best stand treatment alternative according to the objective function and restrictions defined by the user. Forest growth is modelled in 5-year steps. In this study, the input data came from an inventory of young stands, to ensure a realistic starting point for the simulations. All treatments and their financial outcomes were simulated in Heureka, apart from PCT.

Inventory of regenerations

An inventory of young stands was carried out in 2018 at three locations in Sweden. These were denoted as northern, central and southern areas (Figure 1 and Table 1). Data about clear-felled areas was obtained from Sweden's National Forest Agency, and 9, 5 and 10 stands regenerated with Norway spruce (*Picea Abies* (L.) Karst.) were selected within the northern, central and southern areas respectively. Clear-felling of these stands was estimated to have taken place in 2009–10 in the northern area, 2010–12 in the central area and 2012–13 in the southern area. Measurements were carried out on 10 systematically distributed circular plots within each stand. All trees judged to have been planted were measured within a radius of 5.64 m, while a radius of 1.78 m was used for naturally regenerated trees. The height of each tree was measured to the nearest 10 cm, and tree species was also recorded. Data describing site characteristics, as per the Swedish site quality evaluation system (Hägglund and Lundmark 1977), was recorded for each plot. The site index (H100) for spruce was estimated for each plot based on site factors. The average site and stand characteristics of the plots included in the inventory are presented in Table 1. The tree-wise data and site parameters from the inventory in 2018 were used as input to the simulations.

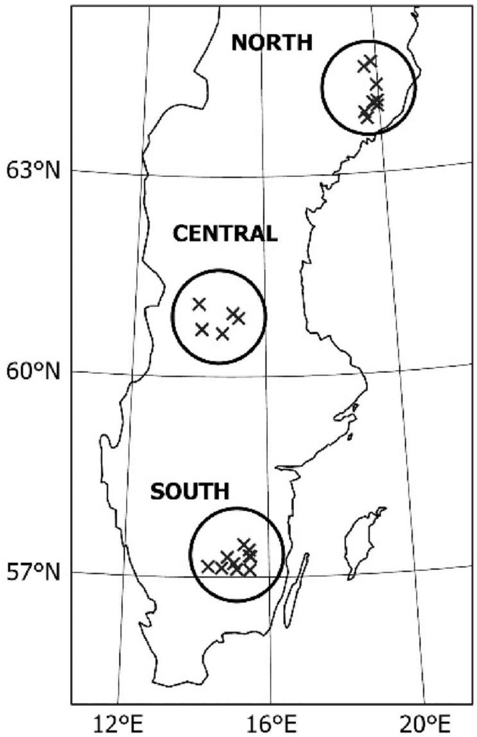

Figure 1. Location of the inventoried stands used as input to the simulation. The three clusters of stands were located in northern (9 stands), central (5 stands) and southern Sweden (10 stands).

Simulations

Simulation of PCT

Three different alternatives of PCT were simulated:

- PCTBAU: Traditional PCT. The probability of becoming a future main stem was estimated using functions described in Elfving (2010a). The functions were based on data from the HUGIN young stand survey (Elfving 1982), reflecting common PCT practices of the 1970s–1980s. The dominant strategy during this period was to promote main stems among vigorous conifers. Separate functions were used for conifers and broadleaves. The probability of being selected as a main stem was calculated for each tree in the data set. Main stems after PCT were selected by generating random numbers.
- PCTJ: PCT aimed at an inverse J-shaped dimension distribution with a decreasing number of stems with increasing size classes. As some trees were below 1.3 m (no DBH), height was used as measure of tree dimension. All spruce trees were divided into four size classes according to tree height, increasing from class 1 to 4. The width of each class was $H_{max}/4$, where H_{max} was the height of the largest tree. The aim was to achieve stem numbers following PCT at a ratio of 0.54, 0.27, 0.13 and 0.07 for classes 1, 2, 3 and 4 respectively.
- PCTU: PCT aimed at a uniform distribution with equal numbers of trees in all size classes. All spruce trees were divided into four size classes according to tree height, increasing from class 1 to 4. The width of each class was $H_{max}/4$, where H_{max} was the height of the largest tree. The aim was an equal number of stems in all size classes following PCT.

The selection of main stems was carried out plot-wise within each stand. All strategies aimed to leave 1800 trees ha^{-1} after PCT. Main stems were selected from the spruce available, including both planted and naturally regenerated trees. If there was not enough spruce on the plot, complementary main stems were selected first from Scots pine (*Pinus sylvestris* L.) and then birch (*Betula pendula* Roth and *Betula Pubescens* Ehrh.). For all alternatives, the selection of main stems of pine and birch was carried out as per the TRAD alternative.

Simulation of growth and treatments in Heureka

Stand development in Heureka (Version 2.16) is estimated using empirical models describing growth, ingrowth and mortality (Elfving 2010a; Fahlvik et al. 2014). The system requires input data about the site (e.g. latitude, site index, vegetation type), stand (age, management history) and trees (tree species, height or diameter).

Growth modelling is separated into two stages in Heureka, with a different set of models being used for young and established stands. The transition from young to established forest occurs at a stand height of 6–7 m. In Heureka, height

Table 1. Stand characteristics of the inventoried regenerations used as input to the simulations. Height is the arithmetic mean tree height. Height and tree species distribution refers to the total number of stems.

								Tree species distribution (%)			
Region	No. of stands		Site index	Age (yr)	No. of spruce trees ha^{-1}	Total no. of trees ha^{-1}	Height (m)	Spruce	Pine	Birch	Other
North	9	Mean	17.9	9.4	2500	24,100	0.9	14	5	49	31
		Min	14.3	9	1100	6800	0.7	5	1	10	0
		Max	20.8	10	4600	39,700	1.3	25	14	75	81
		SD	2	0,5	1000	9500	0.2	7	5	25	26
Central	5	Mean	24.1	8.8	1500	5700	1.1	30	26	33	11
		Min	21.5	8	800	4700	0.8	18	2	10	0
		Max	25.6	9	1900	7300	1.2	43	41	44	35
		SD	1.6	0.4	400	1100	0.2	10	15	14	15
South	10	Mean	29	6.9	3700	19,800	1.1	25	10	52	13
		Min	24.7	6	2100	6600	0.8	14	1	25	1
		Max	31.8	7	6100	30,000	1.5	51	23	71	43
		SD	2.2	0.3	1500	7300	0.2	11	7	15	12

development in young stands is estimated, while stand development of established forests is based on basal area growth functions.

In the present study, tree-wise height increment models and diameter-height models by Nyström and Söderberg (1987) were selected to estimate development in young stands. Basal area development in established stands was estimated using a combination of stand-wise and tree-wise growth models, which is the default in Heureka. The stand-wise model (Elfving 2010b) determines the level of growth while the tree-wise models (Elfving 2010c) are used to distribute growth to single trees (Fahlvik et al. 2014). Stand-wise basal area growth is estimated by a single model. The model includes independent variables describing the proportion of all conifers, Scots pine, specifically and birch. Tree-wise growth was estimated using separate models for different tree species. The tree-wise models include distance-independent competition indices. In height increment models for young stands the sum of squared heights of trees larger than a subject tree is used to express competition relative to social status. Accordingly, the basal area of trees larger than the subject tree is used as an expression of competition in the tree-wise basal area growth models (Elfving 2010c). The models for young stand development are based on the nation-wide HUGIN young stand survey (Elfving 1982). The growth models for established forest are based on data from permanent plots within the Swedish National Forest Inventory (NFI) and are representative of all forest land in Sweden (Elfving 2010a).

Mortality and the influence of damage on single tree growth in young stands were modelled according to Näslund (1986). Mortality in established stands was estimated using models by Elfving (2014). The models are based NFI data and estimate single tree mortality each 5-year period as a function of tree (BHD, basal area of larger trees), stand (e.g. dominant height and stand age) and site properties (e.g. site index, soil moisture) as well as thinning history. Ingrowth of trees with a diameter at breast height (DBH) $\geq$ 4 cm in established stands was estimated following Wikberg (2004). The models are based on the development of small trees within permanent NFI plots and estimates the abundance and size of ingrown trees each 5-year period as a function of the over-story (basal area and species), stand age and site properties (e.g. site fertility, soil moisture).

The default configurations in Heureka were used for thinnings and selection cuttings (Heureka Wiki 2022). The thinning form is defined by setting the relationship between different tree size classes. First, the trees are divided into small (A) and large (B) trees according to the quadratic mean diameter. Each group is subdivided into two groups of smaller (A1, B1) and larger (A2, B2) trees. The distribution of removal between each pair of smaller and larger trees is controlled by setting a value of between −1 and 1, where 0 indicates uniform removal,<0 greater removal of small trees and >0 greater removal of large trees. The relationships A/B, A1/B1, A2/B2 were set to −0.2, −0.1 and −0.1 respectively, for thinning from below. The corresponding settings for selection cuttings were 0.1, 0, 0.2 respectively, resulting in greater removal of larger trees. The minimum diameter of cut trees for conventional thinning was 7 cm and for selection felling 8 cm.

Economic parameters

Planting density was assumed to be 2000 spruce plants ha^{-1} in northern Sweden and 2300 ha^{-1} in central and southern Sweden. The regeneration cost, including soil preparation and plantation, was set to 710, 1050 and 1050 € ha^{-1} for northern, central and southern Sweden respectively (Eliasson 2022).

Time consumption at PCT was based on time studies of motor-manual PCT (Bergstrand et al. 1986; SLA Norr 1991). The cost for motor-manual PCT was 33 € h^{-1}.

Costs for felling were calculated from productivity norms for thinning (Brunberg 1997) and final felling (Brunberg 2007). Forwarding costs were based on productivity norms as set out by Brunberg (2004). The costs for forwarders and harvesters were 66 and 94 € h^{-1} respectively at thinning, and 75 and 104 € h^{-1} at final felling.

The price list for spruce timber included two quality classes with a maximum price of 59 € m^{-3} for class 1 and 40 € m^{-3} for class 2 timber. Four quality classes were used for pine timber, with a maximum price of 45 € m^{-3} for class 1 and 32 € m^{-3} for class 4 timber. The minimum top diameter of timber logs was 14 cm, and pricing varied with the dimension of the logs. The distribution of spruce timber logs across classes was 87% class 1 and 13% class 2. For pine timber, the distribution was 57% class 3 and 12% class 4, with the remaining 31% split between class 1 for butt logs and class 2 for middle and top logs. No timber assortment was used for other tree species.

The price of pulpwood was 25 and 29 € m^{-3} for spruce and birch respectively and 23.5 € m^{-3} for other tree species. The minimum top diameter of pulpwood was 5 cm.

Simulation and evaluation of conversion management scenarios

Five management scenarios were simulated:

- BAU: Clear-felling system. PCT aimed at promoting dominant and co-dominant main stems of spruce (PCTBAU). Two commercial thinnings (CT) from below according to thinning guidelines provided by the National Forest Agency of Sweden (Skogsstyrelsen 1985a, 1989).
- CPCTJ: Conversion management starting at PCT. PCT aimed at an inverse J-shaped dimension distribution, with decreasing numbers of stems with increasing size classes (PCTJ). All further cuttings were carried out as selection cuttings.
- CPCTU: Conversion management starting at PCT. PCT aimed at a uniform dimension distribution (PCTU). All further cuttings were carried out as selection cuttings.
- CT1: Conversion management starting at the time of first CT in BAU. PCT identical to BAU. All further cuttings were carried out as selection cuttings.
- CT2: Conversion management starting at the time of second CT in BAU. PCT and first CT identical to BAU. All further cuttings were carried out as selection cuttings.

In the first step, the inventory data was input to Heureka and stand development was simulated up to a mean height of dominant trees of ca. 3 m, at stand level (Figure 2). Next, tree-wise output was collected from Heureka, and PCT treatments (PCTBAU, PCTJ and PCTU) were simulated in the statistical program R (R Core Team 2022). Tree data following PCT was then returned as input to Heureka for further simulations.

In the second step, preliminary simulations were carried out to determine the timing and other parameters of thinnings and selection cuttings for each stand and scenario. The thinning regime in BAU was set according to the thinning guidelines provided by the National Forest Agency of Sweden (Skogsstyrelsen 1985b, 1989) and comprised two thinnings. The performance of the first commercial thinning in CT2 was identical to the first thinning in BAU. The timing of the first selection cutting in CT1 and CT2 was identical to the timing of the first and second commercial thinning in BAU, respectively. With these parameters fixed, more model runs were done to determine the timing and other parameters of all the following selection cuttings in CT1 and CT2 and all the selection cuttings in CPCTJ and CPCTU. The selection cutting program followed two alternative guidelines related to conventional thinning. The target basal area after cutting was set to 75% (T75) and 60% (T60) of the basal area in thinning guidelines provided by the National Forest Agency of Sweden (Skogsstyrelsen 1985b, 1989), respectively (Figure 2). The target basal area used as guidance to perform thinnings was set to 85% (T75) and 70% (T60) compared to conventional guidelines. The rationale for reducing basal area limits compared to traditional guidelines was to enhance structural diversity by stimulating recruitment of trees and by influencing stand structure through selection.

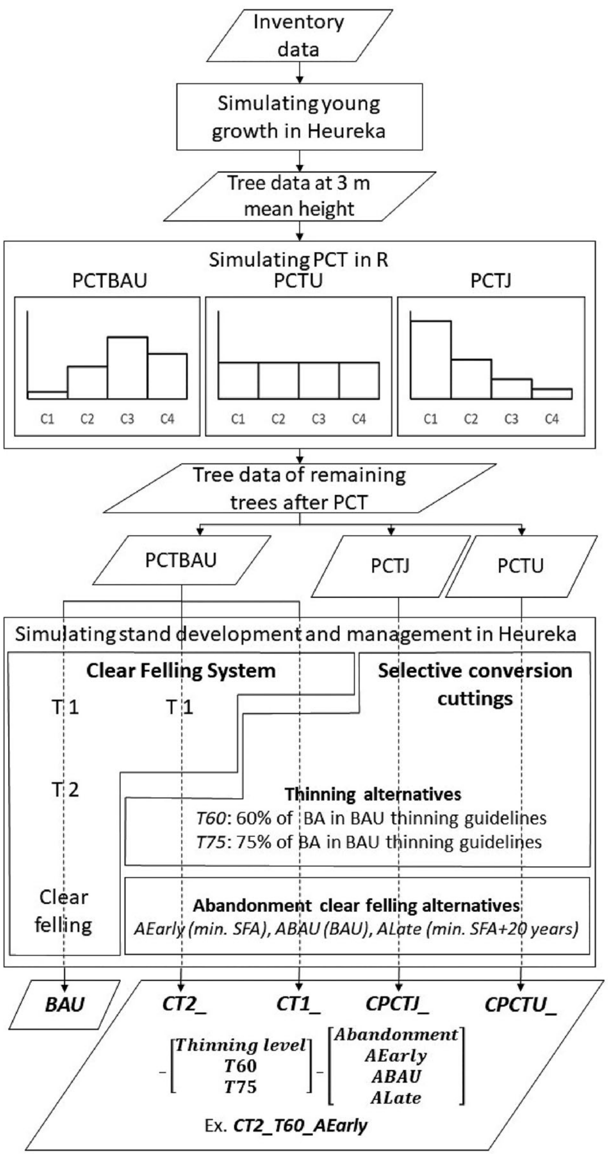

Figure 2. The structure of the scenario simulation. Pre-commercial thinning aimed at leaving larger trees (PCTBAU), a uniform distribution (PCTU) or an inverse J-shaped distribution (PCTJ). The scenarios simulated in Heureka were traditional management (BAU) with two commercial thinnings (CT 1, CT 2) and clear felling, conversion to selection forestry (SF) initiated at PCT (CPCTJ, CPCTU) or at the time of first (CT1) or second (CT2) commercial thinning in BAU. Scenarios for basal area after thinning were 75% (T75) and 60% (T60) compared to conventional guidelines (Skogsstyrelsen 1985a, 1989). Scenarios for abandonment of conversion forestry was continuous SF and clear felling at the same age as in BAU (ABAU), ending SF at minimum cutting age according to Swedish forestry act (SFA) and clear felling at max LEV (AEarly) and ending SF at minimum cutting age +20 years and clear felling at max LEV (ALate).

In the third step, the concluding phase of each scenario was designed. In the BAU scenario, only the timing of the clear cutting had to be determined. In the scenarios with conversion management, the timing of abandonment of the conversion management and the timing of the clear cutting had to be determined both. Note that the abandonment of the conversion management here means only the prohibition of continued selection cuttings and not necessarily an immediate clear-felling. The thinnings and the selection cutting until the abandonment were imported as per previous step. Three different options for abandonment of conversion management were simulated (Figure 2):

- AEarly: The decision to abandon conversion management was taken at the minimum allowable clear-felling age according to the Swedish Forest Act (Skogsstyrelsen 2023). No further selections cuttings were carried out after this point.
- ALate: The decision to abandon conversion forestry was taken 20 years past the minimum allowable clear-felling age according to the Swedish Forest Act (Skogsstyrelsen 2023). No further selections cuttings were carried out after this point.
- ABAU: The decision to clear-fell conversion forestry coincide with the timing of clear-felling in the BAU scenario (see below concerning the clear-felling timing in BAU). Conversion forestry continued to a minimum of 5 years before clear-felling.

The timing of clear-felling was optimized in Heureka within the timeframe allowed by each scenario and abandonment option with the objective of maximum LEV_{BAU} (Eq. 1) and LEV_{CONV} (Eq. 2) in the BAU and the conversion scenarios, respectively. Exceptions were the conversion scenarios with ABAU abandonment option where the clear-felling timing was imported from the BAU scenario.

Land expectation value (LEV) for BAU was calculated according to:

$$LEV_{BAU} = \left(\sum_{t=0}^{u} R_t \times (1+r)^{-t} \right) \times \frac{(1+r)^u}{(1+r)^u - 1} \quad (1)$$

where R is the net income from regeneration, PCT, thinnings or final felling; t is the time since last final felling (years); u is the rotation length (years) and r is the interest rate.

The economic calculations assumed that management would return to a clear-felling system following clear-felling under CPCTJ, CPCTU, CT1 and CT2. LEV for these scenarios was calculated as

$$LEV_{CONV} = \left(\sum_{t=0}^{u_{CONV}} R_t \times (1+r)^{-t} \right) + (LEV_{BAU} \times (1+r)^{u_{CONV}}) \quad (2)$$

where R is the net income from regeneration, PCT, thinnings, selection cuttings or final felling; t is the time since last final felling (years); u_{CONV} is the time of abandonment by clear-felling (years); LEV_{BAU} is the LEV for BAU and r is the interest rate.

Data about stand development and the costs and incomes from cuttings were generated using Heureka. Separate simulations were carried out for interest rates of 1%, 2% and 3%.

Mean annual volume increment (MAI) was calculated for the period between the start of the simulation and final felling. MAI included standing volume, removals (incl. PCT) and mortality.

Kurtosis and skewness of diameter distributions after PCT and at clear-felling was calculated in the statistical program R.

Results

No management strategy achieved a distinct inverse J-shaped curve over the simulated period. PCTJ showed the greatest average proportion of small trees and the greatest positive skewness after PCT (Figure 3). PCTBAU resulted in a greater proportion of large trees and the greatest mean diameter. The most even distribution amongst size classes and the lowest value of kurtosis at PCT were achieved in PCTU. The proportion of individual trees retained across all simulated PCT alternatives was, on average, 76%, 95% and 82% for the southern, central and northern study areas respectively.

Compared to BAU, conversion strategies with the abandonment option ABAU resulted in a more positively skewed dimension distribution at the time of final felling (Figure 4). This effect was most pronounced in strategies with early introduction of conversion management and heavy selection cutting (T60) but the difference between options CPCTJ_T60_ABAU and CPCTU_T60_ABAU was only minor. The average proportion of the total stem number at final felling (DBH > 4 cm) consisting of simulated ingrowth was greatest for CPCTJ_T60_ABAU and CPCTU_T60_ABAU (47%) and lowest for BAU (23%).

The characteristics of thinnings and selection cuttings, over the period from the start of the simulations to the time of final felling, are presented in Table 2. Selection cuttings in Heureka resulted in an average basal area of 12 and 15 m^2 ha^{-1} (84 and 126 m^3 ha^{-1}) after removal in CPCTJ_T60_ABAU in northern and southern Sweden, respectively. The corresponding figures if conversion was initiated at the time of the second conventional thinning (CT2_T60_ABAU) was 18 and 20 m^2 ha^{-1} (163 and 211 m^3 ha^{-1}), respectively.

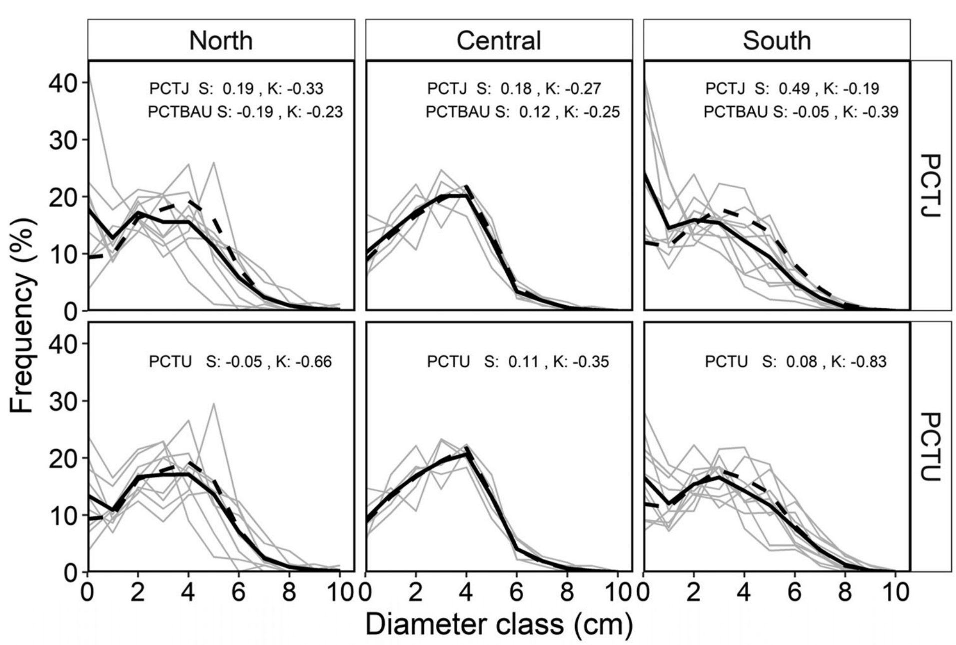

Figure 3. Diameter distribution after different conversion treatments at pre-commercial thinning (PCT). The distribution is presented for each stand (grey line) and as an average for each region (black solid line). In addition, the average diameter distribution after traditional PCT (black dashed line) is presented as a reference. The frequency refers to the relationship between the stem number in each class and the total number of stems. Average skewness (S) and kurtosis (K) is presented for each treatment and region. For abbreviations of PCT alternatives, see Figure 2.

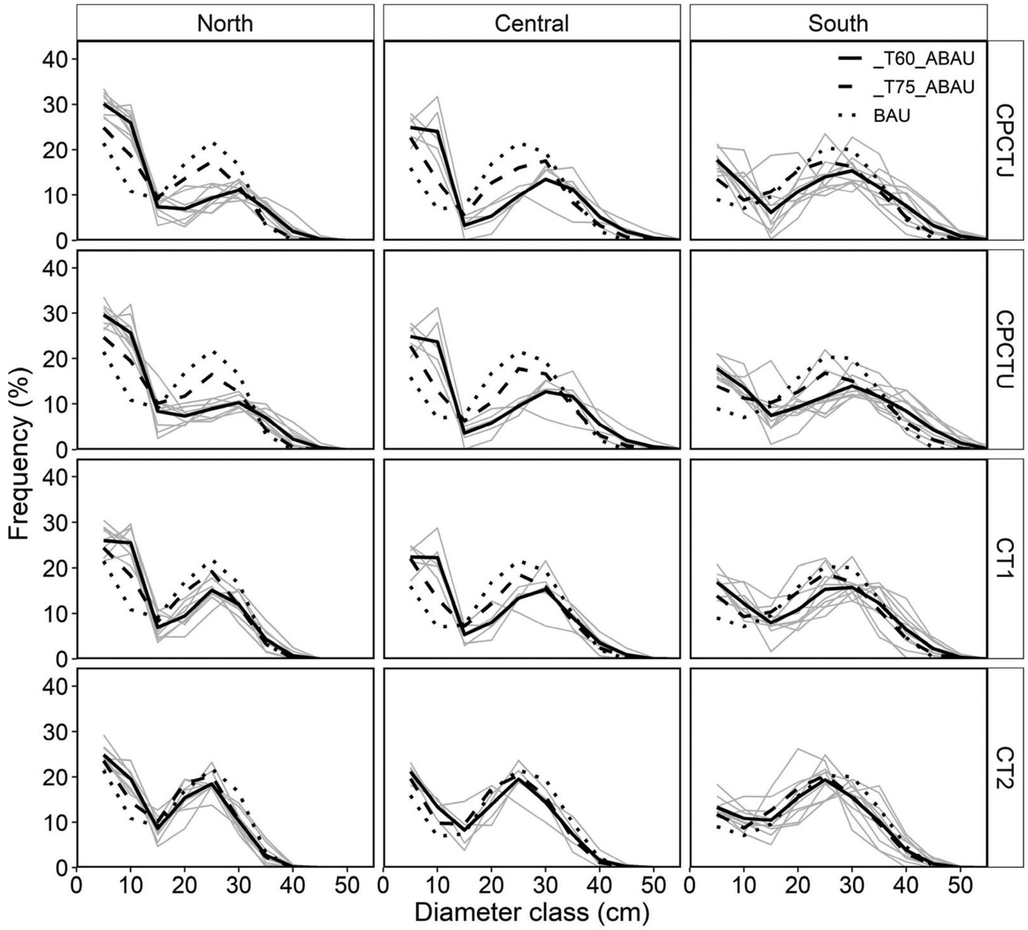

Figure 4. Diameter distribution for each region and conversion strategy at the time of final felling in abandonment scenario ABAU. Average (black solid line) and stand-wise (grey solid line) distributions are presented for selection cutting scenarios T60. Average distribution is also presented for selection cutting scenarios T75 (dashed line) and traditional BAU (dotted line). The frequency refers to the proportion of the total stem number within each diameter class. For abbreviations of conversion strategies, see Figure 2.

Abandonment scenario AEarly resulted in the lowest number of selection cuttings, whereas ALate had the greatest number of selection cuttings and the longest rotations, in average (Table 2).

Compared to BAU, conversion to selection cutting resulted in reduced MAI during the simulation period. This difference was greater for early conversion than for conversion at a later stage and greater for cutting alternative T60 compared to T75 (Figure 5). MAI compared to BAU was, on average, 25% and 5% lower in CPCTJ_T60_ABAU and CT2_T60_ABAU respectively. MAI was slightly greater (4%) for CPCTU_T60_ABAU compared to CPCTJ_T60_ABAU. There were only minor differences in MAI between abandonment options, with the lowest average production found for ALate.

In general, early introduction of conversion and lower target basal area after cutting resulted in reduced LEV compared to BAU, and the difference depended on the interest rate (Figure 6). An interest rate of 3% resulted in a negative LEV for all scenarios in Northern Sweden. On average BAU generated the greatest LEV at an interest rate of 1%, while the best performing conversion strategies became equally profitable at higher interest rates. CPCTJ produced a lower LEV on average than the other conversion strategies in southern Sweden. LEV varied considerably between different stands within regions, mainly due to differences in site fertility and production. However, the trend in LEV for each strategy was generally consistent across stands within a region. The influence of abandonment option on LEV was minor. AEarly produced in average a greater LEV than abandonment at a later decision point in ALate at 1% interest rate.

The extracted volume of timber and pulpwood at final felling was greater for BAU than for other strategies at abandonment option ABAU (Table 3). BAU also resulted in the greatest total volume of extracted timber over the simulation period, while the volume of pulpwood was equal to that produced by the conversion treatments. Further, BAU produced a greater mean diameter (Dg) of extracted logs at final felling, and slightly greater total amount of harvested trees overall, than the conversion strategies. This difference tended to be greater with early initiation of conversion forestry and with lower target basal area after selection cutting.

Discussion

The long-term target of the conversion strategies in this study was to achieve a spruce dominated full-storied forest with inversely J-shaped diameter distributions (cf. Ahlström and Lundqvist 2015; Lundqvist 2017). In young forests, initiating

Table 2. Characteristics of thinnings, selection cuttings and rotation length for each scenario, abandonment option and interest rate over the period from start of simulation to time of final felling. Average is presented for number of conventional thinnings or selection cuttings (N), basal area before (B_{bef}, m^2 ha^{-1}) and after (B_{aft}, m^2 ha^{-1}) removal and rotation length (RL, year). For abbreviations of scenarios and abandonment options, see Figure 2.

						Interest rate (%)											
						1				2				3			
	Rel.	Aband.	Conventional thinnings			Sel. thinnings				Sel. thinnings				Sel. thinnings			
Strategy	TG	timing	N	B_{bef}	B_{aft}	N	B_{bef}	B_{aft}	RL	N	B_{bef}	B_{aft}	RL	N	B_{bef}	B_{aft}	RL
BAU			2	31	24				95				84				77
CPCTJ	_T60	_AEarly				3.6	21	13	88	3.6	21	13	84	3.6	21	13	78
CPCTU						3.5	21	14	88	3.5	21	14	82	3.5	21	14	78
CT1						3.0	26	16	93	3.0	26	16	86	3.0	26	16	79
CT2			1	28	22	1.2	33	20	96	1.2	33	20	88	1.2	33	20	77
CPCTJ	_T75	_AEarly				2.9	25	17	95	2.9	25	17	86	2.9	25	17	77
CPCTU						2.9	25	17	93	2.9	25	17	85	2.9	25	17	75
CT1						2.8	28	19	96	2.8	28	19	85	2.8	28	19	77
CT2			1	28	22	1.2	33	23	96	1.2	33	23	86	1.2	33	23	76
CPCTJ	_T60	_ALate				5.3	21	14	100	5.3	21	14	100	5.3	21	14	99
CPCTU						5.1	21	14	96	5.1	21	14	96	5.1	21	14	96
CT1						4.5	24	16	97	4.5	24	16	96	4.5	24	16	96
CT2			1	28	22	2.9	28	18	97	2.9	28	18	96	2.9	28	18	94
CPCTJ	_T75	_ALate				4.5	25	18	98	4.5	25	18	96	4.5	25	18	96
CPCTU						4.5	26	19	97	4.5	26	19	96	4.5	26	19	96
CT1						4.2	27	20	96	4.4	25	17	95	4.2	27	20	94
CT2			1	28	22	2.6	31	22	97	2.6	31	22	92	2.6	31	22	91
CPCTJ	_T60	_ABAU				5.0	21	14	95	4.2	21	14	84	3.8	21	13	77
CPCTU						5.0	21	14	95	4.2	21	14	84	3.8	21	14	77
CT1						4.4	24	16	95	3.6	25	16	84	3.0	25	16	77
CT2			1	28	22	2.9	28	18	95	2.2	30	18	84	1.6	32	19	77
CPCTJ	_T75	_ABAU				4.4	25	18	95	3.6	25	18	84	3.3	25	17	77
CPCTU						4.4	26	18	95	3.7	25	18	84	3.4	25	18	77
CT1						4.0	27	20	95	3.5	27	20	84	2.9	28	19	77
CT2			1	28	22	2.8	31	22	95	2.1	32	22	84	1.6	33	23	77

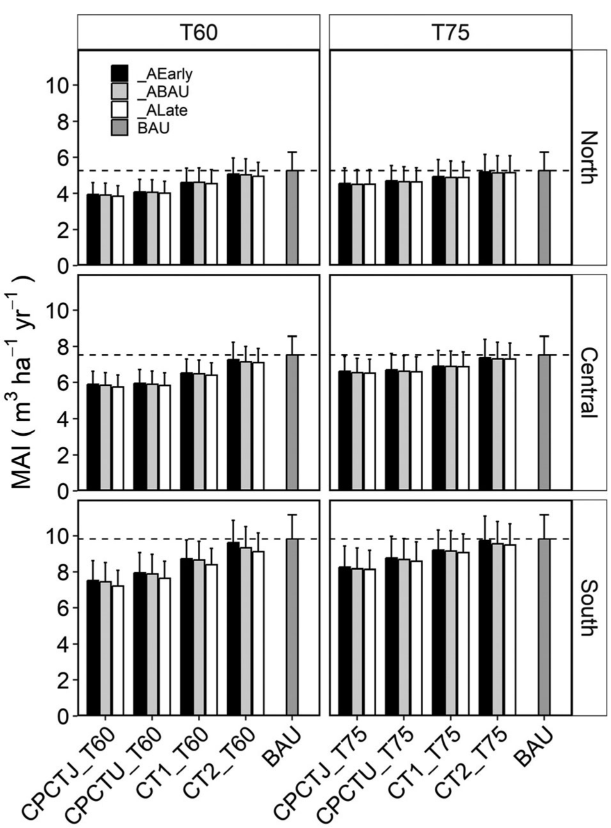

Figure 5. Mean annual volume growth for different abandonment options AEarly (black), ALate (white) and ABAU (grey). In addition, the volume production of a traditional clear-cutting system (BAU) is presented (dark grey bar, dashed line). Volume production was calculated separately for stands located in northern, central and southern Sweden and for selection cutting scenarios T60 and T75. Simulations were based on an interest rate of 2%. For abbreviations of strategies and scenarios, see Figure 2.

conversion by applying different PCT had an immediate but moderate influence on stand structure. Findings of greater positive skewness of the diameter distribution in PCTJ and a more negative value of kurtosis in PCTU were in line with the intended outcome. The target density of 1800 spruces after PCT was chosen to be sparse enough to allow for some selection but dense enough to ensure long-term production and to facilitate size differentiation among the remaining trees. However, the common practice of planting 2000–2500 stems per hectare in spruce regenerations, combined with early mortality, restricted the possibilities for influencing stand structure at PCT by selecting stems. This was most obvious in the central region where the average number of spruces was below the target density after PCT. Consequently, almost all individual trees selected as main stems were identical across all PCT alternatives within the central region.

Even by the end of the simulations, the target of an inverse J-shaped diameter distribution was not achieved for any conversion strategy. The earlier conversion was introduced in the simulations and the lower target basal area was after selection cutting, the greater the discrepancy in stand structure in the mature stand, compared to BAU. A shift towards a diameter distribution characterized by a decreasing stem number with increasing dimension was most pronounced when the conversion was introduced at PCT. The diameter distribution of ingrown tree peaked at less than 10 cm for all management strategies, resulting in a bimodal distribution by the end of the simulations.

The timing seems to have been more important than the choice between PCT strategy PCTJ and PCTU in terms of the

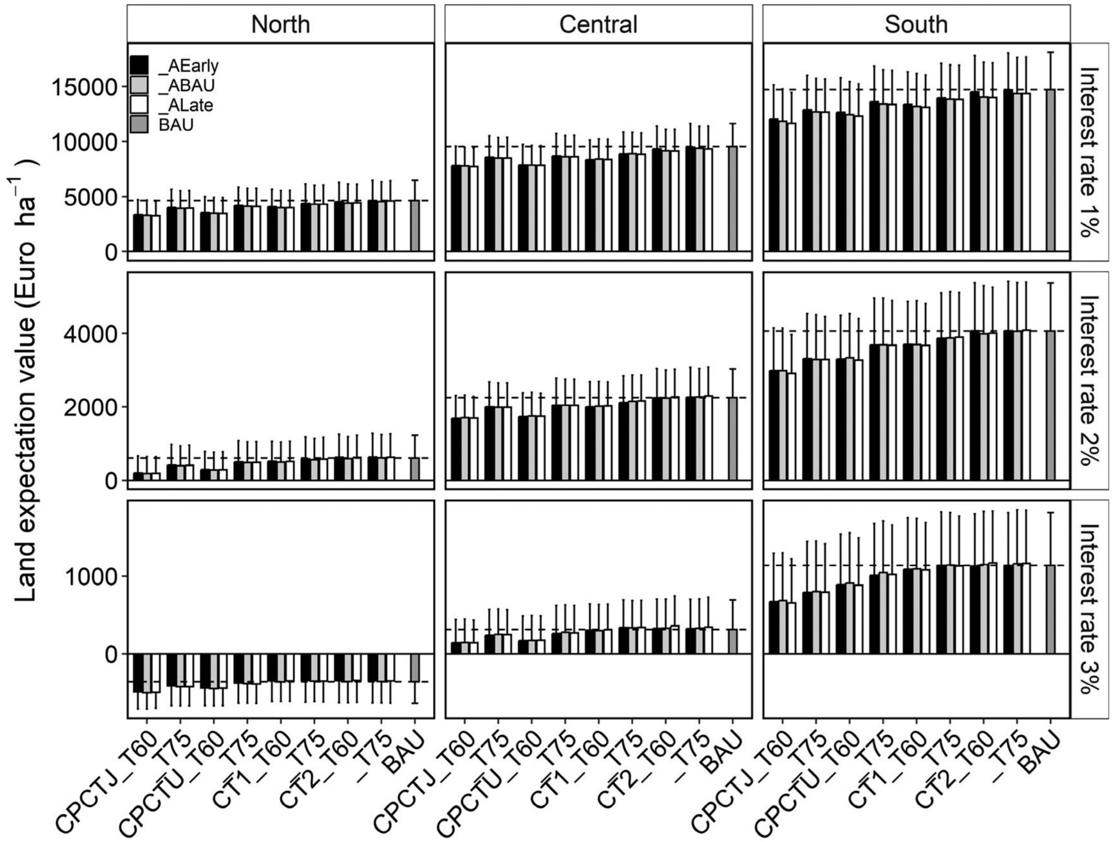

Figure 6. Land expectation value at the time of establishment for different conversion strategies and for the abandonment options AEarly (black), ALate (white) and ABAU (grey). The dashed lines represent LEV of a traditional clear-cutting system (BAU). LEV was calculated as a mean for stands located in northern, central and southern Sweden, using interest rates of 1%, 2% and 3%. For abbreviations of strategies and scenarios, see Figure 2.

stand structure in the mature stand, as both strategies resulted in similar distributions. Postponing the conversion resulted in reduced scope to influence the stand structure within the studied timeframe, both because fewer selection cuttings were carried out, and because traditional thinnings from below carried out at earlier stages of later conversions narrowed the size distribution. This observation aligns somewhat with Hanewinkel and Pretzsch (2000) who found that thinnings and cuttings had limited influence on stand structure during conversion of Norway spruce, and instead claimed that successful regeneration was a more important factor. Our findings also echo those of Schütz (2001), who mentioned late introduction as one of the main explanations for the failure of conversion forestry, in part because ageing of the initial stand limits the scope for maintaining the canopy trees during the transformation period.

Early introduction of conversion resulted in greater reduction of mean annual volume increments during the simulated stand development. This was probably an effect of higher levels of removal during simulated selection cuttings, resulting in lower average standing volume compared to traditional management under BAU. How removals were distributed relative to diameter distribution varied between management strategies, which may also have influenced growth. Thinnings in BAU were carried out from below, whereas selection cuttings were focused on the removal of the largest trees. Long-term thinning experiments in Sweden have indicated lower production for Norway spruce

Table 3. Volume of pulpwood and timber and quadratic mean diameter (D_g) at harvest in abandonment option ABAU in relation to a clear-felling system (BAU, 100%) at simulations using 2% interest rate. Separate figures are presented for final felling and for the total removal from the start of the simulation until final felling. For abbreviations of conversion scenarios, see Figure 2.

			Final felling			Total		
Strategy	Removal	Aband. timing	D_g	Pulpwood	Timber	D_g	Pulpwood	Timber
CPCTJ	_T60	_ABAU	93	47	43	93	94	70
CPCTU			94	47	44	94	95	74
CT1			91	50	47	96	102	83
CT2			92	53	51	99	99	94
CPCTJ	_T75	_ABAU	94	65	57	97	98	81
CPCTU			94	65	60	98	99	86
CT1			93	65	59	99	102	90
CT2			94	68	64	100	99	97

after thinning from above compared to thinning from below (Nilsson et al. 2010). The finding of lower production in conversion forestry than in BAU aligns with Drössler et al. (2014): in their simulations the volume of production under conversion management was 60% of that under conventional management after 50 years.

Despite lower volume production than BAU, our results suggest that there is a limited economic risk in introducing conversion at the thinning stage (CT1 and CT2). If the transformation to an uneven-aged stand structure is unsuccessful, or if management goals change, conversion can be abandoned without significant economic losses. BAU was generally more profitable at low interest rates whereas CT1 and CT2 had equal LEV compared to BAU at 3% interest rate. Aiming at transformation at PCT reduced LEV for all tested interest rates and inverse J distribution was less profitable than a uniform distribution. This could be explained by the lower total production and lower average dimension of harvested trees in CPCTJ compared with those under other management alternatives. The influence of different PCT strategies was mitigated by the limited scope for selecting main stems where regeneration was relatively sparse. When clear felled at the same time (ABAU), the total production and volume of harvested timber at clear felling was greatest in BAU and decreased with early initiation of conversion forestry. On the other hand, the economy of selection cuttings benefited from high thinning grades and removals oriented towards the largest trees. This may be one reason for the equal or slightly greater profitability achieved by CT1 and CT2 compared to BAU at high interest rates (cf. Vítková et al. 2021). A lower MAI for abandonment ALate compared to AEarly might partly explain the general trend of slightly lower LEV for the former scenario. The delayed abandonment in ALate implied a greater total volume of extractable wood during the rotation. However, the average volume of commercial assortments was greater for AEarly compared to ALate at clear felling. This means that a greater proportion of the wood in ALate was harvested at selection cuttings, where the operational costs are greater compared to clear felling.

The resulting stand density for the simulated conversion scenarios was greater than that recommended by Pukkala et al. (2010) and Juutinen et al. (2018) for optimal management of uneven-aged spruce dominated stands. Pukkala et al. (2010) simulated target diameter cutting at 20-year intervals and suggested that post-harvest basal area of 4–12 m^2 ha^{-1} (lower on less fertile sites) would be economically optimal at 2% interest rate. However, Lundqvist (2017) stressed the positive relationship between standing volume and production in a selection system and recommended moderate harvest strength to retain high production and reduce damage to the remaining stand.

Our simulations did not consider any differences in damage between the management alternatives. The thinning grades were generally greater in the conversion alternatives. Previous studies of Norway spruce have found a positive relationship between thinning intensity and damage caused by wind (Persson 1972; Wallentin and Nilsson 2014). Removals at selection cuttings were also oriented towards the largest trees. Initially, this may increase the risk of wind damage, as the trees most adapted to wind are removed (c.f. Persson 1972). However, in the longer run, an uneven-aged stand structure may promote a greater individual tree stability (Mason 2002).

Conclusion

The simulations described in this study indicate that early conversion management promotes the shift towards a full-storied stand structure. However, with a slow transition of ingrowth into larger diameter classes in the simulations, the size stratification did not result in the target J-shape distribution within the simulated period. Further, conversion management can be introduced at the thinning stage and abandoned without any major economic risk within the time frame of a normal rotation under BAU. The introduction of conversion management at PCT was consistently less profitable compared to BAU for all abandonment scenarios. Potential economic losses tend to be smaller at greater interest rates. Aiming at an inverse J-shaped size distribution at PCT was less profitable than PCT aiming at a uniform distribution and thus slightly increases the economic risk of a conversion attempt. Delaying the abandonment of conversion management past the ordinary rotation length had a minor negative economic impact. Adequate conversion management for reaching equilibrium, and the consequences for long-term production and economy of heavy and early thinning from above under the various conversion strategies, need to be studied further.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability

Data are available upon request from the corresponding author.

Authors contributions

NF performed the simulations in Heureka and the processing and analysis of data. JS initiated and coordinated the study. EH planned the field work and data collection.

All authors were involved in the conceptualization of the study and in the writing of the manuscript.

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