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Modelling effects of regeneration method on the growth and profitability of Scots pine stands

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ABSTRACT

Despite numerous studies there are still uncertainties regarding regeneration strategies that are optimal for productivity and profitability. Thus the aim of this study was to establish effects of three regeneration methods (planting, direct seeding and natural regeneration) on the production and profitability of Scots pine (*Pinus sylvestris* L.) stands in southern Sweden. Long-term stand development was simulated, with the StandWise application of the Heureka decision support system, starting from short-term regeneration outcomes observed in several field experiments at sites with relatively high productivity (H100 site indices, i.e. heights of dominant pines at 100 years: 27–30 m). Financial and production results of each approach were assessed in terms of Land Expectation Value (LEV) and Mean Annual Increment (MAI), respectively, across a whole rotation. Planting on clear-cuts with 1600–3265 seedlings per hectare resulted in the highest profitability and production, whereas high-density planting (10,000 seedlings per hectare) resulted in negative LEV. However, sensitivity analysis showed that the results depended on the interest rate. Retention of seed-trees incurred additional costs relative to single-operation clear felling. In contrast, retention of shelter-trees had good financial results (at 0% and 2.5% interest rate), although they depended on the site index and average tree size.

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Forest economy; forest management; forest stand; growth; Land Expectation Value; regeneration method; Scots pine

Introduction

Scots pine (*Pinus sylvestris* L.) is the most widely distributed coniferous tree species in the world (Mirov 1967) and the second most important commercial tree species in Sweden after Norway spruce (*Picea abies* (L.) *Karst.*). In 2018, the growing stock of Scots pine in Sweden amounted to 1352 million m^3, corresponding to ca. 39% of the total national stock (SLU 2018). Clear-cutting regimes have been generally applied in commercial Swedish forestry, and conventional methods for regenerating Scots pine stands are planting, direct seeding and natural regeneration with seed trees or under shelterwood. However, the naturally regenerated area of Scots pine forest decreased from about 40% of the total regeneration area in 2000 to about 10% in 2018 (SFA 2018).

Active stand establishment involves a series of silvicultural operations, such as site preparation, planting, seeding or natural regeneration, cleaning and pre-commercial thinning (PCT) (Hyytiäinen et al. 2006). In combination with site conditions, these management practices are major determinants of the new stands' growth, quality and hence subsequent management requirements. The qualities and quantities of initial inputs are often related to substantial financial investments that must be compensated for long periods. To be economically rational, the investments need to pay off in terms of increases in revenues from harvesting, income from other uses, and/or reductions in rotation periods. In commercial forestry, the regeneration method providing maximum financial returns from growing timber and retaining high aesthetic and biodiversity values is desired.

For a long time, forest researchers and companies in northern Europe have intensively sought ways to increase the cost-effectiveness of regeneration, particularly methods that could improve seedling survival and establishment (Nilsson et al. 2010b). Hence, short-term effects of various regeneration treatments have been reported in numerous empirical studies (Karlsson 2000; Örlander and Nilsson 1999; Örlander et al. 1990; Davies 1985). The results have provided valuable guidance for forest management. However, knowledge of regeneration success and juvenile growth *per se* is not sufficient for comparing the financial results of different regeneration methods. Information about revenues from harvests, and non-wood benefits over the entire period from regeneration to final felling (or a period of comparable duration if uneven-aged management is applied) is also required for robust assessment and selection of management options (Hyytiäinen et al. 2006).

Unsurprisingly, given the commercial importance of Scots pine (and predominance of clear-cutting regimes), there have been several attempts to evaluate the long-term financial consequences of applying different regeneration methods in even-aged Scots pine plantations in Scandinavia, as

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briefly reviewed here. Hyytiäinen et al. (2006) combined experimental data, process-based forest growth models and stand-level economic optimization to investigate effects of several regeneration and soil preparation methods. Their results showed that planting and sowing yielded the highest stand value at 1% interest rate, but natural regeneration was the optimal regeneration method at 3% interest rate, and sowing provided comparable results to natural regeneration at 5% interest rate. Simonsen (2013) assessed the profitability of planting and natural regeneration with seed trees across sites with a range of site indices in northern Sweden. Their results indicated that planting was only the optimal regeneration method for highly productive sites, e.g. with H100 site indices (heights of dominant pines at 100 years) of at least 26 m for sites at latitude 60°N. Glöde et al. (2003) compared natural regeneration, direct seeding and planting on four study sites, two in northern and two in southern Sweden, and concluded that natural regeneration provided the best financial outcomes at all locations. However, they only investigated sites with relatively low fertility (H100: 24 and 20 m in southern and northern Sweden, respectively). Zhou (1998) investigated the optimal management and rotation length following natural regeneration with seed trees in northern Sweden. In addition, Zhou (1999) developed an optimization model for choosing planting or seed-tree regeneration methods, considering uncertainties in stocking levels, based on a case study in northern Sweden. Gong (1998) considered theoretical aspects of selecting decision support models for determining financially optimal planting densities in pine plantations, particularly in northern Sweden. The optimal investments in stand management and its intensity have also been studied by several authors (Tahvonen et al. 2013; Uotila et al. 2010; Hyytiäinen et al. 2005). Nevertheless, although all these studies provided valuable information or indications of important factors to consider, substantial uncertainties remain. This is at least partly because of “the necessity of optimizing all of the management variables simultaneously”, so (for example) “previous results concerning sensitivity to timber price and the relationship between maximum sustainable yield and economic solutions do not hold true in models that provide a more realistic description of forest management” (Tahvonen et al. 2013). Moreover, there is particularly limited information (and correspondingly high uncertainty) regarding the profitability of different methods for regenerating Scots pine stands in Sweden, particularly on high-fertility sites in southern Sweden, south of latitude 60°N.

Forest growth simulators are useful tools for both research and practical forestry. They are often used to evaluate long-term effects of various silvicultural measures, and address gaps in knowledge and uncertainties such as those outlined above. One that is widely used in Sweden is the Heureka decision support system (Heureka DSS), which projects the growth of stands during whole rotation periods in two stages (Wikström et al. 2011). First, growth in the young stands is modelled based on functions presented by (Nyström 2000) and height-diameter relations developed by Nyström and Söderberg (1987). Further development, after the stands reach an average height of approximately 7 m, is simulated using basal-area growth functions developed for mature forests (Fahlvik et al. 2015; Elfving and Nyström 2010). Clearly, under- or overestimation of the stand growth in the first stage will lead to bias in the second stage (Fahlvik et al. 2015). Therefore, use of empirically validated starting values after the initial young phase from controlled experiments is highly advantageous for long-term simulations.

The objective of this study was to reduce some of the uncertainties outlined in this Introduction by using the Heureka StandWise application to assess effects of three establishment methods (planting, direct seeding and natural regeneration) on the long-term production and profitability of Scots pine stands in southern Sweden. In contrast to some earlier studies, effects of variations associated with differences in young forest models were eliminated by initializing the simulations with empirical data from stands at stages within the range covered by mature forest growth models. Furthermore, the data used were obtained from experiments in which two or more regeneration methods were applied to plots at the same sites, while earlier reports refer mostly to differences between neighbouring stands that were assumed to have similar growing conditions. The management implications of the choice of regeneration method were assessed in terms of Land Expectation Value (LEV) and Mean Annual increment (MAI) under financially optimal (maximum LEV) rotation lengths.

Materials and methods

The simulations presented in this paper are largely based on material observed in three field experiments located at the following sites in southern Sweden: Linnebjörke (57°00′N, 15°10′E, 225 m a.s.l.), Tagel (57°1′N, 14°36′E, 200 m a.s.l.), and Tönnersjöheden (56°41′N, 13°05′E, 70 m a.s.l.). Henceforth, these sites (described in the following sections) are referred to as Sites I, II and III, respectively. Observations of material in selected plots included in a nationwide thinning experiment were also used to provide estimates of missing data for Sites II and III, as described below.

Study area and experimental design

Site I

Originally, the experiment at this site was designed to study effects of shelterwood density and the timing of its removal on Scots pine growth and wood quality (Beland et al. 2000). Site I has typical characteristics of a relatively high fertility, forested site in southern Sweden, with an estimated site index (H100 for Scots pine) of 27 m, corresponding to a MAI of about 7.2 m^3 ha^{-1} $year^{-1}$. The soil is moist podzol, the vegetation type according to (Hägglund and Lundmark 1977) is “blueberry” and “broadleaved grass”, the ground is flat, and the site conditions are relatively homogenous. Before the experimental treatments, the 69-year-old stand was dominated by Scots pine, which accounted for 61% of the total standing volume. The mean standing volume and stem density was 284 m^3 ha^{-1} and 573 stems ha^{-1}, respectively. There is no documentation of stand management history prior to the experiment. However, there are indications that it was regenerated by direct seeding with seeds of a German provenance (a widely applied technique in the early twentieth century). In January 1992, the first cuttings divided the stand into three parts: one that was clear-cut, one where seed trees were retained (at ∼150 stems ha^{-1}) for a standard retention period (ca. 6 years), and one where shelterwood (∼200 stems ha^{-1}) was retained for a longer period (Table 1). Pine was favoured when selecting shelter or seed trees. The whole area was fenced to exclude browsing by ungulates.

The new generation of Scots pine was established by planting, natural regeneration and direct seeding. Soil scarification (disc trenching) was applied on all plots. Planting was done using seedlings originating from seeds collected from the old stand, at three initial planting densities (1600, 3000 and 10,000 seedlings ha^{-1}) in a randomized block design (Figure 1). Two blocks were established on the clear-cut and one block in shelterwood of each density. Each treatment had one repetition per block, except planting with 1600 seedlings ha^{-1}, which was not applied under the seed trees. In addition, plots for natural regeneration were established in each block under both seed and shelter trees. Plot-size varied within the blocks, ranging from 956 to 1945 m^2 (mean: 1644 m^2). Plots planted with 10,000 seedlings ha^{-1} were subjected to PCT (15 years after planting), in which naturally regenerated tree species were removed. Naturally regenerated plots were also subjected to PCT, leaving 1600 trees ha^{-1} in half of each plot and 4444 trees ha^{-1} in the other half. Direct seeding failed due to extensive frost heaving and was excluded from the study.

Seedlings were affected by needle cast caused by *Lophodermium seditiosum* and Brunchorstia disease caused by *Gremmeniella abietina* in the first years after establishment. The highest mortality was observed among naturally regenerated seedlings. In addition, parts of the fence were periodically destroyed during the observation period. Thus, some browsing damage occurred. Storm damage to the overstory occurred during the period 1993–1995 and additional losses occurred in the shelterwood in 2005 during storm Gudrun (Table 1).

Site II

The experiment at this site was a demonstration trial (Figure 1), the main objective being to study effects of the three focal regeneration methods on growth and volume production of Scots pine (Kardell 2013). The estimated H100 for Scots pine was 30 m, corresponding to a MAI of 8.8 m^3 ha^{-1} $year^{-1}$ (Hagglund and Lundmark 1981).

The regeneration methods (direct seeding, planting and natural regeneration under the seed trees) were each applied in two plots with an average size of 900 m^2. The treatments were not randomized and there were no buffer zones between the plots. Half of the stand was clear-felled and in the other half seed-trees were retained. Soil was scarified by disc-trenching in all plots, and the entire area was subsequently fenced. In all plots, naturally regenerated trees, mostly birch, were removed in a PCT 16 years after the start of the experiment. Seed trees were harvested after six growing seasons.

Site III

The experiment at Site III included two naturally regenerated and two planted Scots pine stands (Figure 1) located within 1 km of each other (Agestam et al. 1998). Each stand had similar site conditions (estimated H100 for Scots pine 27 m on average, corresponding to an MAI of ca. 7.2 m^3 ha^{-1} yr^{-1}, with dry podzolic soil and all stands fenced). Planting was done on clear-cut areas with seedlings of a local provenance at densities ranging between 1600 and 6400 seedlings ha^{-1}. Broadleaved trees were removed in a PCT from both of these areas. The natural regeneration treatment involved retention of seed trees. Half of each naturally regenerated stand was subjected to PCT to 4500 seedlings ha^{-1}, while the other half was left as a PCT-free control. Data were collected before the first thinning. Plot sizes varied between 400 and 1000 m^2. The area was not fenced.

Data collection at the three sites (I–III)

The regeneration was inventoried 17–24 growing seasons after initiation of the experiments (Table 2). At every site, the diameter at breast height (dbh) of each tree was recorded in four 100 m^2 circular sampling plots, systematically placed in each treatment plot. Fifteen trees of each arboreal species present were also systematically selected in each of the circular sampling plots, then their height and height to the first living branch were measured. The height and diameter measurements of sample trees were used to parametrize the following diameter-height relationship model for each treatment plot (Näslund 1937):

$$H(D) = BH + \frac{D^x}{(aD + b)^x} \tag{1}$$

Here, H is the tree height (m), D is the tree diameter at breast height (cm), BH is the breast height (m), x is 3 for Norway spruce and 2 for all other tree species, a and b are parameters.

Table 1. Seed and shelter trees after cutting in 1992, and both before and after cuttings in 1998. Data concerning storm-felled (Storm f.) trees were collected after storms in 1993, 1995, 1998 and 2015. bc and ac indicate before and after cutting, respectively.

	Seed trees					Shelter trees				
Year	No. trees *ha^{-1}*	Height *m*	Basal area *m^2ha^{-1}*	Dbh *cm*	Volume *m^3ha^{-1}*	No. trees *ha^{-1}*	Height *m*	Basal area *m^2ha^{-1}*	Dbh *cm*	Volume *m^3ha^{-1}*
1992 ac	154	23.9	11.5	30.4	122	198	23.8	14.5	30.2	153
Storm f. 1993	*18*		*1.4*	*30.5*	*14*	*13*		*0.8*	*28.1*	*9*
Storm f. 1995	*3*		*0.2*	*28.4*	*2*	*2*		*0.1*	*28.0*	*2*
Storm f. 96–98	*2*		*0.2*	*31.0*	*2*	*4*		*0.3*	*28.4*	*3*
1998 bc 1998 ac	129	23.9	11.4	33.2	121	179	23.9	15.1	32.5	159
						75	24.0	6.8	33.7	73
Storm f. 99–15						*12*		*1.1*	*34.0*	*11*
2015						63	25.2	7.6	38.8	80

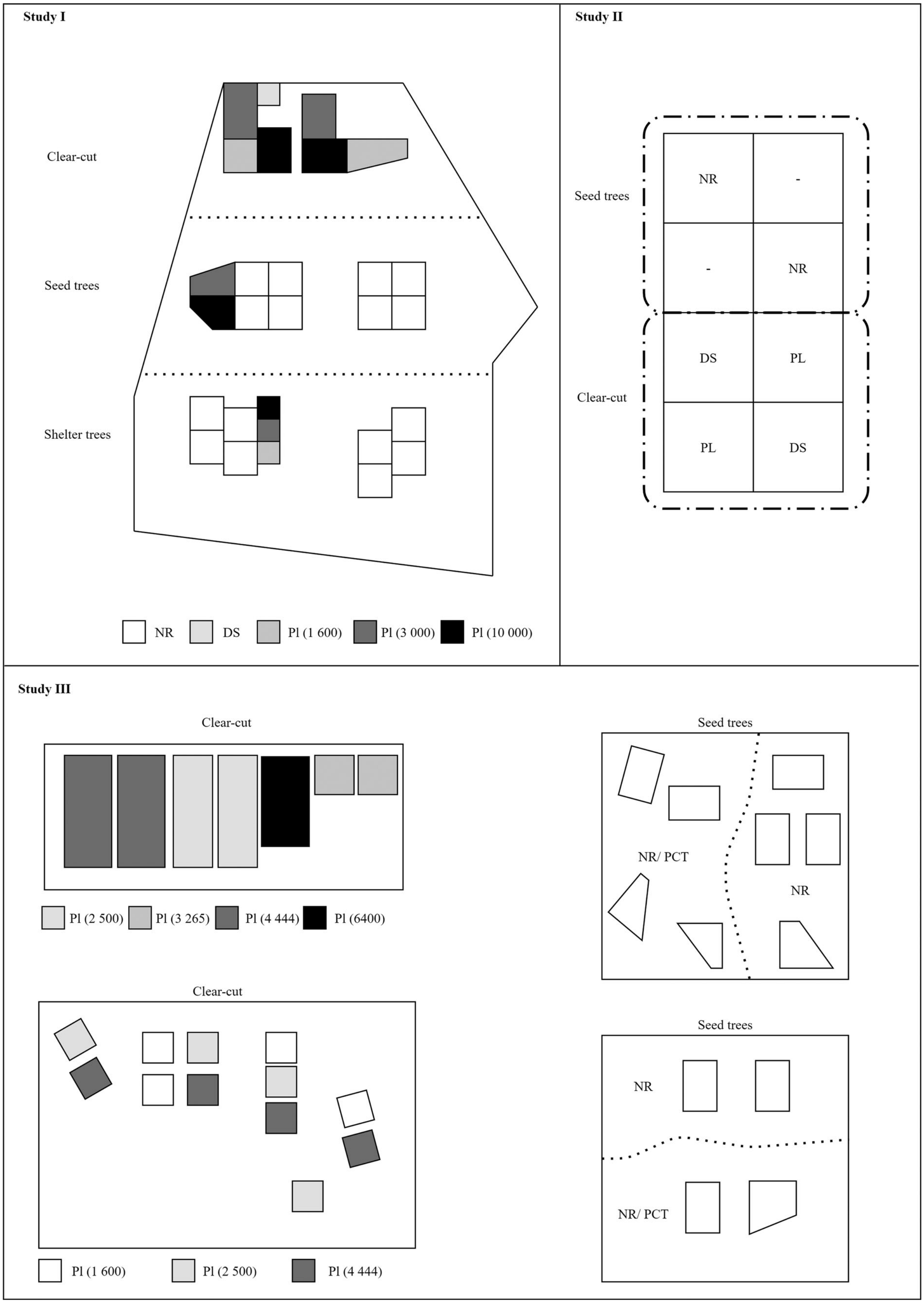

Figure 1. Schematic experimental design at all study sites (I–III). Abbreviations: NR, PL, DS, PCT refer to natural regeneration, planting, direct seeding, pre-commercial thinning, respectively. Numbers in the parenthesis refers to initial planting densities (number of seedlings per hectare).

Table 2. Parameters of stands at all three experimental sites at indicated ages, showing means of plot values, which were used for modelling. Regeneration methods: PL – planting, NR – natural regeneration, DS – direct seeding. PCT refers to pre-commercial thinning.

Regeneration method	Initial density *No. trees* ha^{-1}	Age *years*	Dominant height *m*	No trees ha^{-1}	Basal area m^2ha^{-1}	Volume m^3ha^{-1}
Site I						
PL/Clear-cut	1600	24	13.48	1537	23.20	134
PL/Clear-cut	3000	24	13.86	1867	28.14	175
PL/Clear-cut	10,000	24	13.85	3175	27.22	167
PL/Seed-trees	3000	24	11.44	2100	23.84	126
PL/Seed-trees	10,000	24	12.21	2325	19.74	109
PL/Shelter-trees	1600	24	10.54	1925	14.73	72
PL/Shelter-trees	3000	24	12.20	2237	18.28	101
PL/Shelter-trees	10,000	24	12.14	2675	16.60	90
NR/Seed-trees	1600	24	9.71	1450	13.81	64
NR/Seed-trees	4444	24	10.35	3194	17.44	82
NR/Shelter-trees	1600	24	8.96	1450	6.25	26
NR/Shelter-trees	4444	24	9.55	3700	11.56	49
Site II						
DS	–	25	13.43	2044	26.18	162
PL	2000	25	12.92	2145	23.60	136
NR/Seed-trees	–	27	13.14	1938	23.98	139
Site III						
PL	1600	17	7.14	1579	14.83	54
PL	2500	17	8.12	2307	18.49	75
PL	3265	17	9.81	3244	24.70	117
PL	4444	17	8.58	3990	23.90	101
PL	6400	17	9.66	5612	30.17	142
NR	No PCT	31	12.85	5488	33.58	194
NR	PCT	31	13.16	3350	32.13	190

Simulations

The StandWise application of the Heureka DSS was used for all modelling reported here. Data describing the stand growth, as well as both thinning and harvesting operations at the three sites described above, were imported to the software as tree lists, then subjected to two kinds of simulations. First, the development of the overstory (seed and shelter trees) was simulated during the period from the first release cutting until its full removal 6–25 years later. Second, the new stand's development was simulated from the latest inventory in which it was measured, until final felling by clear-cut. At Sites II and III the latest inventory of the young stand occurred 9–18 years after final overstory removal. At site I some of the overstory was still left at the time of the inventory (Table 1), and the overstory removal and young stand inventory were assumed to have occurred simultaneously. Separate simulations of stands with overstory retention were needed to assess its direct financial effects, relative to a clear-cut alternative. The concept of the financial result of overstory retention is explained later in the text. Figure 2 illustrates graphically how the two simulations slices fit together.

Overstory

Overstory development was modelled in Heureka from the time of the first release cutting until removal of the last seed and shelter-trees. For Site I, starting values for the simulations were drawn from the old stand data, recorded when the experiment was established. The timing and intensity of the release cuttings were applied according to the documented management in the experiment (Table 1).

Overstory data were not available for Sites II and III. Hence, overstory development was modelled using data obtained from 10 selected plots from a nationwide thinning experiment encompassing sites with similar conditions to Sites II and III (Nilsson et al. 2010a). The selected plots were located in the southern part of Sweden, south of 60° N latitude. H100 site indices for Scots pine at the plots varied between 21 and 27 m.

The time of the first release cutting was chosen according to the optimal rotation, defined as the rotation that maximized the LEV. For each stand, three scenarios (representing development following regeneration with seed trees, with a shelterwood and reference clear-cut) were simulated. Wind damage levels were chosen according to previous findings that on average 9% of the overstory trees were wind-felled during the first seven years after cutting in shelter woods in

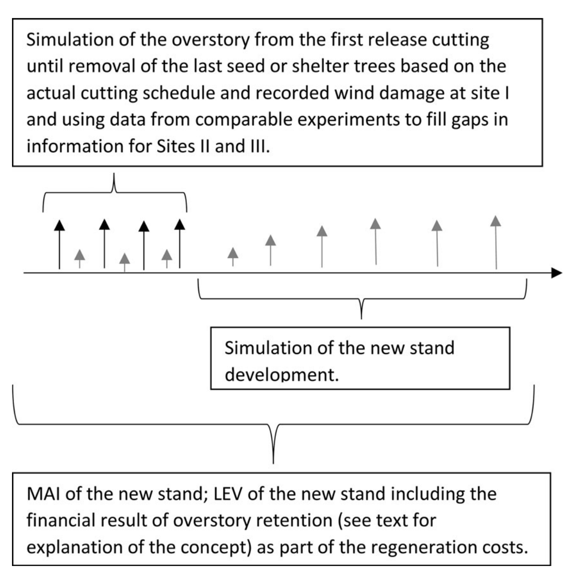

Figure 2. Schematic representation of the simulations in the study.

Table 3. Financial results of overstory retention at Site I in EUR ha^{-1}. Observed wind damage level refers to the wind damage registered during the observation period.

	Wind damage level	Seed trees Observed (~16%)	Seed trees Low (4%)	Seed trees Moderate (9%)*	Seed trees High (14%)	Shelter trees Observed (~7%)	Shelter trees Low (4%)	Shelter trees Moderate (9%)*	Shelter trees High (14%)
Interest rate	0%	−73	308	149	−9.58	2478	2677	2345	2012
	2.5%	−368	−32	−172	−312	568	704	477	251
	4%	−526	−213	−343	−473	−159	−48	−233	−419

*Moderate wind damage of 9% is the observed probability of wind-throws in shelterwoods in southern Sweden, during a 7-year period after first release cutting (Nilsson et al. 2006).

southern Sweden (Nilsson et al. 2006). This ("moderate") level and two additional levels: moderate plus and minus one standard deviation ("high (+4%)" and "low (−4%)", respectively) were tested in the simulations.

Financial result of overstory retention

The financial result of overstory retention was used as an approximation of the effect of choosing natural regeneration rather than clear-cutting on the profitability of the previous rotation. When negative, it constitutes a cost that should be assigned to the new, naturally regenerated stand. In contrast, if positive it constitutes a financial "bonus" that can be assigned to the new stand. It was defined as the difference between the sum of discounted revenues from release cuttings until complete removal of the overstory and the revenue from a reference clear-cut. Calculations were done for three interest rates: 0%, 2.5% and 4% (Table 3). The timber value of the wind-felled seed/shelter trees was assumed to be equal to the variable costs of removing these trees. However, the fixed cost for starting the machinery operation was added at each occasion. Three wind damage levels were also included in sensitivity analyses, using recorded wind damage at Site I and data from comparable experiments (Nilsson et al. 2010a) to fill gaps in information for Sites II and III.

A multiple linear regression model (MLR) was used to analyse the variation of financial result of overstory retention for the 10 plots included in a nation-wide thinning experiment (the average results to be used as proxies for the financial results at sites II and II), calculated at no interest rate and with the moderate wind damage level (9%). MLR was conducted using R software, version 3.6.1 (Team 2013).

New stand

Starting values for the simulations were drawn from data obtained in the experiments presented above (Table 2). Further stand growth was simulated until final felling at the time of MAI culmination.

To account for the effect of release after removal of the last remaining shelter-trees at Site I (75 trees ha^{-1} at the time of the inventory), data on the overstory trees were included in the input. The shelter trees were then removed during the first period of the simulation. The time span between removal cuttings and the understory inventory in other naturally regenerated plots was much longer (9-18 years). Thus, the release effect was assumed to be captured by the understory data.

Thinnings were applied according to thinning guidelines obtained from the forest owners association Södra. A dominant height of 22 m was an upper limit, above which thinnings were not conducted.

Financial calculations

The financial performance of tested regeneration methods was compared in terms of LEV (Faustmann 1849) with the following formula:

$$LEV = \frac{1.0p^u}{(1.0p^u - 1)} * NPV \quad (2)$$

where LEV is the land expectation value, u is the length of the rotation period, p is the interest rate, and NPV is net present value of the costs and revenue streams from the first rotation.

Calculations were done with two interest rates: 2.5% and 4% (Brukas et al. 2001). The economic calculations included all costs and incomes related to management activities throughout the rotation. The cost for seedlings, including planting costs, was 0.42 EUR per seedling, while costs of mechanical soil scarification and PCT were 238 and 229 EUR ha^{-1}, respectively. Costs of supplementary planting (+20%) were also added to costs for all planted parcels. Timber prices were applied according to the roadside pricelist for the region of Växjö (2019). Harvester costs for thinning and final felling operations were set at 118 and 127 EUR/hour, respectively, and corresponding forwarder costs at 71 and 75 EUR h^{-1}, respectively. In Heureka, harvester-forwarder productivity is estimated using time consumption functions presented by Wikström (2008).

Results

Financial results of overstory retention

Seed tree retention at Site I (Linnebjörke) incurred costs under all conditions except in simulations with 0% interest and either low or moderate wind damage. The financial result of shelter tree retention was positive at 0% and 2.5% interest rates, but negative at 4% interest rate (Table 3). Wind damage significantly affected the financial result of overstory retention (Tables 3 and 4). At 2.5% interest rate, the financial result of retaining seed and shelter trees was about 300 and 450 EUR ha^{-1} lower, respectively, with high wind-damage than with low wind damage.

The financial results of overstory retention at Sites II and III were estimated from simulations of overstory development for comparable plots in a nationwide thinning experiment

Table 4. Average financial results of overstory retention in EUR ha^{-1} (means with standard errors in parentheses) obtained from simulations of stand development in 10 long-term experimental plots (GG-experiment) at two interest rates and three wind damage levels.

		Seed trees			Shelter trees		
	Wind damage level	Low (4%)	Moderate (9%)*	High (14%)	Low (4%)	Moderate (9%)*	High (14%)
Interest rate	0%	−119 (27)	−247 (26)	−375 (27)	1980 (246)	1690 (228)	1399 (209)
	2.5%	−390 (27)	−503 (29)	−616 (31)	149 (133)	−38 (120)	−187 (96)
	4%	−510 (44)	−607 (52)	−745 (34)	−463 (72)	−621 (66)	−780 (60)

*Moderate wind damage of 9% is the observed probability of wind-throws in shelterwoods in southern Sweden, during a 7-year period after first release cutting (Nilsson et al. 2006).

(Table 4). For seed trees, it was negative regardless of the interest rate and wind damage level. The result of shelterwood retention was positive at 0% interest rate, and at 2.5% interest rate with low wind damage. The estimated result at 2.5% interest rate was on average 95% higher for shelterwood retention than for retaining seed trees, regardless of the wind damage level. At 4% interest rate, retention of seed and shelter trees had roughly equal financial results.

Results of the multiple regression analysis indicated that the financial result of shelter tree retention is affected by site index and average tree size (Table 5), becoming increasingly positive (or less negative) with increases in either site index or average tree size (Figure 3). However, correlations between these variables and the financial result of retaining seed trees are weak.

Overall, estimates of the financial results of overstory retention at Site I were higher than the estimates derived from the nation-wide thinning experiment.

Volume production in the new stand

At Site I, the average simulated MAI was on average 8.9% and 5.2% higher, at all planting densities, on the clear-cut (7.7 m^3 ha^{-1} year^{-1}) than in plots with retained seed and shelter trees, respectively. On average, natural regeneration yielded 18.5% lower MAI than planting, with or without shelter or seed-trees. However, natural regeneration was not tested on the clear-cut.

The highest MAI under each treatment was observed on the parcels with 3000 seedlings (or stems or remaining after PCT) ha^{-1}. Planting with 3000 seedlings ha^{-1} on a clear-cut yielded the highest overall MAI (8.3 m^3 ha^{-1} year^{-1}) of all combinations of regeneration treatment and seedling density (Figure 3).

In contrast, the MAI was lowest (5.6 m^3 ha^{-1} year^{-1}, on average) in naturally regenerated plots that were pre-commercially thinned to 1600 stems ha^{-1} with either seed or shelter trees. The differences in this respect between naturally regenerated plots with shelterwood or seed trees and the same numbers of stems after PCT were negligible (Figure 4). In naturally regenerated plots, the MAI was on average 14.71% higher when 4444 stems ha^{-1} were retained after the PCT than when 1600 stems ha^{-1} were retained (Figure 4).

At Site II, direct seeding yielded the highest MAI (8 m^3 ha^{-1} year^{-1}), which was 15.1% higher than the MAI yielded by planting. Volume production in naturally regenerated plots was slightly higher than in planted plots in the clear-cut (Figure 5).

Results for Site III indicated that the MAI in plots planted on the clear-cut increased with increasing planting density and ranged from 7 to 10 m^3 ha^{-1} year^{-1}. Natural regeneration under seed trees yielded on average 40.2% lower MAI. PCT in naturally regenerated plots had little effect on volume production (Figure 6).

Economic performance of the regeneration methods

Results from site I showed that at 2.5% interest rate, planting with 1600–3000 seedlings per hectare under shelter-trees yielded 12.6% higher LEV than planting with corresponding densities on the clear-cut. Furthermore, natural regeneration under the shelter trees resulted in 9.6% higher LEV than planting (with 1600–3000 seedlings ha^{-1}) on the clear-cut. Natural or artificial regeneration under seed trees resulted in substantially lower LEV. Planting with 10,000 seedlings per hectare resulted in negative LEV, regardless of shelterwood density (Table 6).

At the higher (4%) interest rate, all investments in stand establishment resulted in relatively low or negative LEV, according to calculations including the financial result of overstory retention with the wind damage level recorded in the actual experiment (Table 2).

At Site II, direct seeding yielded the highest LEV at both 2.5% and 4% interest rates (45.1% and 19.1% higher LEV than planting and natural regeneration, respectively, at the 2.5% interest rate), assuming a moderate level (9%) of wind damage to the seed trees (Table 3).

At site III, LEV decreased with increases in initial planting density, at 4%interest rate. However, at 2.5% interest rate, LEV remained rather stable up to an initial density of 3265 seedlings ha^{-1}. Further increase in initial planting density resulted in substantial reduction of LEV. At 2.5% interest rate,

Table 5. Results of linear regression analysis of effects of increases in site index (H100, in m) and average tree size (dbh, in cm) on the financial result (in EUR ha^{-1}) on overstory (shelter tree) retention.

	Seed trees					Shelter trees				
	Estimate	SE	t-value	*p*-value	pEta-sqr*	Estimate	SE	t- value	*p*- value	pEta-sqr*
Intercept	39,841	503.97	0.791	0.452	0.073	−5654.58	1675.04	−3.376	0.00970	0.5875
Site index (H100)	−27.47	24.33	−1.13	0.29	0.137	226.02	80.86	2.795	0.02337	0.4941
Average tree size	0.9	5.51	0.163	0.874	0.003	63.69	18.31	3.479	0.00834	0.6020

*pEta-sqr: partial determination coefficients for the relationships between SI and tree size versus financial result.

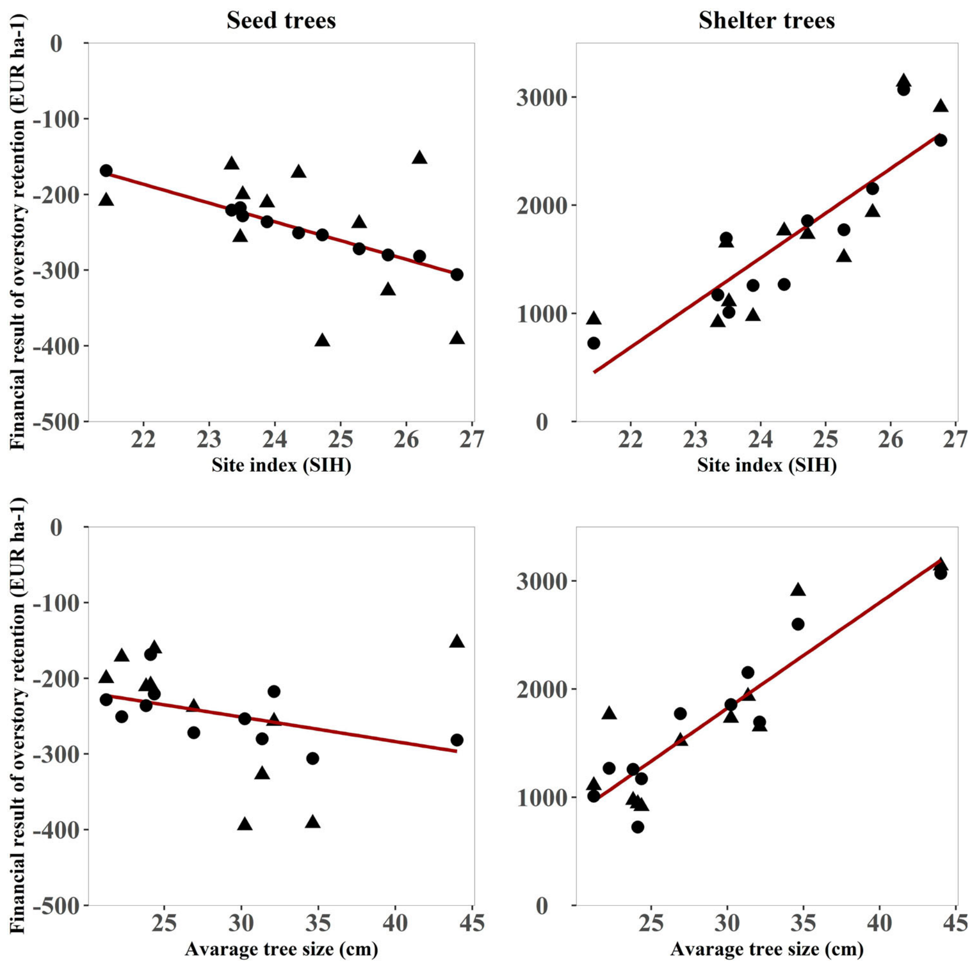

Figure 3. Dependence of financial results of seed tree (first column) and shelter tree (second column) retention on site index (H100 in m) and average tree size (dbh in cm). Circles and triangles indicate values based on fitted and observed overstorey development data.

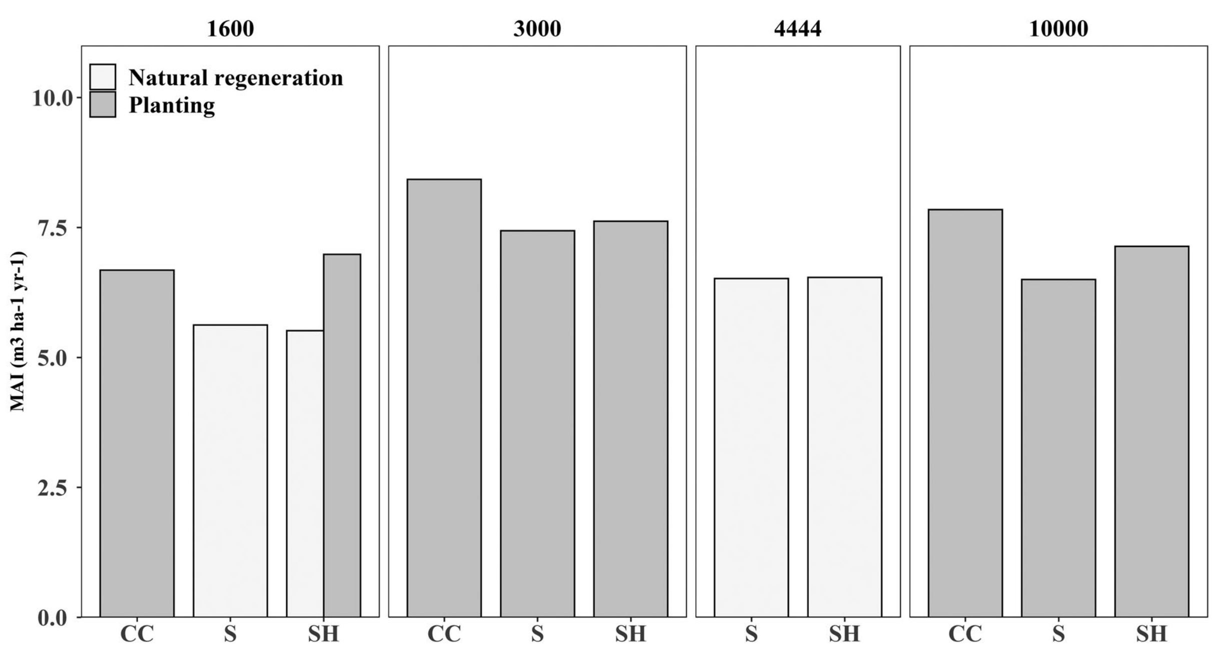

Figure 4. Estimated MAI (m^3 ha^{-1} year^{-1}) at Site I. Numbers in the top row are initial planting densities or numbers of stems after PCT (seedlings ha^{-1}). CC, S and SH refer to clear-cut, seed trees and shelter trees, respectively.

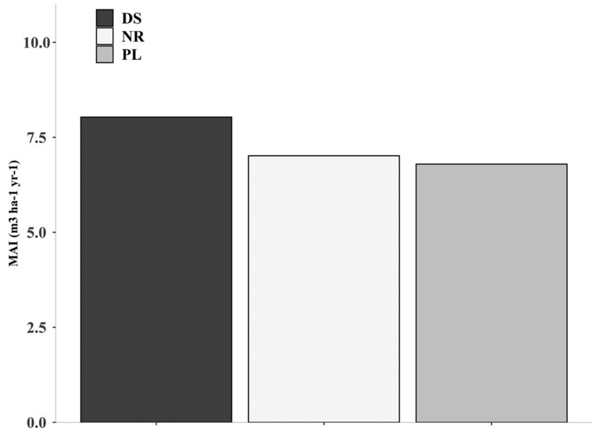

Figure 5. Estimated MAI (m^3 ha^{-1} year^{-1}) in plots subjected to direct seeding (DS), natural regeneration (NR) and planting (PL) treatments at Site II.

planting with densities of 1600–3265 seedlings ha^{-1} yielded on average 43.7% and 80.1% higher LEV than planting with 4444 and 6400 seedlings ha^{-1}, respectively. At 4% interest rate, planting with 4444 and 6400 seedlings ha^{-1} resulted in negative LEV. Naturally regenerated plots that had been pre-commercially thinned yielded 19.1% higher LEV than controls (at 2.5% interest rate). Natural regeneration with PCT resulted in 38% and 73% lower LEV than planting with 2500 seedlings ha^{-1} at 2.5 and 4% interest rates, respectively. Moderate wind damage to the seed trees was applied in the calculations.

Discussion

Volume production

Estimated MAI in the simulated rotations was higher in planted than in naturally regenerated stands at Sites I and III, but not Site II. Higher production in planted stands was also observed in a previous study by Ekö (1994), and is consistent with comparisons of yields in naturally regenerated and planted Norway spruce stands by (Klang 2000). The lower growth of naturally regenerated stands may be partly due to competition from the seed or shelter trees. This hypothesis is supported by numerous investigations of effects of retained trees on growth of Scots pine seedlings (Valkonen et al. 2002; Valkonen 2000; von Sydow and Örlander 1994; Ackzell and Lindgren 1992; Kuuluvainen and Pukkala 1989). Furthermore, planted seedlings tend to suffer less from competition from ground vegetation than naturally regenerated seedlings. This may facilitate their establishment, accelerate their juvenile growth and hence shorten their exposure to damaging biotic and abiotic factors. In contrast, Kuuluvainen and Pukkala (1989) found that proximity of seed trees impairs growth of grasses and herbs. Thus competition from ground vegetation could be weaker under seed or shelter trees than in open clear-cut areas (Karlsson and Nilsson 2005; Petersson and Örlander 2003; Nilsson et al. 2002; von Sydow and Örlander 1994). Natural regeneration also usually results in stands with a more heterogeneous structure, which may have lower volume production than otherwise similar stands with more homogeneous structure (Binkley et al. 2013; Binkley 2011). The higher production of planted stands has also been attributed to genetic improvement. However, in this study, planted seedlings had the same genetic origin as naturally regenerated seedlings.

In planted stands, the total volume production increased with increases in planting density (Figure 2), due to associated increases in basal area, as observed in several spacing experiments with Scots pine (Agestam et al. 1998; Pettersson 1992; Huuri et al. 1987; Huuri and Lahde 1985). Our results also show effects of the competition from seed and shelter

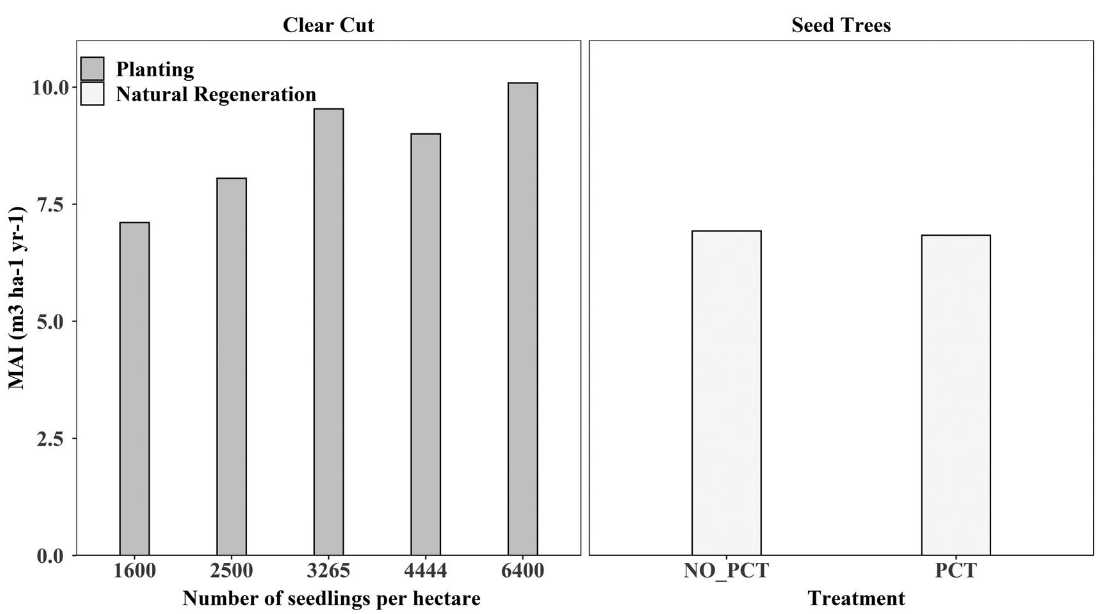

Figure 6. Estimated MAI (m^3 ha^{-1} year^{-1}) at site III in plots on the clear-cut and under seed trees. PCT refers to pre-commercial thinning.

Table 6. LEV ha^{-1} with indicated stand establishment procedures at 2.5% and 4% interest rates at all study sites (I–III). Regeneration methods: PL – planting; NR – natural regeneration; DS – direct seeding. PCT refers to pre-commercial thinning.

Site I	Density (seedlings ha^{-1})	Interest rate 2.5%			Interest rate 4%		
		Clear-cut	Seed-trees	Shelter-trees	Clear-cut	Seed-trees	Shelter-trees
PL	1600	2638		3357	450	−1049	186
PL	3000	2502	1208	2525	31		−552
PL	10,000	−3277	−4006	−2871	−4631	−5323	−4120
NR	1600		1649	2732		−15	281
NR	4444		1758	2957		−14	431
Site II		Interest rate 2.5%			Interest rate 4%		
		Clear-cut	Seed-trees	Shelter-trees	Clear-cut	Seed-trees	Shelter-trees
PL	2000	2412			768		
DS			4396			1302	
NR			3555			45	
Site III		Interest rate 2.5%			Interest rate 4%		
		Clear-cut	Seed-trees	Shelter-trees	Clear-cut	Seed-trees	Shelter-trees
PL	1600	3717			967		
PL	2500	3642			665		
PL	3265	3621			485		
PL	4444	2059			−580		
PL	6400	731			−1793		
NR	No PCT		1839			148	
NR	PCT		2274			263	

trees on the planted seedlings. For planted seedlings, MAI was on average 8.9% and 5.2% higher in clear-cut plots than in plots with seed and shelter trees, respectively. These estimates agree well with findings by Nilsson et al. (2006).

It should be noted that damage to seedlings and trees might affect the total volume production. Extensive damage to the seedlings by *Lophodermium* needle cast and Brunchorstia disease was probably the main reason for low stems number in naturally regenerated plots at Site I (Table 2). Furthermore, strong competition from hairy grass at Site II resulted in patchy natural regeneration, which may have reduced the volume production in those stands. Browsing could have affected the result at Site III, which was not fenced. However, no data on browsing damage to the seedlings/trees was collected.

Browsing was previously found to have a substantial effect on both production and economy in Scots pine stands (Nilsson et al., 2016). Thus fencing might have led to overestimates of volume production. Costs of fencing were not included in the calculations, as they would have resulted in largely negative financial results, complicating presentation and discussion of relative differences in LEV between the studied regeneration methods. Admittedly, the financial outcomes obtained in the study represent an idealized situation where browsing is kept at a negligibly low level.

Financial outcomes

The financial outcome of the simulated Scots pine rotations depended on the regeneration method, interest rate and site. Overall, planting in clear-cut plots with 1600–3265 seedlings per hectare resulted in the smallest variation in LEV of all the tested methods, across the three study sites at 2.5% interest rate. This indicates that planting may be the most reliable regeneration method at high fertility sites (Table 4). Similarly, Simonsen (2013) found that planting was the optimal method on productive sites located in northern Sweden with site indices (H100) ranging from 16 to 28 m. Our results also indicate that initial densities higher than 3256 seedlings per hectare result in substantially poorer financial outcomes at such sites than lower densities, in accordance with results of modelling by Hyytiäinen et al. (2005). Furthermore, planting 10,000 seedlings ha^{-1} was unprofitable, due to high initial investments that were not compensated by increases in harvesting revenues. Overall, the results clearly confirm the importance of appropriate planting densities for maximizing the profitability of wood production (Coordes 2013; Tahvonen et al. 2013; Hyytiäinen et al. 2005; Gong 1998).

In accordance with findings by Glöde et al. (2003), planting under seed trees resulted in relatively poor financial outcomes, due to combined costs of planting, usually negative financial results of overstory retention and lower production than planting on clear-cuts. In contrast, planting under shelterwood resulted in higher LEV, despite anticipated reductions in volume growth (relative to planting on clear-cuts), due to the low initial costs and especially the positive financial result of overstory retention. Thus, planting under shelterwood with a long retention period could be considered a good alternative to the common clear-cutting system for fertile Scots pine sites. However, further tests with larger numbers of plots would be needed to validate these results. Natural regeneration under seed trees yielded lower LEV than planting on clear-cuts with moderate initial densities at 2.5% interest rate. However, the results indicate that under some conditions it could be competitive to planting on clear-cuts, even at high-fertility sites. The financial results of natural regeneration under shelter trees were comparable to those of planting on clear-cuts. This was partially due to relatively low initial investments and neutral or positive financial results of overstory retention, which compensated for a lower volume increment.

Our results reveal very high variation in the outcome of direct seeding among regeneration sites. *Inter alia*, it yielded the highest MAI and LEV at Site II, but totally failed at site I. Both Glöde et al. (2003) and Hyytiäinen et al. (2005) found that it outperformed natural regeneration and planting at all interest rates at medium fertility sites, due to relatively low costs of establishment and high volume production. However, sowing on medium and high fertility sites is associated with risks of abundant ground vegetation outcompeting small seedlings, especially on clear-cuts. Miina and Saksa (2008) highlighted the importance of careful site selection for good regeneration outcomes from planting, sowing and natural regeneration. Accordingly, the results from our study likely reflect both the potential and uncertainties or risks associated with direct seeding on fertile sites.

The high interest rate substantially limited the alternatives for profitable wood production. At the 4% interest rate, most of the investments became economically irrational (Table 4), suggesting that both planting and natural regeneration are difficult to justify at higher interest rates. However, these results were highly dependent on costs of management and the harvest, pulp and timber prices applied. Earlier studies showed that natural regeneration was more profitable than planting at 3–5% interest rates (Simonsen 2013; Hyytiäinen et al. 2006; Glöde et al. 2003), but results of those studies should be compared cautiously due to differences in site properties, applied growth models and timber prices. For instance, timber prices are higher in Finland than in Sweden, which may facilitate profitable wood production especially at higher interest rates, and studies by Hyytiäinen et al. (2005) confirmed the sensitivity of economic outcomes to price changes.

Natural regeneration or narrow spacing tend to promote higher quality timber than sparse planting (Liziniewicz 2014), mainly because it increases selection possibilities and leads to smaller branches through increases in competition between trees (Agestam et al. 1998). The effects of initial spacing on wood quality are probably stronger at high fertility sites, as Persson (1977) found that quality at a given spacing is inferior at more fertile sites. Regeneration under shelter trees also positively affects future wood quality, according to Ekö (1994). However, growth models used in Heureka do not account for effects of initial spacing density, or pre-commercial and commercial thinnings, on wood quality, except their effects on diameter growth. Thus, our analyses may underestimate the financial results for naturally regenerated, seeded and densely planted strands if high-quality timber attracts higher premiums in the future.

Our calculations indicate that seed-tree retention incurs additional costs compared to clear felling that are, in many cases, roughly equal to or larger than the savings obtained by avoiding planting. In contrast, retention of shelter trees can have good economic results (at 0% and 2.5% interest rates) although it varies, depending on site index and average tree size. Generally, the financial result of overstory retention declined with increases in interest rate. At 4% interest rate, costs of leaving the shelter trees were comparable to those of retaining seed trees. Furthermore, the sensitivity analyses indicated a strong effect of wind damage on the cost of overstory retention. The potential severity of naturally regenerated stands' increased susceptibility to wind damage after release cuttings has been previously highlighted (Örlander 1995), and the increased frequencies of windthrows naturally resulted in additional financial losses.

Conclusion

Planting seems to be the most suitable regeneration method on fertile sites such as those included in this study. Direct seeding can provide successful regeneration even on relatively fertile sites, but the method is rather unpredictable. Seed tree retention almost always incurs additional costs, compared to single-operation clear felling, which are often comparable to and sometimes larger than the potential savings from the avoided planting. This regeneration method is often less financially favourable than clear-cutting and planting due to the combination of lower volume production and costs associated with the seed tree removal. Regeneration under shelter-trees with a long retention period may be a competitive alternative to a conventional clear-cutting regime, mostly due to low initial investments and no additional costs related to overstory retention. However, the assessment presented here should be regarded as a case study. The lack of a statistically valid design of the original experiments and geographical limitations must be taken into account when generalizing the results.

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

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