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ORIGINAL PAPER

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Abstract

Controlling the long-term effect of management on the quantity and properties of individual boards is a fundamental challenge for silviculture. Within this basic study on Douglas-fir, we have investigated the sensitivity of the net present value (NPV) to three most common planting densities and a prominent pruning strategy. We therefore have applied an individual tree growth model, which represents intrinsic stem structure as a result of crown competition. The model extrapolated board strength development to the rotational age of 70 years, starting from real and comprehensive data recorded from experimental Douglas-fir plots at the age of 20 years. Total volume production increased from about 1600 m^3 ha^{-1} for 1000 and 2000 trees ha^{-1} to 1800 m^3 ha^{-1} for 4000 trees ha^{-1}. The economic superiority of the lowest density stands increased considering the NPV at inflation-adjusted interest rates of 0%, 2% and 4%: Given an interest rate of 2% and no pruning, the NPV at 2000 was at about 50% of the one at 1000 trees ha^{-1}. The NPV at 4000 trees ha^{-1} was even negative. Generally, artificial pruning was not effective. The revealed financial trade-off between growth and timber quality in young stands underlines the importance of silvicultural guidelines, which quantify the effect of management on yield per strength class and financial outcome.

Keywords Management tool · Processing chain · Strength grading · Timber quality

Introduction

The early control of crown dynamics through establishment spacing has been considered as highly relevant for balancing both dimensional growth and timber quality development (Smith and Reukema 1986; Mitchell et al. 1989). On

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the one hand, foresters maintain high initial stand densities that result in a rapid lifting of the crown base and an early suppression of branches along the lower and most valuable stem region (Reukema and Smith 1987). Wider spacing, on the other hand, fosters diameter growth of future crop trees. Reduction in knottiness by pruning is a common technique for modifying spacing effects on wood structure and quality.

The definition of wood quality results from classifying wood according to its suitability for a certain purpose (Trendelenburg and Mayer-Wegelin 1955). For example, any customer preference and legal quality standard typically relate to a specific part of the production chain, e.g., standing tree, log, sawn timber or veneer. As this study considers Douglas-fir in particular, we focused on the wood usage in the field of construction. Within this scope, the quality of the final product is most precisely defined by structural sawn timber grading. Strength and stiffness of Douglas-fir boards strongly depend on knottiness and wood density (Whiteside et al. 1977). These internal structure characteristics of the stem such as knottiness, wood density, fiber deviation or microfibril angle result from growth, crown dynamics, competition and thus from stand density (Mitchell 1975; Pretzsch and Rais 2016). Dead branches of Douglas-fir persist over a long

time, as natural self-pruning is slow and only mildly dependent on spacing (Reukema and Smith 1987; Hermann and Lavender 1990). Hence, the time span between competition-induced branch mortality within young Douglas-fir trees and the corresponding enhancement of wood quality can be as long as 60 years (Cahill et al. 1988). A pivotal decision for further stirring the timber quality development of Douglas-fir is whether to apply artificial pruning or not (Carter et al. 1986; Smith et al. 1997).

Previous work has investigated the influence of initial stocking levels on stem, crown and branching characteristics of Douglas-fir, and the resulting quantity and quality of timber using empirical data (Carter et al. 1986; Klädtke et al. 2012; Rais et al. 2014; Grace et al. 2015). Empirical studies, however, are often limited to an observation time range that is markedly shorter than the rotational period. Within the study at hand, we therefore apply an individual tree growth and board strength model (Poschenrieder et al. 2016) to extrapolate wood quality development of intensively monitored Douglas-fir experimental plots (Rais et al. 2014; Klädtke et al. 2012) to the time of final harvest. The mechanistic simulation model relates the long-term influence of stand density, growth potential and competition to sawn timber properties due to internal stem structure development. It has been modified specifically to the growth potential and the competition effect on stem and crown development observed within a subset of these plots. Based on the simulated bending strength per individual board, we calculate the net present value (NPV) for each of the three management pathways, which correspond to an initial stocking of 1000 ha⁻¹, 2000 ha⁻¹ and 4000 ha⁻¹. The NPV is defined as the sum of the revenues minus the sum of costs, suitably discounted along time (Price 1989). In particular, we consider the effect of the interest rate, of the pruning decision and of the price for high-quality timber on the NPV per each pathway.

We searched for answers to the following questions, using model-based future projections:

1. How sensitive is the NPV to establishment spacing without pruning?
2. To which extent does pruning influence the NPV in addition, and how strongly do different prices for different strength classes determine the economical effect?

Materials and methods

The growth and board-strength simulation model has been documented and evaluated in detail by Poschenrieder et al. (2016). Table 1 shows the equations with their parameterization sample size and parameter values. The model described mechanistically the major relevant linkages reaching from stand management and site influence via individual tree competition and growth, to crown shape and branch dimension and further down to knottiness, wood density and strength of the individual board. To that end, the model on the one hand had a retrospective part that reconstructs stem-structure development per individual tree based on empirical growth data and allometric rules. Input parameters for assessing wood quality were knot sizes such as the DEK (DIN 4074) or the tKAR (BS 4978), year ring width or cambial age (see Table 1). Stem eccentricity or out-of-roundness was not taken into account. On the other hand, it included a prospective part that aims at predicting the future development of stem structure by description of the growth process on annual time increments. Both parts required a stand inventory: The retrospective model part used the inventory for defining the final state of reconstruction. In turn, the prospective part used the same inventory as the initial condition for growth prediction. That setup inventory was the well-documented earliest per-plot inventory of 1989 that referred to a tree age of 19 years (Poschenrieder et al. 2016).

In Poschenrieder et al. (2016), model simulations had been aligned to stand structure and growth conditions through growth and board strength evaluation (a). In contrast, the study at hand investigated the sensitivity of the NPV to both planting density and pruning assuming a rotational period of 70 years (b). In addition, we conducted two simulations per each plot set (1000, 2000, 4000), i.e., one that applied pruning and one that did not. If the pruning option was not explicitly annotated in the following, all results presented referred to simulation without pruning (Fig. 1).

Thinning and pruning in the simulation model

Within our sensitivity study, we applied the same thinning program to all plot sets, whether pruning was to be used or not. Thinning prescription has been described and reasoned by the Douglas-fir spacing experiment in Klädtke et al. (2012) or Weller and Spellmann (2014). An exponentially falling guide curve (Fig. 2) defined the maximum count of live trees to persist per unit stand area as dependent on dominant tree height (Kenk and Hradetzky 1984). Stand density was guided through thinning at each 3 m step along the curve. In the simulation runs, we selected the same future crop trees, which were also selected on the experimental sites due to their spatial distribution and their vitality. In each thinning intervention, the future crop trees were fostered by removing competitors. Simulated future crop trees exclusively were pruned up to a stem height of 6 m and once at a dominant tree height of 15 m.

Table 1 Equations of DBH growth, tree height, crown shape, branch size and board strength given with parameterization sample size and parameter values

Algorithm	Equation	Number	Specification	Sample size	a_0	a_1	a_2	a_3	a_4
Growth quantile (cm y^{-1})	$p_q = a_0 \times d^{a_1} \times e^{(-a_2 \times d)}$	1	$q=95$	2080	1.02	0.324	0.028		
			$q=50$	2080	0.693	0.328	0.04		
			$q=5$	2080	0.382	0.301	0.049		
Predicted DBH growth (cm y^{-1})	$\Delta d(d) = p_{95}(d) \times e^{a_0 + a_1 \times S}\left(a_2 + a_3\bar{D} + a_4(d - \bar{d})\right)$	2	Any	5713	−0.348	−0.0004	−0.038	0.181	0.032
Reconstructed DBH growth at given DBH (d) (cm y^{-1})	$\Delta d(d) = p_1(d) \times \alpha + p_0(d) \times (1 - \alpha)$	3							
Growth corridor (lower)	$p_0 = p_5$ and $p_1 = p_{50}$ if $P_{5,n} \le d_{t0} < P_{50,n}$	4							
Growth corridor (higher)	$p_0 = p_{50}$ and $p_1 = p_{95}$ if $P_{50,n} \le d_{t0} < P_{95,n}$	5							
Weight	$\alpha = \dfrac{d(t_0)-L_0}{L_1-L_0}$ where $L_0 = \sum_{i=1}^n p_{0,i}$ and $L_1 = \sum_{i=1}^n p_{1,i}$	6							
Height (m)	$h = h_0 + (a_0 + a_1 \times d_g) \times e^{\frac{a_2 + a_3 \times d_g}{d}}$	7	$P=1000$	866	−4.33	1.27	−4.21	−0.155	
			$P=2000$	1579	−0.27	1.29	−2.80	−0.20	
			$P=4000$	865	2.65	1.34	−2.00	−0.24	
Crown base height (m)	$\mathcal{B} = h \times (1 - e^{a_0 + a_1 \times \ln(d) + a_2 \times d})$	8	Any	3599	0.630	−0.944	−0.0122		
Crown diameter (m)	$\mathcal{C} = a_4 \times e^{a_0 + a_1 \times \ln(d) + a_2 \times h + a_3 \times \ln\frac{h}{d}}$	9	Any	594	0.597	0.0845	0.0340	−0.887	1.25
Branch diameter (mm)	$d = a_2(a_0 + a_1 \times 1)$	10	Any	991	4.78	8.68	1.2		
Wood density (kg m^{-3})	$\rho = a_0 \times e^{\frac{-a_1}{\mathcal{A}}} + a_2 + a_3 \times \mathcal{W}$	11	Any	802	162	39.9	494	−7.11	
Bending strength (N mm^{-2})	$s = a_0 + a_1 \times \rho + a_2 \times \mathcal{E} + a_3 \times \mathcal{A} + a_4 \times \mathcal{K}$	12	$\mathcal{A} \le 20$	606	−32.0	0.150	−18.3	0.504	−21.3
			$\mathcal{A} > 20$	103	−45.0	0.175	−5.43	0	−3.64
Wood density (kg m^{-3})	$\rho = a_0 + a_1 \times \mathcal{W} + a_2 \times \mathcal{D}$	13	any	802	515	−10.7	2.28		
Bending strength (N mm^{-2})	$s = a_0 + a_1 \times \rho + a_2 \times \mathcal{E} + a_3 \times \mathcal{D} + a_4 \times \mathcal{T}$	14	any	709	−45.22	0.18	−10.69	0.53	−25.81

D Diameter at breast height (DBH, 1.3 m) (cm), $\overline{D}$ mean distance of nearest neighbors (m), S Local stand density index within 2.5×crown radius, p Growth quantile, A Weight, h_0 Breast height, const = 1.3 m, d_g Quadratic mean stem diameter (QMD) (cm), 1 Branch length, P Planting density, $\mathcal{A}$ Mean cambial age of board, $\mathcal{W}$ Mean ring width of board, $\mathcal{E}$ DEK of biggest knot in board (DIN 4074-1 2012), $\mathcal{K}$ tKAR (BS 4978, 2007), $\mathcal{T}$ Top diameter of log

Fig. 1 Data flow for model development and parameterization—introduced by Poschenrieder et al. (2016)—aligned the model to the experimental plots and their surveys (**a**). Based on the model, simulations run over a rotational period of 70 years were made (**b**)

(a)

Development and parametrisation of the model — Poschenrieder et al. (2016)

(b)

Simulations / temporal extrapolation
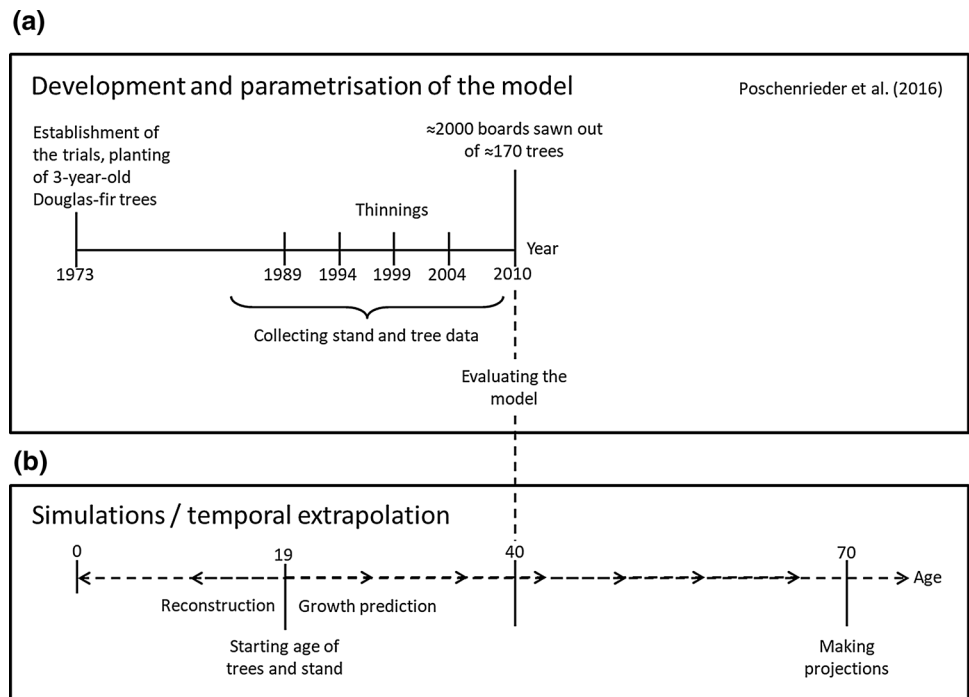
Fig. 2 Thinning was controlled by a guide curve provided in Kenk and Hradetzky (1984), the guide curve controls competitive pressure through maximum tree number per ha as dependent on dominant height

Number of trees after thinning in trees ha^{-1}

Dominant height in m
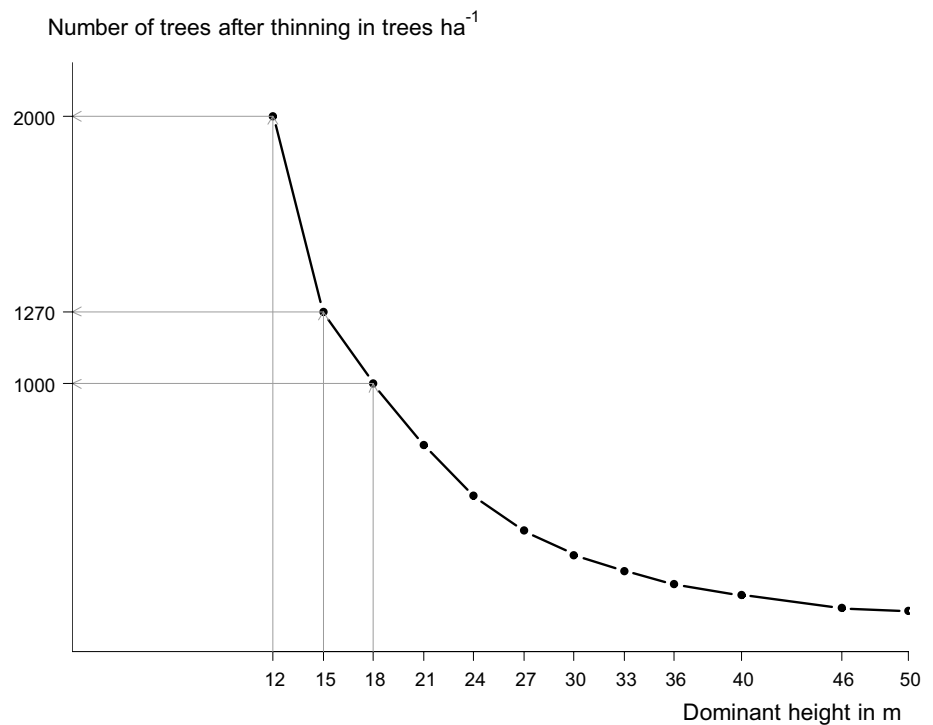
Bucking of logs and sawing of boards

Whenever a simulated tree was removed in the course of thinning or through final cut at the end of the rotation period after 70 years, the model dissected the tree's stem into as many saw logs as possible. The criteria for a saw log were a minimum length of 4.1 m and a top diameter larger than 20 cm under bark. Remaining small-sized logs were considered as pulpwood when their top diameter was larger than

Table 2 Assumed prices of timber per m³ for pulpwood, residual wood and sawn timber, which were used in the simulations

	Roundwood	Sawn timber					
		Residual wood	Strength class, EN 338				Appearance class knot-free
	Pulpwood		C30	C24	C18	Reject	
Price (€ m⁻³)	45	30	300	250	220	160	300[a]

Strength classes in accordance with EN 338 (2016)

[a] The reference price of 300 € m⁻³ for knot-free boards was assumed to increase to 400, 500 and 600 € m⁻³; the different price options took into account higher timber quality and in particular favored timber of pruned logs

10 cm and less than 20 cm without bark and the minimum log length larger than 2 m.

Each saw log is described by (1) annual rings as determined by annual growth and (2) stem-internal branch fractions as determined by crown size. A sawing module derived boards from each sawn timber log. It applied a sawing pattern that aimed at obtaining as many center boards as possible of the preferred cross section of 50 mm × 150 mm. That pattern was typical for a cant sawing system used for straight sawing. Thereafter, a grading module assigned each board to one of the European strength C-classes (EN 338) on the basis of DIN 4074 grading standard for softwoods. The strength class combination C30, C24 and C18 (plus rejects) was used as these are currently the most commonly used strength classes for visually graded wood.
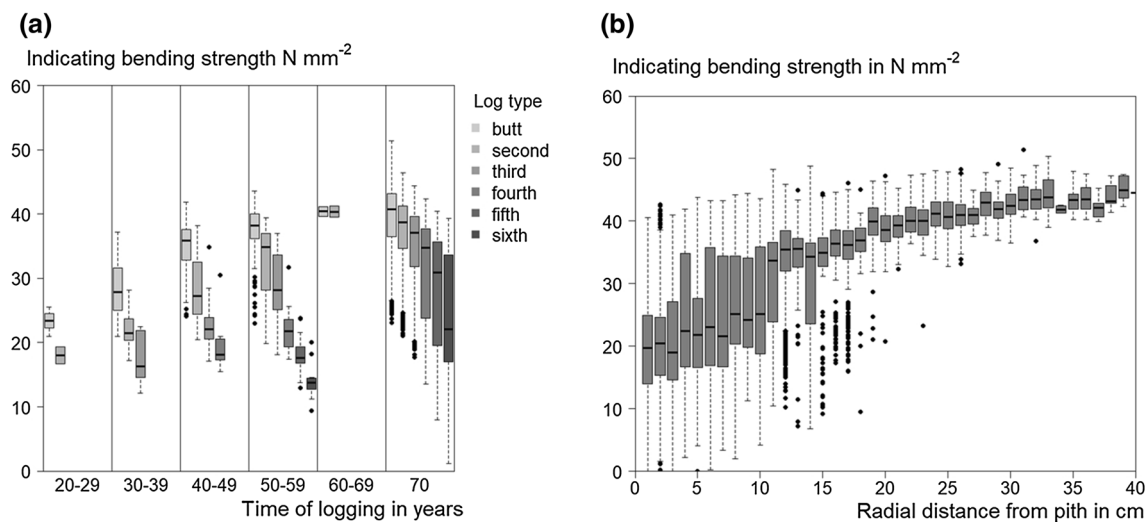
Economic evaluation

In order to measure and compare the profitability of the different stand treatment options, the NPV was determined by calculating the costs and benefits for each period (Thommen and Achleitner 2012). The NPV considered all future cash flows over the entire life of an investment and discounted them to the present. The entire rotation period was subdivided into 10-year periods, and all the negative and positive cash flows per each 10-year period were assumed to incur in its middle. Exempt were establishment and—if applicable—pruning costs, which both were not averaged over a 10-year period: Instead, they referred to the exact year, in which planting, respectively, pruning took place. Similarly, the benefits from the final clear-cutting occurred at a stand age of 70 years. Finally, the present value of each period was determined by discounting its future value at a periodic rate of return and all the discounted future cash flows were summed up to get the NPV. Three different interest rate options were realized: 0%, 2% and 4%.

Establishment costs were assumed to be 1.5 € per tree (Beinhofer and Knoke 2011). Pruning costs were supposed to be 8 € per tree (Beinhofer and Knoke 2011), i.e., 1200 € ha⁻¹ for 150 future crop trees per ha. Pruning costs occurred at an age of 20 years. Remaining benefits of pruning were calculated by subtracting the benefits of pruning from the benefits without pruning. To get the monetary difference (Fig. 5), the remaining benefits were discounted by inflation-adjusted interest rates (0%, 2% and 4%) over the time range between pruning and harvest and finally compared with the discounted costs. Wood prices per unit volume were generally defined on a per-assortment basis (pulpwood, residual, sawn timber) and moreover in detail per sawn timber strength class (Table 2).

As pruning affected only future crop trees, we focused on the benefits at the time of clear-cutting only and on the

Table 3 Simulation results over a 70-year rotation period with a final clear-cutting for different establishment spacings: Column "removed trees" shows number, average dimension and volume, column "logs" shows volume of pulpwood and of saw logs, column "sawn timber" shows volume of sawn timber with the yields for strength class combination C30/C24/C18; all values presented per 10-year period. In bold figures (without sigma sign), the volume-weighted yield of both strength and appearance classes is shown

Initial planting density (trees ha⁻¹)	Intervention (year)	Harvested trees				Logs		Sawn timber								
		Number (–)	Mean dbh (cm)	Mean height (m)	Volume (m³ ha⁻¹)	Pulpwood[1] volume (m³ ha⁻¹)	Sawlog volume (m³ ha⁻¹)	Volume (m³ ha⁻¹)	C30 (%)	Knot-free (%)	C24 (%)	Knot-free (%)	C18 (%)	Knot-free (%)	Reject (%)	Knot-free (%)
1000																
	20–29	26	24.8	17.8	10	5	3	1	0	0	0	0	100.0	0	0	0
	30–39	395	26	21.3	221	90	94	47	0	0	0	0	96.0	2.1	1.9	0
	40–49	215	24.8	24.1	148	43	82	43	0	0	8.2	0	90.6	1.2	0	0
	50–59	39	27.7	29.1	50	7	36	20	1.5	0	19.4	1.1	70.4	1.4	5.8	0.3
	60–69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	70	194	53.3	53.8	1143	41	1003	610	13.3	1.9	20.2	0.4	50.9	2.6	9.9	0.8
					Σ 1572			Σ 721								
									11.3	**1.6**	**18.1**	**0.4**	**56.8**	**2.5**	**8.7**	**0.7**
2000																
	20–29	703	16.8	14.9	117	72	0	0	0	0	0	0	0	0	0	0
	30–39	527	18.2	18.3	150	76	33	16	0	0	2.7	0	90.2	7.1	0	0
	40–49	210	16.0	20.1	63	27	21	11	0	2.8	25.4	1.9	69.9	0	0	0
	50–59	16	17.2	25.5	7	2	3	2	14.1	0	40.4	0	45.6	0	0	0
	60–69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	70	205	52.2	52.3	1230	42	1077	657	15.1	1.8	20.2	0.6	48.6	2	10.6	1.1
					Σ 1567			Σ 686								
									14.5	**1.8**	**19.9**	**0.6**	**49.9**	**2.1**	**10.2**	**1.0**
4000																
	20–29	1348	12.2	13.2	109	44	0	0	0	0	0	0	0	0	0	0
	30–39	635	13.8	17.7	98	54	2	1	0	0	0	0	100.0	0	0	0
	40–49	78	20.8	26.2	35	19	8	4	3.4	9.9	47.8	4.5	34.4	0	0	0
	50–59	21	24.9	31.2	15	7	5	3	21.1	12.5	27.0	6.2	30.1	3.1	0	0
	60–69	4	21.1	29.8	2	1	0	0	0	0	0	0	0	0	0	0
	70	213	58.2	58.7	1495	46	1315	804	17.7	3.2	19.2	0.8	48.3	3.4	7.2	0.2
					Σ 1754			Σ 812								
									17.6	**3.3**	**19.3**	**0.9**	**48.2**	**3.4**	**7.2**	**0.2**

(a)

Indicating bending strength N mm^{-2}

(b)

Indicating bending strength in N mm^{-2}

Fig. 3 The general behavior of the model in terms of sawn timber quality, independent on the establishment spacing. Sawn timber strength was highest at final cutting, but also the axial log position influenced the strength (**a**). With increasing radial distance from the pith, timber strength increased (**b**)

Table 4 Benefits versus costs of sawn timber per initial planting density and time of intervention (treatment without pruning)

Initial planting density (trees ha^{-1})	Intervention (year)	Benefits		Costs (€ ha^{-1})
		Sawn timber (€ ha^{-1})	All timber (sawn timber, residual wood, pulpwood) (€ ha^{-1})	
1000	0			1500
	20–29	220	500	
	30–39	10370	15830	
	40–49	9600	12710	
	50–59	4540	5340	
	60–69	0	0	
	70	143580	157210	
			$\sum$ **191590**	
2000	0			3000
	20–29	0	3240	
	30–39	3600	7530	
	40–49	2540	4060	
	50–59	490	610	
	60–69	0	0	
	70	155150	169640	
			$\sum$ **185080**	
4000	0			6000
	20–29	0	1980	
	30–39	220	2680	
	40–49	990	1970	
	50–59	790	1170	
	60–69	0	40	
	70	194290	211690	
			$\sum$ **219530**	

Table 5 Net present value (NPV) as dependent on interest rate and initial planting density (treatment without pruning)

Initial planting density (trees ha^{-1})	NPV in € ha^{-1} at interest rate		
	0%	2%	4%
1000	17660	3950	210
2000	15510	2010	− 1520
4000	15950	− 340	− 4460

pruning costs. The costs of pruning were considered for all establishment spacings. All of the 150 future crop trees were pruned. Apart from the strength grading rules, we introduced an aspect of appearance grading: If boards were knot-free—independent on the strength class, different additional cash flows were calculated for the following prices of such boards: 300 € m^{-3} (equal to C30-boards), 400 € m^{-3}, 500 € m^{-3} and 600 € m^{-3} (Table 2).

Within the scope of the sensitivity analysis, the costs of harvesting, transporting and sawing were assumed to be independent of tree size and the amount of logs. These costs were moreover approximated to 90% of benefit, based on a plausible profit margin of 10% as has been reported in the literature (Koskinen 2017). The costs for harvesting, transporting and sawing were automatically considered and reduced the benefits. The specific costs for planting and eventually pruning were considered additionally and reduced the benefits in the second step. If pruning had been applied, i.e., answering the second research question (2), the NPV was calculated and subtracted from a reference, the NPV without pruning. The final variable was called monetary difference.

Results

## How sensitive is the NPV to establishment spacing at no pruning?

The simulation results are given in Table 3. The total volume production was similar for all plot sets, but highest in set 4000 (1754 m^3 ha^{-1}). Due to high stand density, first thinning took place at the age range from 20 to 29 years and a large number of trees were removed. The dimension of these trees was still small, resulting in a pulpwood volume of 44 m^3 ha^{-1}. In contrast, for plot set 1000, the number of trees harvested per hectare at the same age was small. Due to lower spatial competition here, the average diameter of harvested trees was comparatively large, i.e., 24.8 cm compared to 12.2 cm for the 4000 set.

The proportion of volume of harvested trees by thinning (all intervention before final cutting) was 27%, 22% and 15% in ascending order of the establishment spacings. Based on saw log volume, the respective values were 18%, 5% and 1%. In particular, saw logs and thus sawn timber were obtained before the final cutting as a result of thinning in the plot set 1000. At the time of final harvest (intervention "70"), tree volume was the highest within plot set 4000 (1495 m^3 ha^{-1}) and yielded the highest saw log and pulpwood volumes (1315 and 46 m^3 ha^{-1}).

There was an increase in the simulated strength to be observed with tree age (Fig. 3a), which was due to the fact that the timber quality increased with increasing distance from the pith (Fig. 3b). Figure 3 shows results from the
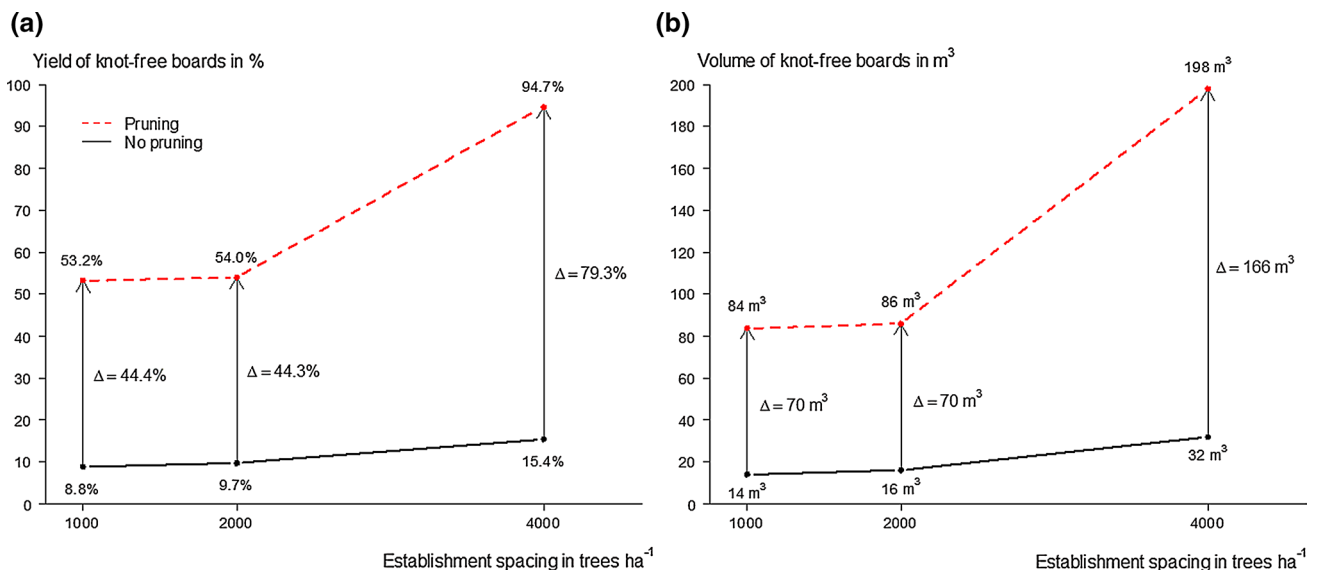
Fig. 4 Impact of artificial pruning on average timber yield (**a**) and volume (**b**) in knot-free boards depending on establishment spacings, only focusing on the pruned logs (= butt logs of future crop trees)
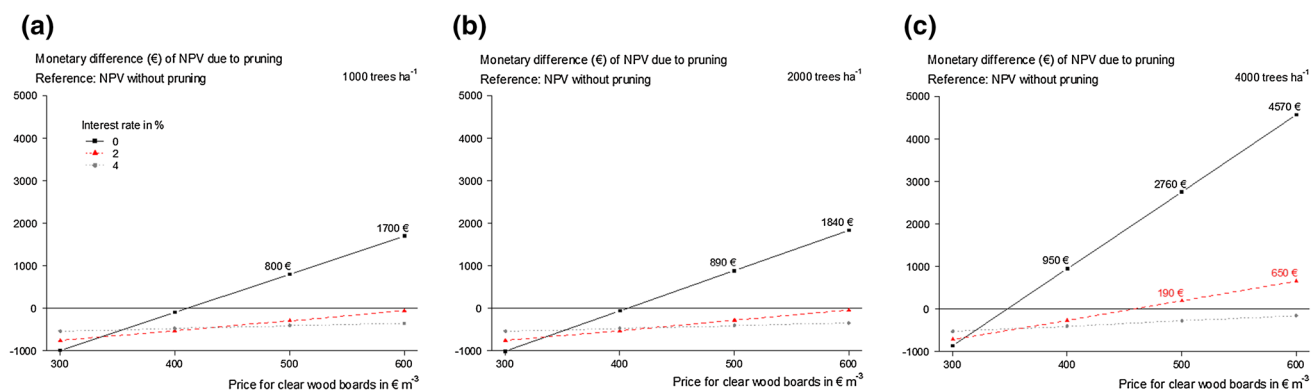
Fig. 5 Additive effect of pruning on NPV in relation to establishment spacing (**a**–**c**), interest rate (line type) and price for knot-free boards (*x*-axis)

simulations over all three spacings. The model also indicated that the quality of the sawn timber decreased axially in the stem (Fig. 3a). All of this resulted in the highest wood quality available at the end of the rotation period. The highest planting density achieved the best results after a 70-year rotation period: The (volume-weighted) yield of the highest strength class, C30, as well as the yield of knot-free boards within plot set 4000 was highest (17.6% and 3.3%) compared to plot sets 2000 (14.5% and 1.8%) and 1000 (11.3% and 1.6%). The lowest reject rate of sawn timber also resulted from an initial stand density of 4000 ha^{-1} (7.2%).

The financial reward which resulted from sawn timber, pulpwood and residual wood depended on the establishment option (Table 4). The densest establishment spacing achieved the highest benefits, as in particular the positive cash flow at the end of rotation period was the highest.

Plot set 1000 achieved the highest NPV for 0%, 2% and 4% interest rate (Table 5). At an interest rate of 4%, the financial return over the rotational period could not counterbalance opportunity costs and investment into planting; only the plot set 1000 stayed positive with 210 € ha^{-1}.

To which extent does pruning influence the NPV in addition?

The influence of pruning on average timber quality of the entire stem was lower than of the butt log, since most of the future crop trees were bucked into more than ten logs of 4.1 m. Pruning was commonly applied at a top height of 15 m. Pruning had a marked influence in particular on the timber yield of the future trees' butt logs (Fig. 4). Due to early branch removal, the knot-free-board yield increased. Throughout all strength classes and only looking at the butt logs of the future crop trees (Fig. 4a), the yields of knot-free boards increased from 8.8 to 53.2% (1000 ha^{-1}), from 9.7 to 54.0% (2000 ha^{-1}), from 15.5 to 94.7% (4000 ha^{-1}). The

volume of knot-free boards increased as well with increasing establishment spacing (Fig. 4b). At the same time, the yield for C30 decreased by 18.5%, 20.9% and 48.8% because lots of the boards were knot-free and graded as such. The figures of Fig. 4 cannot be calculated from Table 3 due to two reasons: Table 3 does not differentiate between tree (normal and future crop tree) and log type (butt log, second log, etc.).

The absolute change of the NPV through pruning—the unpruned simulation runs served as reference—was related to the initial planting density (Fig. 5a–c). It depended on interest rate (annotated by color) and price assumption for knot-free boards (along horizontal axis). The monetary differences of NPV are given with their value only if they were positive. For all three establishment spacings, the NPVs were positive for zero interest rate and knot-free board prices of 500 € m^{-3} or above. Additionally, pruning did have a positive effect on the NPV for plot set 4000 for the combination 0% interest rate and 400 € m^{-3} knot-free board price as well as 2% interest rate and at least 500 € m^{-3} knot-free board price. Assuming an interest rate of 4%, none of the establishment and price options resulted in a positive difference due to pruning.

Discussion

The parameter used for the economic evaluation, the NPV, aggregated the effect of both planting density and pruning on wood quality and production. At the calculation of the NPV, income that was at the beginning of the investment was only discounted by an (assumed) interest rate over a few years. On the contrary, income that arose late at the end of the investment period was minimized over many years—depending on the interest rate. Looking at the 4000 option, the main cash flow over the whole rotation period was focused on future crop trees, positive cash flows due to thinning were comparably low (Table 4). Although timber quality and quantity of

the future crop trees from the 4000 option were superior to the other options, the 1000 option achieved the highest NPV (17660 € without pruning)—also at an interest rate of 0%. Considering higher interest rates of 2% or 4% (Beinhofer 2008), the 1000 option extended its superiority over the other options as early and high benefits of the first thinning intervention out compensated the comparatively low benefit of the final cutting. Stands with high planting density were thinned early, but the harvested trees could be not processed as sawlogs, only as pulpwood. Our results coincided with empirical studies about the coordinated Douglas-fir spacing experiment in South Germany. In a joint study, Klädtke et al. (2012) have thoroughly investigated the economic effect of various planting densities 40 years after the establishment by Abetz (1971). They underpinned a favorable effect of lower to average initial stocking levels from a plausible range of 1000–4000 trees ha⁻¹ based on roundwood grading. From an economic point of view, they recommended an initial tree number in the range from 1000 to 2000 Douglas-fir plants per hectare.

The NPV depends on many influencing factors. Our simulation study focused on several factors (establishment spacing, price for knot-free boards) and suggested the economic effects of their change. Other influencing factors such as the thinning type, the profit margin of 10%, the sawing pattern or the boards' cross sections remained constant. Hence, the main objective was to exemplify the application of the wood quality model to real-world plots and to study whether such a model enabled extrapolation of experimental plot results to an entire rotational period. Therefore, the study at hand investigated whether the sensitivity of the simulation system was plausible.

Within the assumed rotational period, future-crop trees achieved DBHs that are targeted nowadays (Anonymous 2016). The calculated scenarios were strongly based on the management plan with regard to planting density, thinning and pruning, whereby the simulator basically allowed other silvicultural methods to be analyzed. Empirical studies exhibited the potential of Douglas-fir's wood quality focusing on old (future-crop) trees (von Pechmann and Courtois 1970; Möhler and Beyersdorfer 1987; Sauter 1992). The simulated planting densities reflected the recommended current densities (Bayerische Staatsforsten 2012) and were comparable to planting densities from the literature for the Pacific Northwest from 300 to 2960 trees ha⁻¹ (Scott et al. 1998), for Switzerland from 1346 to 2790 trees ha⁻¹ (Schütz et al. 2015), for Belgium from 2200 to 4400 trees ha⁻¹ (Henin et al. 2018) and for Germany from 1000 to 4000 trees ha⁻¹ (Weller and Spellmann 2014; Rais et al. 2014) as well as from 500 to 4000 trees ha⁻¹ (Klädtke et al. 2012).

The model was parameterized with trees of the same planting densities (Poschenrieder et al. 2016). We retained the experimental thinning guide curve (Fig. 2), which

implied a common switch from quality-oriented to dimension-oriented management through control of maximum stand density, starting at a common biological age, as given by top height. The thinning concept caused a convergence of the competitive situation within the rotation, whose consequences were already identifiable at the measured slenderness of dominant trees at an age of 35 (Weller and Spellmann 2014) and of future crop trees at an age of 40 years (Klädtke et al. 2012). In the first years after planting, the highest competitive pressure was among trees from the 4000 option because at those plots simply the highest stand density occurred. As soon as the dominant height was more than 21 m, the number of trees ha⁻¹ was equal irrespective whether initial planting density was 1000, 2000 or 4000 trees ha⁻¹ (Fig. 2). At around this time, the gradient of competition pressure from the 1000 to the 4000 option reversed: Individual tree competition became lowest at the 4000 option since the stand basal area was the smallest as compared to the 1000 and 2000 options. At final cutting, the diameter at breast height was highest for future crop trees grown at the densest establishment spacing option.

The board dimensions, i.e., length and cross section, were set to the same values as used for model parameterization (Poschenrieder et al. 2016) as the simulation focused in particular on the economic link between silvicultural measure and its monetary effect. Concurrently, we took into account that local defects such as knots become more frequent with board length and that timber strength accordingly decreases (Isaksson and Thelandersson 1995; Øvrum et al. 2011; Rais and Van de Kuilen 2017). Similarly, the cross section of sawn timber might influence sawn timber's mechanical properties (Barrett and Fewell 1990; Denzler 2007; Stapel and Van de Kuilen 2013, 2014). The sawing pattern was identical to logs of all diameters, i.e., the amount of large boards (cross section 50×150 mm²) was maximized.

In general, natural pruning of Douglas-fir is slow and not greatly aided by high initial planting density although at closer spacing crowns were reported to lift earlier (Reukema and Smith 1987). Artificial pruning on the one hand allows boosting timber quality by producing knot-free wood much earlier. Knots strongly influenced strength and stiffness of structural products that constitute Douglas-fir's major product market (Lowell et al. 2014). On the other hand, pruning can negatively affect growth through excessive intensity. One-third of the live crown was removed from a Douglas-fir tree without major loss of diameter growth (O'Hara 1991; Maguire and Petruncio 1995; Gartner et al. 2003). In the simulations, the limit of one-third of the living crown was never exceeded. The time until the pruning scars are healed completely and high-quality wood without knots is produced, can be assumed to be 10 years if the pruning takes place at an age of 15 years

(Dobie and Wright 1978). The economic success of pruning depends on many parameters such as tree age, tree and knot size, pruning method, the number of trees being pruned in the stand and finally the sawing pattern. Pruning in this study had been applied at young stage (tree age 20 years) with the intention of keeping the knotty core small and producing small limbs scars. If combined to the 4000 ha^{-1} option of initial planting density, early pruning resulted in the largest amount of knot-free wood produced (Fig. 4), which again may be caused by the thinning concept and its convergence of the competitive situation: DBH at the time of pruning was smallest, DBH at the time of harvesting was largest. However, the most pivotal point for the pruning decision might be its supposed future benefit, which is hard to predict (Mosandl and Knoke 2002). Past prices for pruned logs had been thought to be more lucrative than they turned out to be (Cahill et al. 1988). Further model-based optimization therefore will have to consider a range of possible future benefits from board classes, as attempted by this sensitivity study (300–600 € m^{-3} for knot-free boards).

Conclusion

Using an individual tree model with an integrated sawing simulator and board bending strength prediction module, the main objective of our study was to exemplify the application of its wood quality model to real-world plots. The lowest establishment spacing gave the most NPV in a 70-year rotation plan. Pruning was not a preferable option. In this simulated production chain, many options and settings can be changed in the growth module, in the sawing module, in the grading module and in the economic module and adapted to future questions.

The study implicitly presumed a scenario where forestry and sawmill industry were closely linked. The scenario is not precisely the most prevalent one, where the timber price is typically based on roundwood quantity and quality. The simulation model allows assessing the wood quality similar to that use in the construction sector.

Based on a simulation approach, similar to the one presented, a future analysis might focus on the economic effects of planting and pruning. To this end, it would likely sample economic constraints, such as the profit margin, from a statistical distribution. Such a distribution would be based on a plausible presumption of future market development. However, the application of the model for analysis of management effects on future income was beyond the study's scope.

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