Impact of spacing and pruning on quantity, quality and economics of Douglas-fir sawn timber: scenario and sensitivity analysis

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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 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
mechanistically the major relevant linkages reaching from

time, as natural self-pruning is slow and only mildly depend-
ent 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 characteris-
tics 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 inten-
sively 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 influ-
ence of stand density, growth potential and competition to
sawn timber properties due to internal stem structure devel-
opment. 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 stock-
ing 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 with-
out pruning?
2. To which extent does pruning influence the NPV in addi-
tion, 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 parameteriza-
tion 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 dimen-
sion 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 empiri-

cal 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 camb-
ial 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 develop-
ment of stem structure by description of the growth pro-
cess 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 pro-
spective 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 con-
trast, the study at hand investigated the sensitivity of the NPV
to both planting density and pruning assuming a rota-
tional 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 domi-
nant tree height (Kenk and Hradetzky 1984). Stand den-
sity 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 fos-
tered 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$^{-1}$)  | $p_q = a_0 \times e^{a_1 q} \times e^{-a_2 q} \times e^{d g}$            | 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$^{-1}$) | $\Delta d(d) = P_{q=95}(d) \times e^{a_0 d} + a_1 S/\bar{d} + a_2 \bar{D} + a_3 (d - \bar{d})$ | 2      | Any           | 5713        | -0.348 | -0.0004| -0.038 | 0.181  | 0.032  |
| Reconstructed dbh growth at given dbh (d) (cm y$^{-1}$) | $\Delta d(d) = p_1(d) \times a + p_0(d) \times (1 - a)$ | 3      |                |             |        |        |        |        |        |
| Growth corridor (lower)        | $p_0 = p_5$ and $p_1 = p_{50}$ if $P_{50,n} \leq d_t < P_{50,n}$       | 4      |                |             |        |        |        |        |        |
| Growth corridor (higher)       | $p_0 = p_{50}$ and $p_1 = p_{95}$ if $P_{95,n} \leq d_t < P_{95,n}$     | 5      |                |             |        |        |        |        |        |
| Weight                         | $\alpha = \frac{d h_{t0}}{L_{1} - L_{0}}$ where $L_{0} = \sum_{i=1}^{n} p_{0,i}$ and $L_{1} = \sum_{i=1}^{n} p_{1,i}$ | 6      |                |             |        |        |        |        |        |
| Height (m)                     | $h = h_0 + (a_0 + a_1 \times d_g) \times e^{a_2 d_g}$                  | 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)          | $B = h \times (1 - e^{a_0 + a_1 \times d_g})$                           | 8      | Any           | 3599        | 0.630  | -0.944 | -0.0122|        |        |
| Crown diameter (m)             | $C = a_4 \times e^{a_0 + a_1 \times d_g} \times e^{a_2 + a_3 \times d_g}$ | 9      | Any           | 594         | 0.597  | 0.0845 | 0.0340 | -0.887 | 1.25   |
| Branch diameter (mm)           | $d = a_5 (a_0 + a_1 \times L)$                                         | 10     | Any           | 991         | 4.78   | 8.68   | 1.2    |        |        |
| Wood density (kg m$^{-3}$)     | $\rho = a_6 e^{a_0 + a_1 \times d_g} + a_2 + a_3 + \mu W$               | 11     | Any           | 802         | 162    | 39.9   | 494    | -7.11  |        |
| Bending strength (N mm$^{-2}$) | $s = a_6 + a_7 \times \rho + a_8 + a_9 \times \epsilon + a_{10} + a_{11} + K$ | 12     | $A \leq 20$  | 606         | -32.0  | 0.150  | -18.3  | 0.504  | -21.3  |
|                               |                                                                          |        | $A > 20$      | 103         | -45.0  | 0.175  | -5.43  | 0      | -3.64  |
| Wood density (kg m$^{-3}$)     | $\rho = a_0 + a_1 \times W + a_2 + D$                                  | 13     | Any           | 802         | 515    | -10.7  | 2.28   |        |        |
| Bending strength (N mm$^{-2}$) | $s = a_0 + a_1 \times \rho + a_2 + \epsilon + a_3 + D + a_4 + T$       | 14     | Any           | 709         | -45.22 | 0.18   | -10.69 | 0.53   | 25.81  |

$D$ Diameter at breast height (dbh, 1.3 m) (cm), $\bar{D}$ 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), $L$ Branch length, $P$ Planting density, $A$ Mean cambial age of board, $W$ Mean ring width of board, $\epsilon$ dek of biggest knot in board (DIN 4074-1 2012), $K$ tKAR (BS 4978, 2007), $D$ Distance from pith of board cross-sectional centre, $T$ Top diameter of log.
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...
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 wood and 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 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        | 0        | 0         | 0         | 0         |
|                                          | 30–39               | 395           | 26            | 21.3 | 221          | 90               | 94               | 47        | 0        | 0         | 0         | 0        | 0         | 96.0      | 2.1       | 1.9       |
|                                          | 40–49               | 215           | 24.8          | 24.1 | 148          | 43               | 82               | 43        | 0        | 0         | 8.2       | 0        | 0         | 90.6      | 1.2       | 0         |
|                                          | 50–59               | 39            | 27.7          | 29.1 | 50           | 7                | 36               | 20        | 1.5      | 0         | 19.4      | 1.1      | 0         | 70.4      | 1.4       | 5.8       |
|                                          | 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      | 0         | 50.9      | 2.6       | 9.9       |
|                                          | 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        | 0         | 100.0     | 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       |
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                   | 220      | 500            |
|                                      | 20–29               | 10370    | 15830          |
|                                      | 30–39               | 9600     | 12710          |
|                                      | 40–49               | 4540     | 5340           |
|                                      | 50–59               | 0        | 0              |
|                                      | 60–69               | 0        | 0              |
|                                      | 70                  | 143580   | 157210         |
|                                      | ∑ 191590            |          |                |
| 2000                                 | 0                   | 0        | 3240           |
|                                      | 20–29               | 3600     | 7530           |
|                                      | 30–39               | 2540     | 4060           |
|                                      | 40–49               | 490      | 610            |
|                                      | 50–59               | 0        | 0              |
|                                      | 60–69               | 0        | 0              |
|                                      | 70                  | 155150   | 169640         |
|                                      | ∑ 185080            |          |                |
| 4000                                 | 0                   | 0        | 1980           |
|                                      | 20–29               | 220      | 2680           |
|                                      | 30–39               | 990      | 1970           |
|                                      | 40–49               | 790      | 1170           |
|                                      | 50–59               | 0        | 40             |
|                                      | 60–69               | 0        | 0              |
|                                      | 70                  | 194290   | 211690         |
|                                      | ∑ 219530            |          |                |
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

![Impact of artificial pruning on average timber yield](image)

**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  |
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.

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, Klädte 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 Bayersdorfer 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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