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Effect of harvest interval and intensity on the profitability of uneven-aged management of Norway spruce stands

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This study evaluates the profitability of uneven-aged management in boreal forests, focusing on Norway spruce (*Picea abies* (L.) Karst.). An individual-tree-based model EFIMOD is used to simulate the dynamics of soil organic matter, resource availability and forest growth. Considered management scenarios are constructed by varying the harvest interval and intensity (i.e. post-harvest basal area). Bare land, young stand and several uneven-aged managed mature stands are evaluated as initial stand states in the profitability analysis. The profitability of uneven-aged management is compared with traditional even-aged management. Uneven-aged management is profitable under all considered initial stand states and management scenarios with 3 per cent interest rate. Even-aged management is more profitable than uneven-aged management when the initial stand state is bare land or a young stand. The profitability is usually the opposite when uneven-aged managed mature stands are considered as the initial state. This, however, requires that the most profitable steady-state management regime, involving a 10-year harvest interval and $4\,m^2\,ha^{-1}$ post-harvest basal area, is applied. Conversion of even-aged Norway spruce stand to uneven-aged is financially feasible when the stand structure of the even-aged stand has a wide diameter distribution of standing trees rather than the more restricted range usually associated with conventional management using thinning from below.

Introduction

The prevailing silvicultural system in boreal forests is even-aged management, but recent studies have indicated that this management type may not be either the most profitable alternative or ecologically resilient and the most sustainable system (Cordonnier *et al.*, 2008; O'Hara and Ramage, 2013). Growing public interest in uneven-aged forest management has recently inspired the elaboration of the economics of uneven-aged forest management. However, there are still severe knowledge gaps regarding the management practices of uneven-aged forests and transition period from even-aged to uneven-aged stands (Drössler *et al.*, 2014; Lundqvist, 2017). Particularly in Finland and Sweden, where conifer forests have been managed under an even-aged management system for a long time (Siiskonen, 2007), enhancing the understanding of how alternative management regimes impact the profitability of forestry management is needed to provide landowners with sustainable silvicultural guidance for the management of uneven-aged forests.

Current good practice guidance for forest management is mostly focused on even-aged forestry, where long-term experiments with thinning from below have provided a basis for empirical analyses and model development. For uneven-aged forest management, such a legacy of experimental data is not available, but advanced ecosystem models (e.g. Shanin *et al.*, 2016) that are calibrated with experimental data from a set of uneven-aged stands can be used for the evaluation of management alternatives (Eerikäinen *et al.*, 2014).

Research on optimal uneven-aged forestry has a long history from Adams and Ek (1974) to papers by Rämö and Tahvonen (2014; 2017), which included summaries of previous optimization studies on uneven-aged management. In the optimization of uneven-aged management, the aim is to find out optimal steady-state stand structures and cutting schedules. Previous studies have also compared the profitability of even-aged and uneven-aged management (e.g. Chang, 1981; Haight and Monserud, 1990; Tahvonen, 2009; Pukkala *et al.*, 2010; Tahvonen, 2011; Tahvonen, 2016), finding that uneven-aged management was typically more profitable. In comparison with even-aged management, the relative profitability of uneven-aged management increases with increasing interest rate, increasing forest management costs, decreasing timber prices and decreasing site productivity.

Empirical models were used in most optimization studies. Usually, these are matrix models based on transition probabilities of trees from one size/age class to the next one, estimated with experimental data (as used in Rämö and Tahvonen, 2014; Tahvonen and Rämö, 2016) or growth equations with empirical coefficients (e.g. Wickström, 2000; Pukkala *et al.*, 2010). So far individual-based process models have had limited use in optimizing uneven-aged management due to higher complexity and larger number of parameters in comparison with, for example, the studies on optimization of even-aged management (Niinimäki *et al.*, 2012; Pihlainen *et al.*, 2014). However, individual-based process models have been applied in the optimization of management for rockfall protection (Rammer *et al.*, 2015) and optimization of thinning intensity and frequency (Bonté *et al.*, 2013; Lafond *et al.*, 2014) in uneven-aged stands. It has been shown, however, that the optimization result can be heavily influenced by the growth model used (Tahvonen *et al.*, 2013). Therefore, economic studies on uneven-aged management would benefit from the further development of growth models (Rämö and Tahvonen, 2014).

In this study, we focus on the management of Norway spruce (*Picea abies* (L.) Karst.), which has a high potential for uneven-aged management as a shade-tolerant species. Regarding spruce forests, the results of recent studies (e.g. Pukkala *et al.*, 2010; Tahvonen, 2011) show that the optimal steady-state basal area before/after harvest is about 18–12/9–2 $m^2 ha^{-1}$ (*Myrtillus* site type), depending on the site characteristics including temperature sum and fertility. The results depend also on the values of economic parameters, such as the interest rate used in discounting associated revenues and costs. The higher the temperature sum, fertility or the interest rate, the lower the optimal basal area after harvest. In addition, the results of previous studies suggest that the optimal harvesting interval is about 15–20 years. The lower the interest rate, the longer the optimal harvest interval. Previous studies have optimized simultaneously harvest intervals and intensity, but they have not systematically presented results including different combinations of harvest interval and intensity (post-harvest basal area) and they have not analysed the size of profit differences between alternative management regimes. This information is highly interesting for forest owners and needed to guide policy development and the practice of forest management.

We extend previous studies by examining how harvest interval and intensity affect the profitability of uneven-aged management of Norway spruce forests. This is done by presenting a grid (matrix) in which the financial performance is tabulated against the harvest interval and thinning intensity for each uneven-aged management alternative. The aim is to provide silvicultural guidance for the management of uneven-sized forests, covering not only the economically optimal management regime, but a wide spectrum of different harvest alternatives and associated economic outcomes in the grid (matrix). While developing management guidance for forest owners, it is important to identify the optimal regime for timber production, but as forest owners may have also other objectives than timber production, it is equally important to reveal how the deviation from the optimal regime affects the profitability of forestry, and how close alternative management schedules are to the optimum solution. Such information provides new possibilities to practical decision-making, since trade-offs between management (harvest interval and thinning intensity) and financial performance can easily be depicted with the aid of the grid. In addition, we analyse the economic outcome of the uneven-aged forest management in comparison to conventional even-aged management. Simulations of uneven-aged Norway spruce stands presented by Shanin *et al.* (2016) provided input for the analyses.

In contrast to previous studies, we apply the process-based ecosystem model EFIMOD, which is a spatially explicit, individual-tree- and process-based model that simulates the tree–soil system (Komarov *et al.*, 2003; Shanin *et al.*, 2015, 2016). The first version of the EFIMOD was developed in 1990s for the European Forest Institute (with a model name of European Forest Institute MODel, EFIMOD). Thereafter, the model has consistently been referred to as EFIMOD while authors have further developed and validated the model to various forest management questions (e.g. Komarov *et al.*, 2003; Palosuo *et al.*, 2008; Shanin *et al.*, 2016). The advantage of such process-based models, in comparison with empirical models, is that they can predict the dynamics of key ecosystem properties not only at ambient conditions but also in a changing environment, while empirical models are more limited to the current conditions. An important feature of the EFIMOD model is the detailed and spatially explicit description of above and belowground competition, which allows simulation of the effects related to the selection cuttings. The applied model is calibrated with long-term (30 years) experimental data from stands that have had uneven-aged stand structure.

The growth model and scenarios

Short description of EFIMOD and validation of the model

The EFIMOD is a spatially explicit, individual-based model that simulates the biological turnover in tree–soil systems (Komarov *et al.*, 2003). A simulated stand consists of individual trees which interact with neighbouring trees. Each tree forms a shadow zone and a nutrition zone, the sizes of which depend on the tree size and can overlap with neighbouring trees. Thus, two possible types of tree increment can be calculated: one due to the amount of intercepted solar radiation and another due to soil nitrogen availability. The calculation requires species-specific estimates of leaf or needle and fine root biomass, maximal biological productivity of leaves or needles, and the specific nitrogen consumption rate. The minimal value of these two increment parameters is taken as the annual increment, following Liebig's law of the minimum (Liebig, 1843). The annual net production of each tree is distributed among five compartments (stem, branches, leaves/needles, fine roots and coarse roots). The coefficients of the model are species-specific and it operates with an annual time step.

The forest growth sub-model is linked with the ROMUL sub-model, which describes the dynamics of carbon and nitrogen in soil (Chertov *et al.*, 2001) and calculates the amount of nitrogen available for tree growth. The pools of soil organic matter (SOM) in ROMUL are forest floor, labile humus originating from decomposing root litter, and stable humus within the mineral soil consisting of SOM, originating from humified intermediate products of root litter decomposition, and similar humified products originating from decomposed compounds transported from the forest floor into the mineral layer. They are bonded with soil minerals and have a slow rate of decomposition (Chertov *et al.*, 2001). The rates of decomposition of SOM are dependent on temperature and moisture of the forest floor and the mineral soil as well as on the nitrogen and ash content in the litter. Additionally, ROMUL calculates an amount of mineral nitrogen available for plant nutrition.

The model has previously been calibrated for spruce forests in southern Finland, with local growth and yield tables and experimental data (Shanin *et al.*, 2013, 2014). The EFIMOD was validated (Shanin *et al.*, 2016) with experimental data from 20 permanent observation plots established 1991–1992 for studies on tree and stand development in managed, uneven-aged Norway spruce forests (61°00′N–62°00′, 25°00′– 27°30′E) conducted under the ERIKA research project at the Natural Resources Institute Finland (Eerikäinen *et al.*, 2007, 2014; Saksa and Valkonen, 2011). The validation with experimental data is a common practice for the performance test of complex simulation models (e.g. Troitzsch, 2017). According to the validity testing, the EFIMOD model performed well with reproduction of measured stem number, basal area, height and DBH distribution. Additionally, the EFIMOD was previously compared with empirical based forest growth simulator MOTTI (Palosuo *et al.*, 2008). The comparison showed a good agreement between models for most forest sites.

Simulation scenarios

The simulation experiment was made with climate and soil data that represented conditions of Juupajoki, Finland (61°50′ 47 N, 24°17′35E). The simulation scenarios in this study were designed to estimate the influence of harvest interval and the remaining stand density on dynamics of forest stands in terms of their productivity. The size of the simulation plot was set at 100 × 100 m (1 ha). The initial situation of simulations was the same in all scenarios: 2 000 five-year-old spruce trees, H = 1.4 m and DBH = 0.3 cm established by planting, with admixture of pine (100 trees), birch (100 trees) and aspen (50 trees). According to the scenarios, two pre-commercial thinnings from below were carried out after tree planting: first, 5 years after initialization (tending of sampling stands, 50 per cent removal in terms of basal area) and second, 15 years after initialization (33 per cent removal in terms of basal area). Species other than spruce were mainly removed during these thinnings; however, a proportion of 10 per cent in terms of number of trees was retained if available. The scenarios assumed that only stem biomass was removed, while branches, foliage and belowground parts were left on the cutting area and therefore included in the decomposition process. Since the model has no specialized regeneration module, regeneration was simulated as the emergence of new trees with random displacement. The ingrowth rate (number of newly established trees with DBH > 0.5 cm) and species composition of regeneration were calculated according to equations given in the work done by Pukkala *et al.* (2012) and varied from 10 to 80 trees ha^{-1} a^{-1} for different stand development stages. No artificial planting (except in the beginning) was simulated during the simulation period.

A series of selection cuttings was initiated at stand age of 31 years when the stand reached the basal area of 22.1 m^2 ha^{-1}. The period between two consecutive selection cuttings was defined by the harvest interval R (years). The intensity of selection cutting was defined by the limiting value of post-harvest stand basal area L, (m^2 ha^{-1}), which should be reached after the removal of a part of the largest trees (Figure 1). In brief, the lower the value (post-harvest basal area), the higher the intensity of the thinning conducted. Usually, during the selection cuttings, some trees with DBH > 25 cm need to be retained to ensure sufficient seed production. Therefore, we simulated the retention of 5 per cent of trees of the largest size class. Harvesting in the EFIMOD was simulated as the removal of aboveground biomass of randomly selected trees from all size classes that had DBH ≥ 18 cm. In some scenarios, DBH ≥ 16 cm was used, because it was not otherwise possible to obtain the required post-harvest basal area. The randomized procedure was used to ensure that all tree sizes, from small seedlings to large trees, are intermingled in all parts of the stand (Lundqvist, 2017). Belowground biomass and the certain proportion of aboveground compartments were retained on simulation plot as felling residues. We simulated the removal of 100, 90 and 50 per cent of stems, branches and foliage, respectively (Shanin *et al.*, 2016).

A set of simulation scenarios was obtained by varying both harvest interval and intensity. The duration of the simulation period was 91 years. It was chosen in such a way that the longest rotation (30 years) was repeated twice; in other scenarios, the rotations were repeated to achieve the same total duration of the simulation period. The considered harvest intervals were 10, 15, 20 and 30 years. The values of post-harvest stand basal area were 4, 6, 8, 10, 12 and 16 m^2 ha^{-1}, which is a range suggested in the earlier studies (Pukkala *et al.*, 2010; Tahvonen *et al.*, 2010; Tahvonen, 2011; Rämö and Tahvonen, 2014, 2015; Shanin *et al.*, 2016) and therefore allows comparison of the results.

The scenario of unmanaged stand development (UNMGD) was used as a reference. It assumed the growth of trees without any management interventions. The regeneration was simulated in the same way as in scenarios with selection cuttings.

The scenario of traditional even-aged management (TRAD) started with the same planting and pre-commercial thinnings as in scenarios with selection cuttings. Two thinnings from below were simulated at 34 (basal area was reduced from 27 to 18 m^2 ha^{-1}) and 44 years (basal area was reduced from 29 to 18 m^2 ha^{-1}). Final harvesting was simulated at a stand age of 61 years, when mean stem DBH reached 27.2 cm and basal area reached 31 m^2 ha^{-1}. Principally, this management regime (TRAD) represents a sub-optimal management (cf. Niinimäki *et al.*, 2012), but it closely resembles current practical forestry for even-aged spruce management in Finland (see Äijälä *et al.*, 2014) with adequate financial performance (net present value exceeding 2 500 € ha^{-1} with 3 per cent discount).

To assess the economic benefits of the management strategies, the amount of merchantable wood was calculated in terms of proportion of timber assortments of different quality and total volume of harvested wood. The individual stem volumes were calculated with stem taper curve functions using

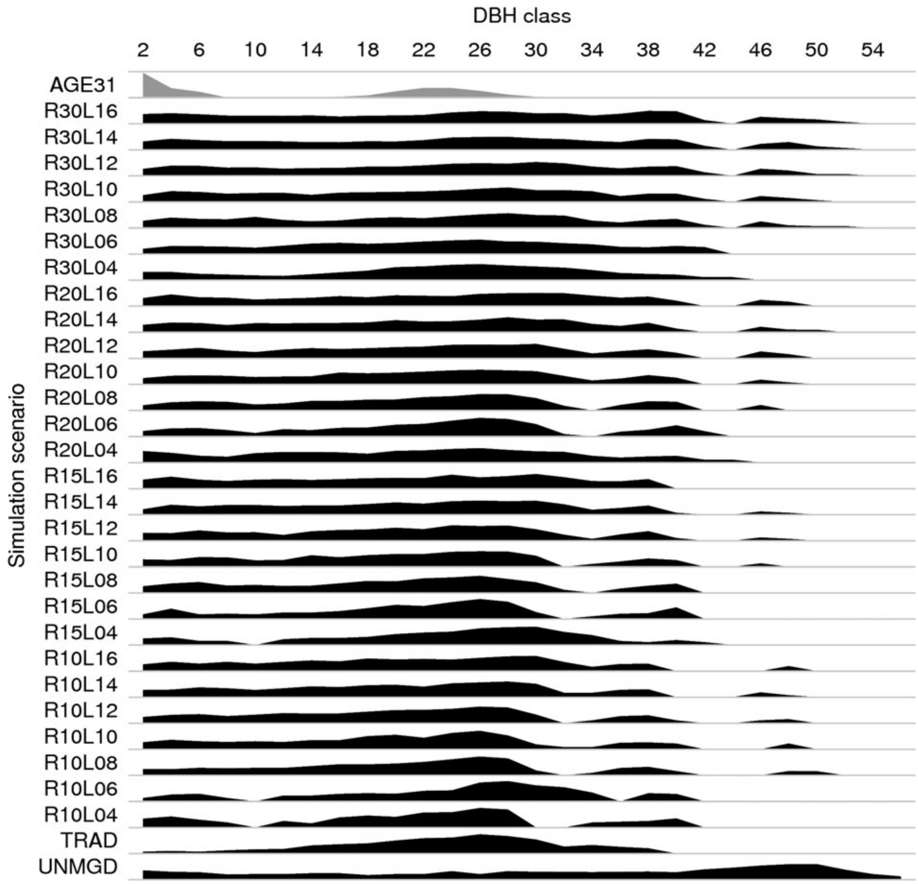

Figure 1 Distribution of standing trees among DBH classes before the first harvest (AGE31, the same distribution for each scenario) and before the last harvest, according to simulated scenarios. In the code of simulated scenarios for uneven-aged management, R10–R30 refer to a harvesting interval from 10 to 30 years and L04–L16 refer to the post-harvest basal area from 4 $m^3\ ha^{-1}$ to 16 $m^2\ ha^{-1}$, e.g. R15L10 is a harvesting interval of 15 years with the post-harvest basal area of 10 $m^3\ ha^{-1}$. TRAD refers to the simulation of traditional even-aged management (two thinnings and clear-cutting), and UNMGD is the unmanaged reference scenario. For more clarity, the square root transformation was applied to the data when plotting them on the figure to reduce the range between minimum and maximum values and thus make the distribution curves more clearly expressed.

the TapeR package for *R* (Kublin *et al.*, 2013). The curves were first calibrated with empirical data (Laasasenaho, 1982). The proportions of sawnwood and pulpwood were also calculated for each individual stem with the same taper curve functions where sawnwood was defined as the volume of stem section from the stem base until the $D = 16.0$ cm, and pulpwood was calculated as the volume of stem section between $D = 16.0$ and $D = 7.0$ cm (Halonen, 2011). The volume of remaining stem section was considered as tops (Shanin *et al.*, 2016).

Economic analysis and parameter values

The profitability of forestry was defined as the present value of net harvest revenues. As described in the previous section, multiple scenarios with different harvest intensities and intervals were considered. Let us denote the harvest interval (years) in scenario s by $\hat{t}_s$ ($\hat{t}_s = 10$, 15, 20 and 30) and the duration of the simulation period (years) by T, fixed in each scenario. The volumes of harvest ($m^3\ ha^{-1}$) at time period t in scenario s are h_{lts} and h_{pts} for sawlogs and pulpwood (tree species are omitted for clarity). Denote the roadside prices (€ m^{-3}) by p_l and p_p, respectively. The harvest revenues (€ ha^{-1}) at period t in scenario s are $R_{ts} = p_l h_{lts} + p_p h_{pts}$. Let c_{ts} refer to the harvest costs (€ ha^{-1}) at period t in scenario s, including cutting and haulage costs; the interest rate is r. The regeneration costs (€ ha^{-1}) at period t are w_t, including costs of site preparation ($t = 0$), planting ($t = 0$), tending of sapling stands ($t = 5$) and pre-commercial thinning ($t = 14$).

We considered three initial stand structures in examining how harvest interval and intensity impact the profitability of uneven-aged management: (1) bare land, (2) young stand (31 years after artificial regeneration) and (3) uneven-aged managed mature stand (91 years after artificial regeneration). For bare land, the present value of net harvest revenues was calculated as follows:

$$\pi_s^1 = -\sum_{t=0}^{a} w_t e^{-rt} + \sum_{t=a}^{T-\hat{t}_s} (R_{ts} - c_{ts}) e^{-rt} + (R_{Ts} - c_{Ts}) e^{-rT} (1 - e^{-r\hat{t}_s})^{-1} \quad (1)$$

in which t is the time (years). In addition, a denotes the year for the first harvest period and T the year for the last harvest period, which were equal in each scenario ($a = 31$ and $T = 91$), that is, the artificial regeneration phase and the length of the simulation period were the same in each scenario, but the harvest regime, starting at year a, differed. The steady-state harvest was approximated by assuming that it equals to the last simulated harvest, which is applied to infinity as shown by the last additive term on the right-hand side of equation (1).

Regarding the young initial stand, the net present value was calculated as shown by the following equation:

$$\pi_S^2 = \sum_{t=a}^{T-\hat{t}_s} (R_{ts} - c_{ts})e^{-r(t-a)} + (R_{Ts} - c_{Ts})e^{-r(T-a)}(1 - e^{-r\hat{t}_s})^{-1} \quad (2)$$

The artificial regeneration phase was omitted, that is, the regeneration costs were treated as sunk costs in this case. The first harvest was conducted at the initial time period ($t_s = a$), that is, 31 years after regeneration. Therefore, in this case, the initial state was the same in all scenarios, but the harvest regime differed. When the initial stand structure represented an uneven-aged managed mature stand, the present value of net harvest revenues was calculated by

$$\pi_S^3 = (R_{Ts} - c_{Ts})(1 - e^{-r\hat{t}_s})^{-1}, \quad (3)$$

where the initial stand structure and associated net revenues differed between scenarios.

For comparison, we also calculated the present values of harvest revenues for even-aged management under the three initial stand structures, applying the classical Faustmann model (Faustmann, 1849). For bare land, the net present value was calculated as

$$\pi_F^1 = \left(-\sum_{t=0}^{a} w_t e^{-rt} + \sum_{t=a}^{T^*} (R_{tF} - c_{tF})e^{-rt}\right)(1 - e^{-rT^*})^{-1}, \quad (4)$$

in which T^* denotes the clear-cut stand age (61 years). In addition to clear-cutting the net revenues, $R_{tF} - c_{tF}$, in equation (4), cover revenues and costs of thinnings (at 34 and 44 years). Regarding the young and the uneven-aged managed mature initial stands, present values of net revenues were calculated using equations (5) and (6), respectively:

$$\pi_F^2 = \sum_{t=a}^{T^*} (R_{tF} - c_{tF})e^{-r(t-a)} + \pi_F^1 e^{-r(T^*-a)}, \quad (5)$$

$$\pi_{FS}^3 = R_{TFs} - c_{TFs} + \pi_F^1, \quad (6)$$

In equation (6), the harvest volume associated with the net revenues, $R_{TFs} - c_{TFs}$, includes the volume of the last harvest, according to the uneven-aged management, plus the volume of the standing timber after the last harvest for each scenario.

We used a 3 per cent interest rate as a basis level in the calculations but assessed also the effects of 1 and 5 per cent levels on the profitability of uneven-aged management. In addition, we used the average of regeneration costs from 2010 to 2015 in Finland, adjusted by the cost-of-living index. The costs of site preparation were 359.90 € ha^{-1}, while that of planting were 744.90 € ha^{-1}, the tending of sapling stands 250.00 € ha^{-1} and pre-commercial thinning 413.87 € ha^{-1} (Anonymous, 2016). Similarly, we used real average roadside prices of the years 2011–2015: pine sawlog 58.3 € m^{-3}, pine pulpwood 29.7 € m^{-3}, spruce sawlog 57.4 € m^{-3}, spruce pulpwood 31.0 € m^{-3}, birch sawlog 47.3 € m^{-3} and birch pulpwood € 30.6 m^{-3} (Anonymous, 2016).

For uneven-aged management, total logging costs (including cutting and forest haulage) were based on a study by Surakka and Siren (2007) in which selection cuttings were conducted in four stands. Time consumption and productivity (based on cut-to-length harvesting system) were measured and, according to those measurements, we modelled total logging costs by a non-linear regression. In the model, average stem volume (dm^3) and cutting removal (m^3 ha^{-1}) were independent variables, and total logging costs were determined by the following formula: $f = y_0 + ax + bz$, where f is the total logging costs (€ m^{-3}), x is the cutting removal (m^3 ha^{-1}) and z is the average stem volume of the harvested trees (dm^3). The coefficients were as follows: $y_0 = 10.941$ (P-value < 0.0001), $a = 0.0267$ (0.0004) and $b = -0.0092$ (<0.0001). Since we modelled the combination of cutting and forest haulage simultaneously, the negative coefficient for average stem volume indicates that large stems slightly increase the overall productivity, thus resulting in a decrease in total logging costs. The model was tested to be statistically valid with respect to residual behaviour and P-value of the regression (<0.0001). For instance, with cutting removal equalling 40 m^3 ha^{-1} and average stem volume being 350 dm^3, total logging costs in the uneven-aged spruce stand were 8.80 € m^{-3}.

Total logging costs for the even-aged management scenario (TRAD) were adopted from Nurminen *et al.* (2010). In that study, time consumption was divided into different work phases, and each phase was separately measured, resulting in numerous time consumption and productivity models (Nurminen *et al.*, 2010). Separate models for thinnings (Nurminen *et al.*, 2010, eq. (13), p. 348) and for final felling (Nurminen *et al.*, 2010, eq. (11), p. 348) were applied in this study. Forest haulage was based on the values presented in Figure 5 by Nurminen *et al.* (2010, p. 353; mixed sawlogs with two assortments). Subsequently, we assumed a fixed hourly rate (75 € h^{-1}) for cutting machinery in thinnings and final felling (see Hynynen *et al.*, 2014), and an average forest haulage distance of 250 m was adopted. For instance, in final felling with an average stem volume of 450 dm^3 and a cutting removal of 160 m^3 ha^{-1}, total logging costs for even-aged management were 5.1 € m^{-3}.

Results

Stand structure and timber production

In comparison to TRAD, the simulated uneven-aged management resulted in a wider tree diameter distribution, a larger proportion of small-diameter trees, and the presence of large-diameter trees (Figure 1). In general, uneven-aged management with high post-harvest basal area resulted in a high proportion of large-dimension trees in harvests (Figure 2) and wider diameter distribution of remaining trees in comparison to traditional management (Figure 1). Also, the proportion of small standing trees was highest in the case of the high post-harvest basal area.

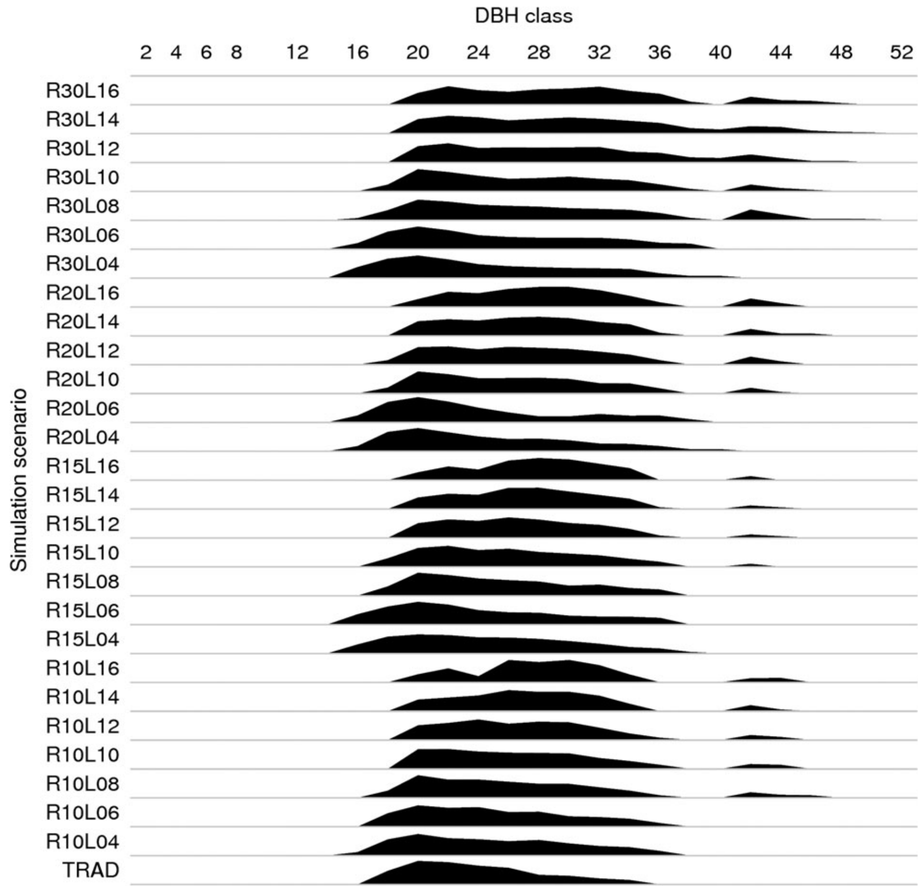

Figure 2 Distribution of harvested trees among DBH classes summarized through all harvest actions. Codes for simulated scenarios are as in Figure 1.

When lower post-harvest basal areas were applied, the diameters of harvested trees tended to be lower, and diameter distribution of standing trees was closer to being normally distributed than with less intensive harvesting. In unmanaged stands, the portion of large-diameter trees was the highest, and the size class distribution in the whole was more uniform (Figure 1).

The total amount of harvested timber volume, summarized through all commercial harvests conducted during the 31–91 simulation years, varied from 330 to 450 $m^3\,ha^{-1}$ and was lowest in the case of a short (10 years) harvest interval and a high post-harvest basal area (>12 $m^2\,ha^{-1}$). The mean annual increment (MAI) between the last two harvests fluctuated between 4.55 and 6.25 $m^3\,ha^{-1}\,yr^{-1}$, being highest with a 30-year harvest interval and with a 14 $m^2\,ha^{-1}$ post-harvest basal area and lowest with a 10-year harvest interval and a 16 $m^2\,ha^{-1}$ post-harvest basal area. In general, the amount of harvested timber decreased and standing volume after the latest harvests increased with increasing post-harvest basal area. Table 1 presents the characteristics (before harvest) of the initial stand states including the initial young and mature stands.

The total amount of harvested timber (in two thinnings and clear-cutting) in the case of TRAD was 490 $m^3\,ha^{-1}$. In the stands of uneven-aged management, the standing stock after the last harvest varied from 53 to 233 $m^3\,ha^{-1}$, depending on the post-harvest basal area level. The volume of the last harvest varied from 46 to 189 $m^3\,ha^{-1}$, increasing with high values of post-harvest basal area and longer harvest intervals. The net revenue of the last harvest varied from 2 364 to 8 826 € ha^{-1}, respectively. The timber volume harvested in the final cutting in the traditional scenario was 330 $m^3\,ha^{-1}$, while the associated net revenue was 14 680 € ha^{-1}.

Table 1 Characteristics of the initial young and mature stands. For mature initial stands, mean values and variation (the half of the range between minimum and maximum values) among different scenarios are presented.

	Young stand	Mature stand
Density, trees ha^{-1}	1626	519 ± 232
Mean DBH, cm	10.2	26.2 ± 4.2
Basal area, $m^2\,ha^{-1}$	22.1	28.4 ± 12.9

Profitability

Management initiated from bare land or young stand

The present value of the net harvest revenue varied between the two initial stand states: bare land and young stand

(Figure 3, see also AGE31 in Figure 1 for the distribution of standing trees in the initial young stand). The older the initial forest stand, the higher the value of standing timber and profit. In addition, there were no regeneration costs involved when the existing stand with ongoing rotation was considered. Thus, the present values of net harvest revenues were clearly higher when the initial state was the young stand compared with the corresponding values with bare land. Regarding the bare land and the young stand, the initial state did not, however, impact the ranking of simulation scenarios in terms of profitability, because the management regimes of scenarios were equal in these two cases. The profitability of uneven-aged management was lower than that of even-aged management (TRAD) when the initial state was bare land (Figure 3a) or young stand (Figure 3b). This is not surprising due to the costs of transition. It will take a long time and several harvests before the stand structure achieves the steady state under uneven-aged management.

Considering initial bare land or the young stand, the highest profit of uneven-aged management was obtained by applying a 15-year harvest interval with a basal area of 4 m^2 ha^{-1} after harvest (R15L04). In the 15-year harvest interval scenarios, the profitability increased with decreasing post-harvest basal area, but regarding the other harvest intervals, this pattern was not that clear. For example, in the 20-year harvest interval scenarios, the basal areas of 6, 8, 10 and 12 m^2 ha^{-1} after harvest yielded almost equal profit. The basal area of 4 m^2 ha^{-1} after harvest provided the highest profit for each harvest interval except for 30-year harvest interval. Considering 30-year intervals, the highest profit was obtained when basal area after harvest was 8 m^2 ha^{-1}. In general, the 10-, 15- and 20-year harvest intervals with basal areas from 4 to 10 m^2 ha^{-1} provided the highest profits for initial bare land and for the young stand.

Interestingly, there were relatively large differences in the profitability between the 15-year harvest interval scenarios when the post-harvest basal area varied, but this was not the case when the other harvest interval scenarios were considered. Considering the bare land, for example, the difference in the 15-year harvest interval between the best (R15L04) and worst (R15L16) scenarios was 27.4 per cent, while for other harvest intervals, the maximum difference was only 19.0 per cent. The average difference in the present values of the net harvest revenues between the best simulation scenario (R15L04) and the other scenarios was 18.0 per cent, respectively. The differences between uneven-aged management scenarios were smaller when the initial state was a young stand, for example, the average difference to the best scenario was only 10.9 per cent. Importantly, however, the best scenario in converting bare land or young stand to uneven-aged managed stand may not be the best steady-state uneven-aged management regime to be applied infinitely after the conversion as will be shown next.

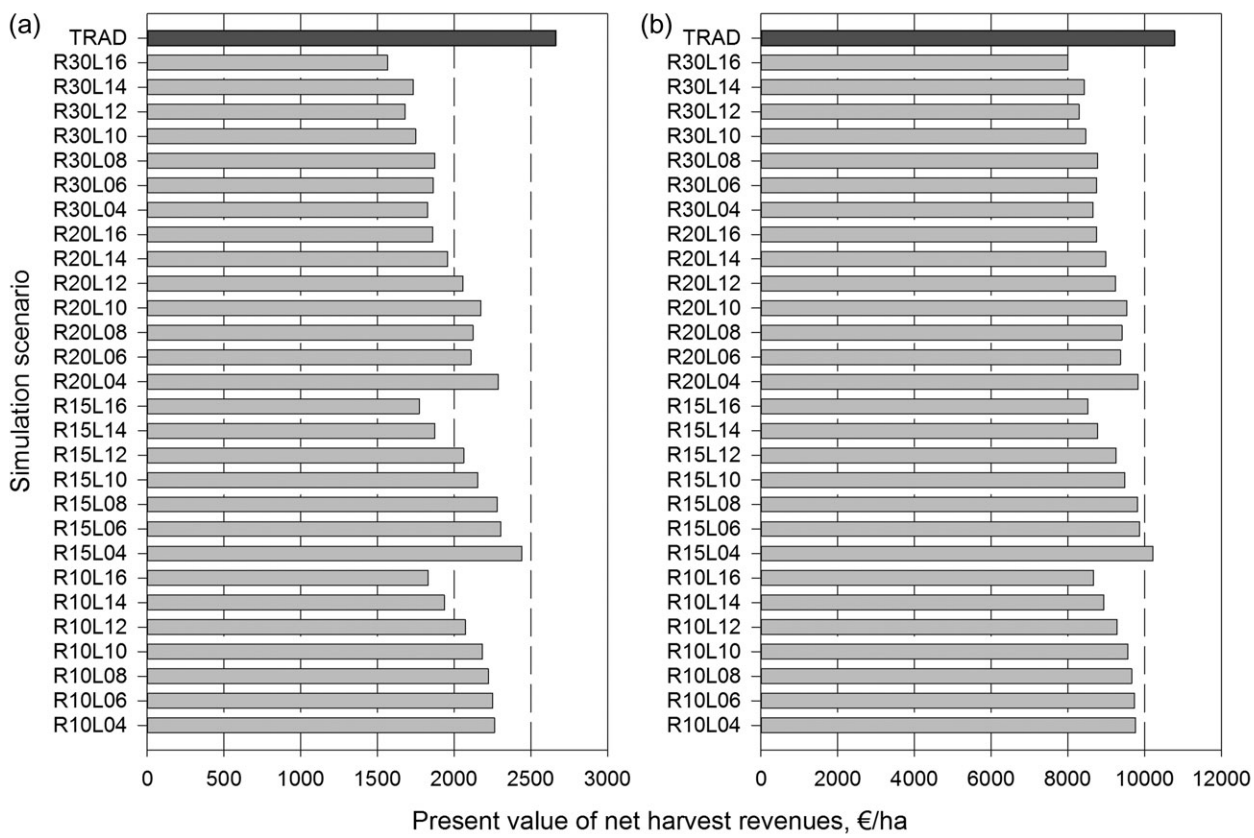

Figure 3 Present values of net harvest revenues for initial stand structures of bare land (a) and initial young stand (b) under uneven-aged and even-aged (TRAD) management by simulation scenarios. All simulations were started with artificial regeneration on bare land, growth in the first 31 years was simulated according to conventional silvicultural treatments. Discount rate was 3 per cent. Codes for simulated scenarios are as in Figure 1.

Management initiated from mature stands with wide diameter distribution

The profitability of uneven-aged management was high when the mature stand, including trees from multiple diameter classes after practising uneven-aged management, was considered (cf. Figures 3 and 4, and see Figure 1 for the distribution of standing trees in the initial stand). In the case when the initial stand structure of the mature stand was kept unaltered by continuing to follow the associated uneven-aged simulation scenario (Figure 4, white bar), the profitability of uneven-aged management was the highest when the initial stand state was obtained by using simulation scenarios R30L16 and R30L14 to date, that is, with large standing stock available for the first harvest. Typically, however, the scenarios with low basal area had a high profit under uneven-aged management. The opposite was true when the uneven-aged simulation scenario used to date was switched to the even-aged management, in which case all standing trees were removed immediately in the first harvest

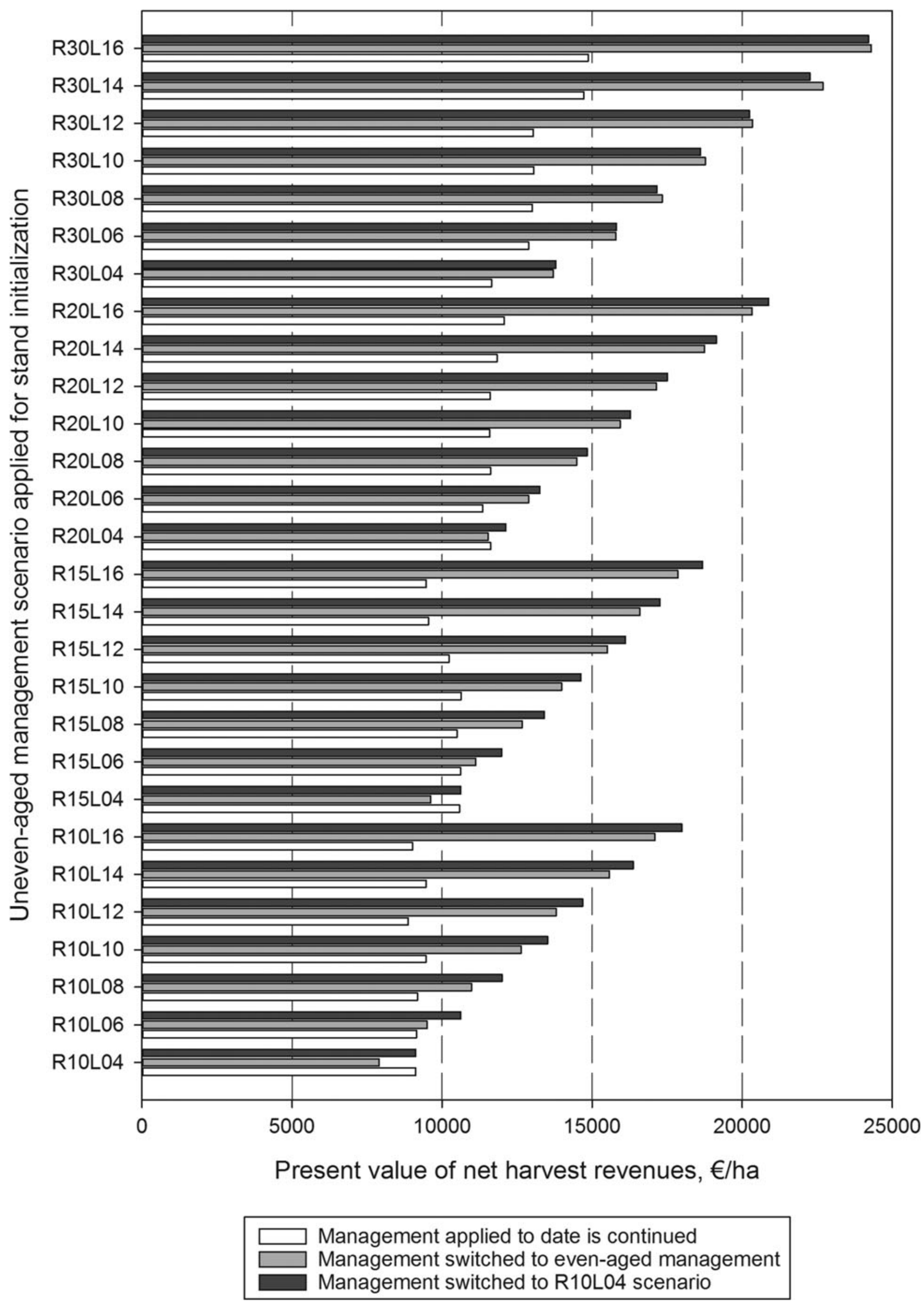

Figure 4 Present values of net harvest revenues for the initial mature stand under uneven-aged and even-aged management by simulation scenarios that are applied for stand initialization. Codes for simulated scenarios are as in Figure 1.

(Figure 4, grey bar). Given the mature stand, the profit of fixed uneven-aged management was higher than the profit of switching to even-aged management when the harvest interval was 10, 15 or 20 years and the post-harvest basal area was 4 $m^2\ ha^{-1}$ (cf. white and grey bars in Figure 4).

The simulation scenario used to date may not, however, provide the highest possible profit when the same scenario is continued. Instead, the associated stand structure of the mature stand needs to be converted to equal the structure of the best steady-state management regime, which was, in our case, R10L04 as shown in the Appendix Table A1 in Supplementary Data. The immediate switch to the best management was achieved by changing the first harvest regime to obtain the post-harvest basal area that was required in the R10L04 scenario and then applying the harvest interval and intensity of the R10L04 scenario for future rotations. Many initial states involved quite large harvest volumes in the first harvest when the management was switched, and therefore, the profitability of uneven-aged management clearly increased compared with the unaltered case (cf. black and white bars in Figure 4). Interestingly, after the conversion, the profitability of uneven-aged management was higher than the profitability of even-aged management for most of the considered initial stand structures (cf. black and grey bars in Figure 4).

The relative profitability of uneven-aged management compared with even-aged management depended on the initial stand structure of the mature stand (Figure 5). The profit increase of simulation scenarios used to date with a switch to the best regime varied between −1.9 and 15.4 per cent. The profit increase was negative (i.e. the relative profitability decreased indicating that the switch to even-aged management yielded higher profit) for initial stand structures that have formed after applying 30-year harvest interval and 8–16 $m^2\ ha^{-1}$ post-harvest basal area. The lower the post-harvest basal area and the shorter the harvest interval used to date, the higher the relative profitability of uneven-aged management.

It is also worth mentioning that a switch to the second and third best R15L04 and R20L04 scenarios yielded higher profit than even-aged management for many of the initial stand structures, identified by the scenarios used to date, similarly as the switch to the best R10L04 scenario (Table 2). On average, the profit increase (omit profit decreases) was 5.2 and 2.9 per cent, respectively. Thus, the profitability of R15L04 was almost as good as the profitability of R10L04. Regarding the other possible

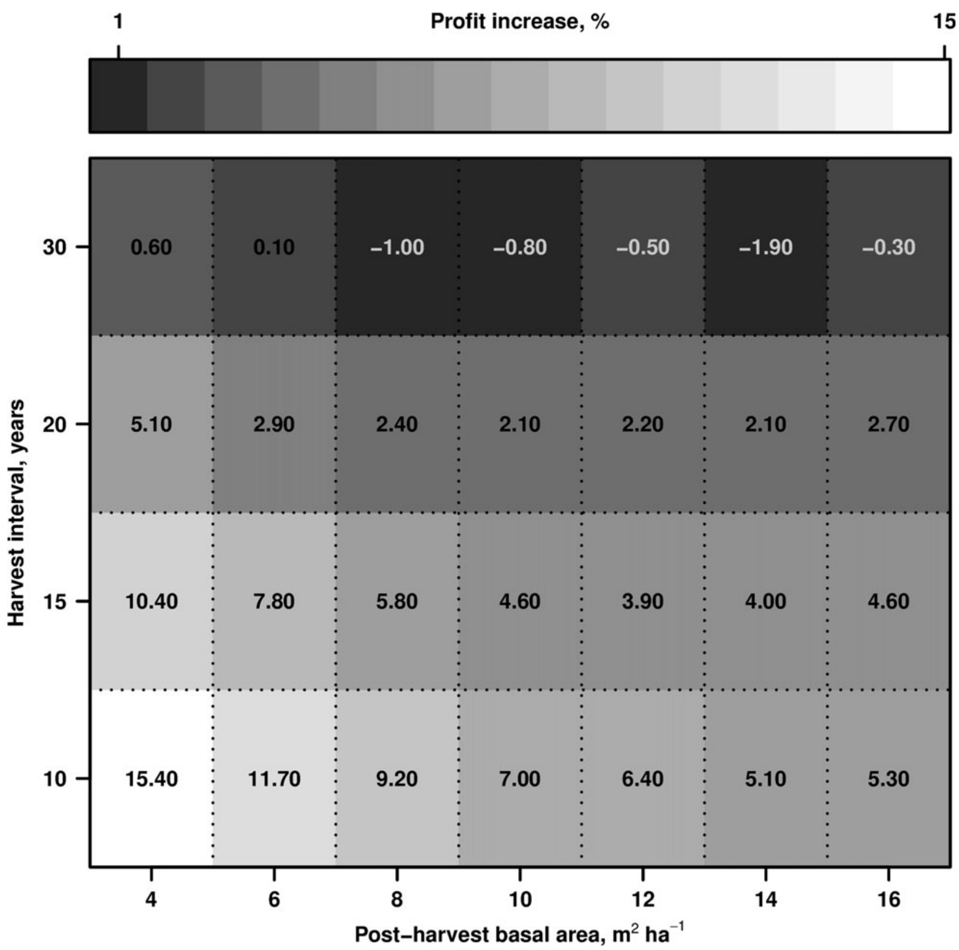

Figure 5 Relative profit increase (%) of uneven-aged management with switch to the best scenario (R10L04) compared with switch to the even-aged management by harvest interval and post-harvest basal area applied to date under uneven-aged management for the initial mature stand.

Table 2 Relative profit increase (%) of uneven-aged management with switch from the scenario used to date (initial stand structure) to the new uneven-aged management scenario compared with switch to the even-aged management for the initial mature stand. Codes for simulated scenarios are as in Figure 1.

Scenario used to date	Scenario switched to							
	R10L04	R10L06	R15L04	R15L06	R20L04	R20L06	R30L04	R30L06
R10L04	15.4	−2.5	14.8	−2.6	8.9	−10.4	−11.9	−22.8
R10L06	11.7	−3.7	11.2	−3.7	6.2	−10.2	−11.1	−20.5
R10L08	9.2	−4.0	8.8	−4.1	4.5	−9.7	−10.5	−18.6
R10L10	7.0	−4.5	6.6	−4.6	2.9	−9.4	−10.1	−17.2
R10L12	6.4	−4.3	6.0	−4.4	2.6	−8.9	−9.3	−15.9
R10L14	5.1	−4.5	4.8	−4.5	1.7	−8.5	−8.8	−14.8
R10L16	5.3	−3.5	5.1	−3.6	2.3	−7.2	−7.4	−12.9
R15L04	10.4	−4.0	10.0	−4.1	5.1	−10.4	−12.0	−20.6
R15L06	7.8	−4.5	7.4	−4.6	3.2	−10.1	−11.6	−18.9
R15L08	5.8	−5.2	5.5	−5.2	1.8	−10.1	−11.2	−17.8
R15L10	4.6	−5.6	4.3	−5.6	0.9	−10.0	−10.9	−17.0
R15L12	3.9	−5.4	3.6	−5.5	0.6	−9.4	−10.0	−15.7
R15L14	4.0	−4.8	3.8	−4.9	0.9	−8.6	−9.0	−14.5
R15L16	4.6	−3.9	4.3	−3.9	1.6	−7.4	−7.6	−12.8
R20L04	5.1	−6.2	4.7	−6.3	0.7	−11.6	−13.6	−20.1
R20L06	2.9	−7.2	2.6	−7.2	−1.0	−12.0	−13.8	−19.5
R20L08	2.4	−7.0	2.1	−7.0	−1.1	−11.3	−12.5	−18.0
R20L10	2.1	−6.6	1.9	−6.6	−1.1	−10.5	−11.4	−16.6
R20L12	2.2	−6.2	1.9	−6.2	−0.8	−9.8	−10.4	−15.5
R20L14	2.1	−5.6	1.9	−5.7	−0.6	−8.9	−9.4	−14.1
R20L16	2.7	−4.6	2.5	−4.6	0.2	−7.7	−7.9	−12.5
R30L04	0.6	−8.6	0.3	−8.7	−3.1	−13.1	−15.1	−20.2
R30L06	0.1	−8.3	−0.2	−8.4	−3.1	−12.2	−13.5	−18.4
R30L08	−1.0	−8.7	−1.3	−8.8	−3.9	−12.3	−13.4	−17.9
R30L10	−0.8	−8.1	−1.1	−8.2	−3.6	−11.4	−12.3	−16.6
R30L12	−0.5	−7.4	−0.7	−7.5	−3.0	−10.5	−11.1	−15.3
R30L14	−1.9	−8.1	−2.1	−8.1	−4.2	−10.8	−11.4	−15.1
R30L16	−0.3	−6.3	−0.5	−6.3	−2.5	−8.9	−9.2	−12.9

switches (not all results are shown), the even-aged management was more profitable than the uneven-aged management. In general, the profitability of the uneven-aged management was more sensitive to the change in the basal area than to the change in the harvest interval.

Effect of interest rate

As expected, the profitability of uneven-aged management depended on the interest rate. With a 1 per cent interest rate, even-aged management was more profitable than uneven-aged management, regarding all initial stand states and simulation scenarios. In the case of bare land or young initial stand, scenario R30L14 provided the highest profit under uneven-aged management. Additionally, the highest profit was obtained by switching to scenario R15L04 when the uneven-aged managed mature stand was considered as an initial stand.

With a 5 per cent interest rate, uneven-aged management was more profitable than even-aged management in 10 of the 28 scenarios in the case of bare land and young stand. Additionally, even-aged management resulted in negative profit and the same also occurred with uneven-aged management except in one scenario (R15L04) in the case of bare land. The switch to scenario R10L04 provided the highest profit in the case of the uneven-aged managed mature initial stand.

Discussion

Profitability of uneven-aged management

Uneven-aged management was profitable under all considered initial stand states and management scenarios with a 3 per cent interest rate. The initial stand state had high importance to the costs of transition and profitability of uneven-aged forest management. As expected, the profitability of uneven-aged management was relatively low when bare land with artificial regeneration was considered as an initial state. In such a case, even-aged management yielded a higher profit than the uneven-aged management. The same result was obtained when considering the young initial stand, but the relative difference in profitability between uneven-aged and even-aged management was smaller. In contrast, previous studies have found that it may be optimal to apply uneven-aged management to the initial state of an even-aged stand (e.g. Pukkala *et al.*, 2010; Tahvonen *et al.*, 2010; Tahvonen and Rämö, 2016). It should be noted, however, that the site productivity was higher in our case than in previous studies, which may explain the seemingly contradictory findings. The profitability of uneven-aged management was higher when the mature uneven-aged managed stand was considered as an initial state. This case represents an initial stand structure with a wide size class distribution. Given these results, we may conclude that the closer the initial stand state is to the optimal steady state of uneven-aged management, the higher the profitability. Hence, from a practical viewpoint, the most suitable even-aged managed stands to be switched to uneven-aged management are mid-age stands that have not been thinned for the last decades, in which case the stand structure tends to resemble a negative exponential distribution (e.g. Danescu *et al.*, 2016). On the contrary, regularly thinned even-aged managed stands close to clear-cut likely have an initial state that is unfavourable for uneven-aged management (Tahvonen *et al.*, 2010).

The profitability of uneven-aged management is also highly dependent on the applied management practice. Consistent with previous optimization studies (Pukkala *et al.*, 2010; Tahvonen *et al.*, 2010; Tahvonen, 2011; Rämö and Tahvonen, 2014, 2015), the highest profit was obtained by harvesting the initial mature stand to a 4 $m^2\ ha^{-1}$ post-harvest basal area and applying a 10- or 15-year harvest interval. The optimal basal area varied in the previous studies with soil fertility and temperature sum, with highest fertility sites having the lowest optimal post-harvest basal areas. In contrast to the previous studies, our results reveal that the profitability of uneven-aged management is more sensitive to the post-harvest basal area than the harvest interval when the uneven-aged managed mature initial stand is considered. In the case of the young initial stand, the management regime has a smaller impact on the profitability of uneven-aged management, because the initial state is not that favourable for uneven-aged management and the transition to the steady state takes time whatever management regime is applied. In addition, our results reveal that the difference in profitability between uneven-aged management regimes is quite low in the case of the young initial stand which suggests that there are many well-performing management alternatives available for forest owners along with the optimal regime for conversion of a young stand from even-aged to uneven-aged.

Stand structure and size distribution of harvested trees

The most profitable steady-state option of the uneven-aged management (R10L04, 10-year interval and 4 $m^2\ ha^{-1}$ post-harvest basal area) resulted in a wide diameter distribution and the presence of large-dimension trees. The result deviates from the view that in the uneven-aged forests, the steady-state stand structure follows a negative exponential distribution (e.g. Pukkala *et al.*, 2010), which was suggested already in the early studies where volume production was optimized (Usher, 1966). The resulting diameter distribution depends on applied routines and assumptions of the simulations (e.g. Rämö and Tahvonen, 2017). In general, the management that maintains multiple canopy layers may result in a bimodal distribution rather than negative exponential distribution (e.g. Lundqvist, 2017).

While our harvesting did not systematically remove all trees above a chosen threshold diameter, in the optimization study by Pukkala *et al.* (2010), all trees above a threshold diameter were harvested. As the selection of harvested trees was not optimized, our analysis may provide conservative estimates for the profitability of uneven-aged management. However, our findings on the diameter distribution of the standing trees after several harvesting cycles of the uneven-aged stands are consistent with Tahvonen (2011), who concluded that there is little support for the idea that optimized harvesting of the uneven-aged stands should maintain a negative exponential distribution. The wide diameter distribution of the growing stock of the uneven-aged management resulted also in large-dimension trees in the harvested volume. Since current markets and assumed timber prices do not provide incentives to produce large-dimension timber, the issue was not further elaborated in this study.

Growth and yield

Our results on growth and yield of uneven-aged management, particularly MAI, fall into the range of earlier studies with similar growth conditions and the same tree species (e.g. Pukkala *et al.*, 2010; Tahvonen *et al.*, 2010). For instance, the best financial performer of this study – uneven-aged management with a 10-year harvest interval and a 4 $m^2\ ha^{-1}$ post-harvest basal area – produced on average 5.4 $m^3\ ha^{-1}\ yr^{-1}$ between the last two harvests, which corresponds well with the optimization results of Pukkala *et al.* (2010, p. 135) and Tahvonen *et al.* (2010, p. 111). According to the empirical studies, the average yields of uneven-aged Norway spruce-dominated forest plots in southern Finland have ranged from 4.6 to 6.6 $m^3\ ha^{-1}\ yr^{-1}$ (Lähde *et al.*, 2001; Laiho *et al.*, 2011). Furthermore, the range of timber production (from 4.5 to 6.2 $m^3\ ha^{-1}\ yr^{-1}$), reflecting the alternative harvest intervals and post-harvest basal area levels applied in this study, is generally in accordance with the majority of earlier studies on uneven-aged management as shown in the review by Kuuluvainen *et al.* (2012).

Uncertainties of the modelling approach

In contrast to previous studies, we applied the spatially explicit individual-tree-based ecosystem model EFIMOD to simulate the dynamics of SOM and forest growth due to resource availability under uneven-aged management. The applied model was considered to be realistic also for the simulations of the uneven-aged stand structures, since it was earlier modified and calibrated to uneven-aged stands (Shanin *et al.*, 2016) as well as to the even-aged stands (e.g. Palosuo *et al.*, 2008). The applied version accounts for a delay in attaining full growth for formerly suppressed trees after partial harvesting (Shanin *et al.*, 2016). The correction factor based on empirical data (Eerikäinen *et al.*, 2007, 2014) was added to the tree increment to simulate such delay, and previous simulations showed that the correction worked logically (Shanin *et al.*, 2016). The uncertainties in simulations may arise from the relatively short time span (20 years) covered by the observations used as a basis for validation of the model. The long-term validation was performed with the regional yield tables, which is limited by stationary conditions and cannot be used for predicting ecosystem response to environmental changes and management interventions. The above-mentioned uncertainties can be eliminated during further development of the model, including more detailed procedures of competition. One of the most important steps in model improvement might be the introduction of a more detailed procedure of heat and water transport in the canopy layer and soil, which should replace the current procedure using pre-compiled scenarios of soil temperature and moisture.

Our approach was not an optimization study *sensu stricto*, since optimization assumes the application of methods of mathematical analysis to find the maximum of target function. However, it is possible only by using the models which can be represented as a system of equations describing the dependence of the target function (e.g. timber yield or economical profit) on the parameters of the model, such as intensity and timing of thinning, rotation period, etc. Since such methods of mathematical analysis are not yet applicable for the growth model applied in this study, our approach was different from optimization studies which have combined process-based growth models and economic optimization (Tahvonen *et al*., 2013; Pihlainen *et al*., 2014). The model applied in this study includes equations that describe growth processes and link them to spatial stand structure (location of competing trees) and to the soil processes. Thus, we used the 'brute-force search' by varying two parameters within the fixed interval and with a fixed discrete step. Therefore, we cannot be sure that we found ultimate optimal combinations of harvest interval and intensity (Tahvonen and Rämö, 2016), but these simulations provide information relevant to decision makers who choose between the shown options in practice. Given that the management regimes were not optimized, our results likely underestimated the profitability of uneven-aged management, in particular, when a young initial stand was examined. An optimal conversion of a young initial stand from even-aged to uneven-aged may include varying harvest intervals and intensities before the steady-state is achieved (Rämö and Tahvonen, 2017). Further, the approach can be improved by using the single-tree selection technique where the choice of tree for removal is dependent not only on its size but also on local spatial structure of stand around this tree.

Other determinants of profitability

Our analysis ignored two issues that have increasing importance and deserve attention when assessing the profitability of uneven-aged management in the changing climate where frequency of strong winds is predicted to increase and pests and pathogens are favoured by a warming climate. In general, uneven-aged forest stands inherently have greater resistance and resilience to the disturbance caused by climate change because of the heterogeneity of stand structure and more potential pathways for post-disturbance management and recovery (O'Hara and Ramage, 2013; Gauthier *et al*., 2015). However, the outcome depends on several specific factors.

First, given that the highest profit was associated with a low post-harvest basal area level, the question is whether uneven-aged forests are more windfirm than even-aged forests. The structure of a stand is an important factor which constitutes the stability of the stand and the risk of wind damage (Mason, 2002). A study by Zeng *et al*. (2010), conducted in boreal conifer forests, suggests that avoidance of gap enlargement and creating new stand edges by thinning or clear-cutting could reduce the risk of wind damage at a landscape level. A more recent study with silver fir (*Abies alba* Mill.) and Norway spruce-dominated uneven-aged forests (Hanewinkel *et al*., 2014) suggests that uneven-aged forests might be less vulnerable to storm damage than even-aged forests. In general, uneven-aged forests tend to have a more favourable height–diameter ratio than even-aged forests, indicating higher individual stability of the trees (e.g. Kenk and Guehne, 2001; Mason, 2002). These findings indicate that our analysis likely underestimated the benefits and profitability of uneven-aged management, as our model did not take into account increased stability of trees (compared with the stability of trees in even-aged management).

The second issue is the relationship between stand structure and damages caused by pests and diseases. According to a study (Piri and Valkonen, 2013) evaluating the risk of pathogens in boreal forests, uneven-aged management tends to favour the secondary spread of *Heterobasidion parviporum* (a root rot) between different tree size classes. Furthermore, allowing the younger trees to grow faster by reducing competition through thinning of suppressed trees seems to promote the resistance against pests and diseases, including *Heterobasidion* root rot (Linares *et al*., 2010). With respect to the risk of *Heterobasidion* root rot, even-aged management might be slightly less risky than uneven-aged management, indicating that our analysis overestimated the profitability of uneven-aged management, but further studies are required to confirm this.

In the present analyses on profitability of the forest management regimes, we considered only timber production, but forests provide also other benefits to landowners and the society, i.e. biodiversity and multiple ecosystem services. We have shown the differences in the profitability between varied forest management regimes, that is, we have also revealed the opportunity costs of not applying the most profitable management regime. The information on opportunity costs of the management options is needed also for the assessments where the primary reason to maintain a continuous forest cover is aesthetic value, recreation activity, wind protection or any other ecosystem service that is difficult to evaluate directly. We have not, however, assessed the impacts of uneven-aged management options on biodiversity and all other ecosystem services. Earlier analyses have shown that the carbon sink of forest soil and trees increases with increasing length of harvest interval and increasing post-harvest basal area (Shanin *et al*., 2016). Furthermore, they showed that natural mortality and quantity of dead wood, which are important for forest biodiversity, increased with the length of the harvest interval and post-harvest basal area, but the economic value of these ecosystem services were not analysed. In addition, Pukkala (2016) has investigated how alternative forest management regimes impact on ecosystem services (see also Pukkala *et al*., 2011 and Peura *et al*., 2018). The analysis showed that continuous cover forestry provided more ecosystem services than the other management regimes. Further research is, however, needed to shed more light on this important and interesting issue.

Conclusions

Uneven-aged management in boreal forests is typically started by switching from even-aged to uneven-aged management, because the prevailing silvicultural system has been even-aged management. In this case, the initial state of the stand has a large impact the profitability of uneven-aged management. The conversion of even-aged to uneven-aged Norway spruce stands is financially feasible when the stand structure of the even-aged stand has a wide diameter distribution of standing trees rather than the more restricted range usually associated with conventional management using thinning from below. The highest profit under uneven-aged management for Norway spruce is obtained by applying an approximately 15-year harvest interval and a low post-harvest basal area. In addition to harvest revenues, forests provide many other benefits to landowners and the society. It would, therefore, be interesting to see whether a switch from even-aged to uneven-aged management can be economically justified when biodiversity and ecosystem services are considered along with harvest revenues, even in the case that it is not profitable in terms of net harvest revenues.

Supplementary data

Supplementary data are available at *Forestry* online.

Conflict of interest statement

None declared.

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