Thinning schedules for spruce stands

Petri P. Kärenlampi

University of Eastern Finland
PO Box 111
FIN-80101 Joensuu

petri.karenlampi@uef.fi

tel. +358-50-371 1851
fax +358-13-251 4422

Abstract

We investigate financial feasibility of a few thinning schedules for spruce stands. Some example stands have previously experienced commercial low thinning, whereas others young stand cleaning only. High thinning is combined with quality thinning, and further growth of trees is estimated using a Norwegian growth model. High capital return rates are gained by diameter-limit cutting to the transition diameter between pulpwood and sawlogs. Repeated thinnings lead to reduction in the capitalization during several decades, the system approaching a stationary state. The transient forest stands investigated shown a significant excess capital return, in relation to the stationary state, and this excess return is due to transient tree size distribution. Correspondingly, capital return rate gained in rotation forestry is somewhat higher than that of stationary continuous-cover forestry, and the volumetric yield is much higher. The productive capacity of stands previously thinned from below apparently has been ruined by that treatment.

1. Introduction

We are interested in the performance of different thinning schedules in forestry. We are interested in financial performance, with consideration of biological opportunities and restrictions. There is a large body of literature discussing the effect of thinning schedules on the net present value of revenues [1, 2, 3, 4, 5, 6, 7, 8, 9]. We find such an approach unsatisfactory, since consequences may be financially devastating [10].

We are interested in thinning as an improvement harvesting contributing to the capital return rate on a forest stand. Provided significant improvement of capital return rate is possible through harvesting, we look forward to further harvestings in order to retain a high capital return rate. We take it granted that removal of trees with obvious quality defects or visible loss of vigor improves further productivity of the stand. In addition to the quality thinning, we investigate the effect of diameter-limit cutting on the capital return rate.

We adopt a practical focus to a few fertile spruce-dominated stands in Eastern Finland, where we collect observations regarding the present structure of the tree populations. Then, the growth of trees, as well as recruitment of new trees, is clarified according to an empirical growth model, constructed on the basis of a large Norwegian dataset [11, 12].

First, we introduce the materials and methods applied. This comprehends a description of the example sites, the applied growth model, as well as financial methods. Then we introduce quality thinning on the basis of quality classification of the trees recorded in field measurements, and combine the quality thinning with diameter-limit cutting. The capital return rate after any thinning is reported, first after quality thinning only, and then as a function of any cutting limit diameter. Finally, we report simulated further development of the stands under repeated diameter-limit cuttings, and discuss some implications of the results.

2. Materials and methods

11 circular plots of area 314 square meters were taken from typical spots of 11 spruce-dominated forest stands in November 2018 at Vihtari, Eastern Finland. Seven of the stands had experienced only young stand cleaning, whereas four of the stands were previously thinned

commercially. Breast-height diameters were recorded, as well as tree species, and a quality class was visually determined for any measured tree.

We find from Fig. 1 that measured plots on sites without any previous commercial thinning were relatively similar to each other: basal area varied from 32 to 48 m²/ha, and the stem count from 1655 to 2451 per hectare (rightmost dot on any curve in Fig. 1). The leftmost dot of any curve in Fig. 1 corresponds to the basal area and stem count of good-quality trees of at most 150 mm of breast-height diameter. Further dots in any curve correspond to basal area and stem count of proper trees of at most 200, 250, 300 and 350 mm of diameter. Correspondingly Fig. 1 indicates that the measured plots did not contain any trees thicker than 350 mm.
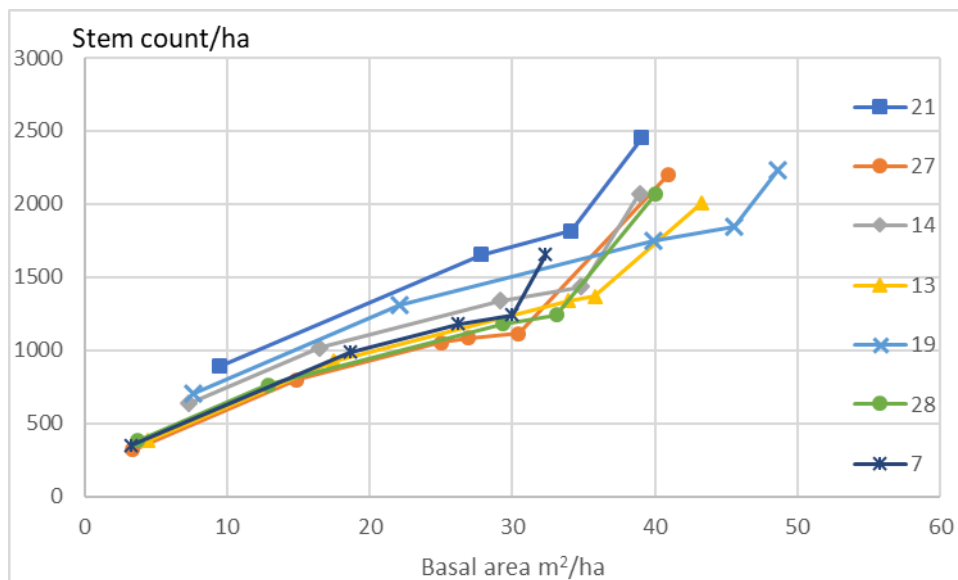

Fig. 1. Stem count and basal area of seven stands not previously thinned commercially. The rightmost dot within any curve includes all trees on the measured plot. Other dots correspond only trees determined to be of acceptable quality for further growing. The leftmost do within any curve corresponds to trees not larger than 150 mm in breast-height diameter. The diameter limit is increased by 50 mm for each step to the right.

We find from Fig. 2 that measured plots on stands previously thinned commercially also were relatively similar to each other: basal area varied from 29 to 49 m²/ha, and the stem count from 891 to 955 per hectare (rightmost dot on any curve in Fig. 1). Again, the leftmost dot of any curve in Fig. 1 corresponds to the basal area and stem count of good-quality trees of at most 150 mm of breast-height diameter, and further dots in any curve correspond to basal area and stem count of good trees of at most 200, 250, 300 and 350 mm of diameter. Correspondingly

3

Fig. 2 indicates that the measured plots did not contain any trees thicker than 400 mm. We also find that the stem counts in the smallest diameter classes in Fig. 2 are rather low, which indicates the sites have experienced thinning from below.
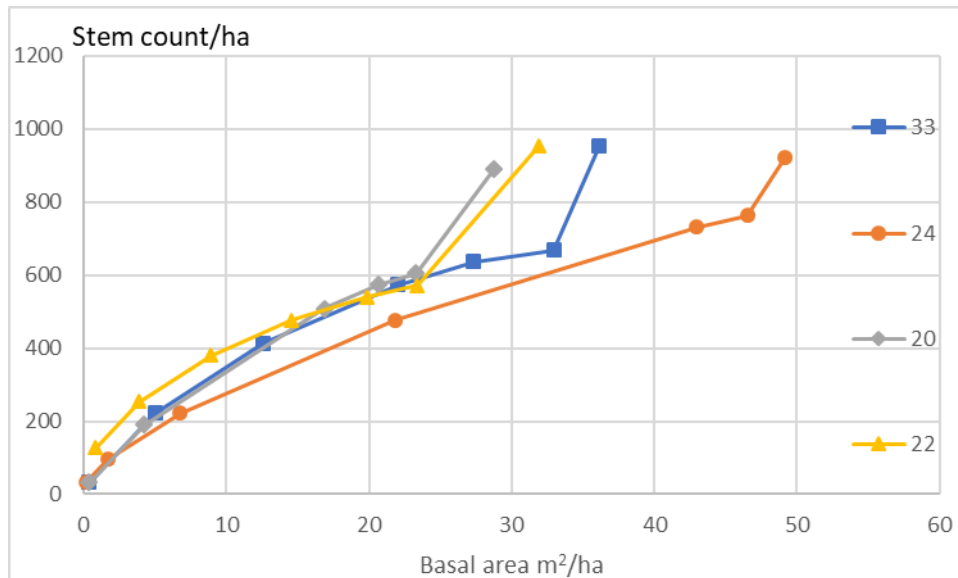

Fig. 2. Stem count and basal area of four stands previously thinned commercially. The rightmost dot within any curve includes all trees on the measured plot. Other dots correspond only trees determined to be of acceptable quality for further growing. The leftmost dot within any curve corresponds to trees not larger than 150 mm in breast-height diameter. The diameter limit is increased by 50 mm for each step to the right.

In order to discuss further development of the example stands, represented by the measured circular plots, some kind of a growth model is needed. We adopt the growth model of Bollandsås et al. [11, 12], discussing not only growth but also mortality and recruitment. Trees are discussed in diameter classes of 50 mm, and each class is represented by its central tree. Growth is computationally implemented in terms of the probability of a tree to transfer to the next diameter class [11, 12, 13].

In order to discuss financial issues, we need to address value growth, instead of merely volumetric growth. For any diameter class, we clarify the volumetric amount of two assortments, pulpwood and sawlogs, according to an appendix given by of Rämö and Tahvonen [14, 15]. The monetary value of the assortment volumes is clarified according to stumpage prices given by Rämö and Tahvonen [14].

In order to determine a momentary capital return rate, or possibly an average capital return rate for a period of a few years, we need to discuss the amount of financial resources occupied. We do this in terms of a financial potential function, defined in terms of capitalization per unit area K. The momentary capital return rate becomes

$$r(t) = \frac{d\kappa}{K(t)dt} \qquad (1).$$

In Eq. (1), the difference between κ in the numerator and K in the denominator relates to eventual operative investment or divestment. The potential (or capitalization) K is immediately affected by any eventual operative investment or withdrawal, and then consequently becomes affected by amortizations. The net return rate $\frac{d\kappa}{dt}$ in the numerator is not immediately affected by investments or withdrawals, but considers eventual investments in terms of amortizations. In addition, investments are likely to contribute to growth: they probably increase growth rate, whereas withdrawals may reduce growth rate. In this paper, we do not discuss investments, amortizations or withdrawals during growth periods where Eq. (1) is applied.

Let us then distribute capitalization $K(t)$ to operative capitalization $O(t)$, and non-operative capitalization $U(t)$. The operative capitalization relates to cumulated growth, as well as eventual investments related to it. Non-operative capitalization may be due to excess demand of real estate, in comparison to supply, recreational values, speculation for future real estate development, etc. Now, Eq. (1) can be rewritten

$$r(t) = \frac{d\Omega + dU}{\left[O(t) + U(t)\right]dt} \qquad (2).$$

In Eq. (2), the difference between Ω in the numerator and O in the denominator again relates to eventual operative investment or divestment. The capitalization O is immediately affected by any eventual operative investment or withdrawal, and then consequently becomes reduced by amortizations. The net return rate $\frac{d\Omega}{dt}$ in the numerator is not immediately affected by investments or withdrawals. Correspondingly, the accumulated net yield $\Omega(\tau)$ may differ from operative capitalization $O(\tau)$ in the occurrence of withdrawals (harvesting etc.). In this paper,

we do not discuss investments, amortizations or withdrawals during growth periods where Eq. (2) is applied.

Eq. (2) reveals that in the case the operative capitalization is much higher than the non-operative capitalization, the role of the latter vanishes. On the other hand, if non-operative capitalization is much higher than operative capitalization, the role of the operative capitalization vanishes. In case the non-operative capitalization is large but constant, the highest operative return might simply be the one corresponding to the greatest average yield rate $\left\langle \dfrac{d\Omega}{dt} \right\rangle$. The situation is somewhat more delicate if there is a nonvanishing time change rate of the non-operative capitalization dU/dt.

In general, we include bare land value in the non-operative capitalization U. In this paper, we discuss the bare land value as the only component of the non-operative capitalization. We assign it a present value of 600 Euros/ha, and an annual appreciation of 3%. Both of these values correspond to local circumstances at Vihtari, Eastern Finland, at the time of writing.

3. Results

31. Stands not previously thinned commercially

Annualized capital return rate after improvement harvesting, as a function of basal area, in the case of stands not previously thinned commercially, is shown in Fig. 3. Again, the leftmost dot of any curve in Fig. 3 corresponds to the basal area of and capital return from trees of at most 150 mm of breast-height diameter. Further dots in any curve correspond to basal area and capital return from trees of at most 200, 250, 300 and 350 mm of diameter. We find that without any exception, the greatest capital return rate is gained if there is, in addition to removal of trees of low quality, a diameter-limit cutting to 200 mm. Such stands, after the improvement harvesting, deliver annual capital return rates from 10,9% to 13,2%. Diameter-limit cutting to 150 mm would give capital return rate in the vicinity of 7%, which in general is greater than that achievable with gentle quality thinning only (Fig. 3).
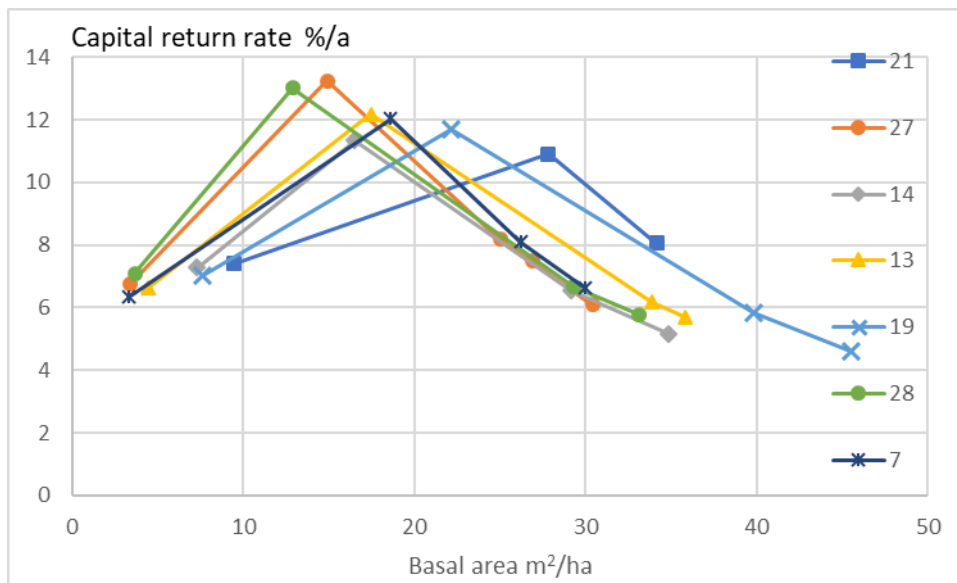
Fig. 3. Capital return rate and basal area of seven stands not previously thinned commercially. The rightmost dot within any curve includes all trees determined to be of acceptable quality for further growing. The leftmost do within any curve corresponds to trees not larger than 150 mm in breast-height diameter. The diameter limit is increased by 50 mm for each step to the right.

The stands will not be in any stationary state after diameter-limit cutting, combined with gentle quality thinning. Annualized capital return rate will evolve along with further growth and diameter-limit cuttings, implemented any five years after the improvement harvesting. We find from Fig. 4 that all stands approach a stationary state within a century, the stationary capital return rate approaching 8% (Fig. 4). There is some variation in the stationary capital return rate, due to somewhat varying site fertility. It is worth noting that all the capital return rates in Fig. 4 correspond to present time. In other words, the bare land value, as well as its appreciation rate, are taken as the present values. In other words, in Fig. 4, the improvement harvesting is assumed to have occurred in variably distant history.

There is a significant excess capital return during the first decades after the improvement harvesting, in relation to the stationary state (Fig. 4). This is due to tree size distributions significantly differing from the stationary state. Some stands show a maximum in the capital return rate immediately after the improvement harvesting. These stands have a mode value of the tree size distribution close to the transition from pulpwood to sawlogs. Some other stands show a maximum in capital return 5…25 years after the improvement harvesting. These stands

7

have a mode value of tree sizes below the transition diameter, and the capital return rate increases as the number of trees approaching the transition diameter increases (Fig. 4).
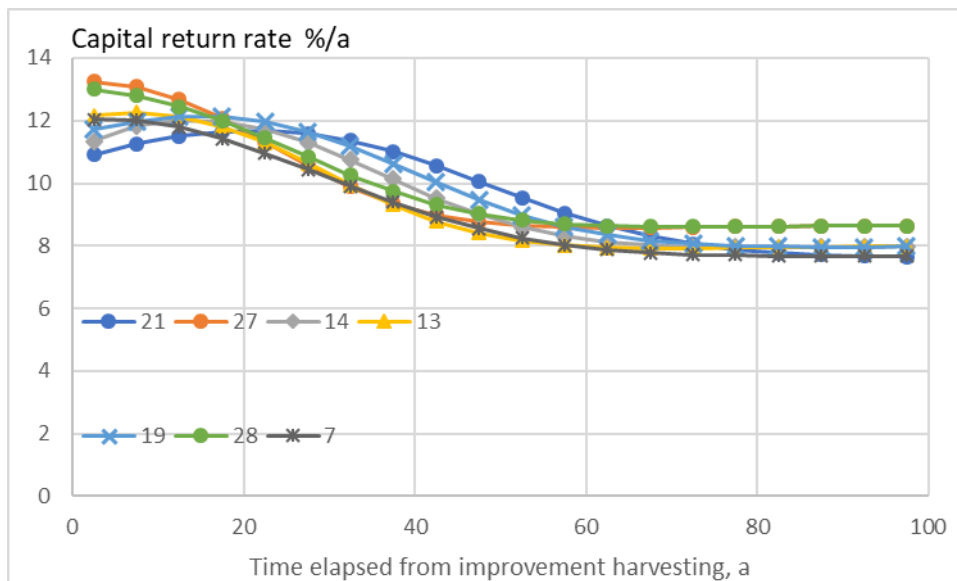

Fig. 4. Evolution of capital return rate within seven stands not previously thinned commercially. The leftmost point corresponds to the first five-year period after the improvement harvesting. Along with repeated diameter-limit cuttings, all stands approach a stationary state.

The experimental stands not being in any stationary state after the improvement harvesting, the capital return rate is not the only one of their features experiencing a transient. We find from Figs. 5 and 6 that the basal area, as well as the stem count per hectare, approach a stationary state. The stationary values of basal area and stem count are rather low, 2.2 m^2/ha and 170 /ha, such low values being related to relatively slow recruitment of new trees [11, 12, 13].

We find from Figs. 5 and 6 that during the first decades after the improvement harvesting, there generally are significant stem counts and basal areas on the example sites without previous commercial thinning. However, there also is significant variability between the stands. We find that in Fig. 1 most of the basal areas have been in the vicinity of 40 m^2/ha, and most of the basal area has been removed in the improvement harvesting (Fig. 5). However, in the case of two stands, a significant amount of basal area has remained (Fig. 5). This obviously is related to the large remaining stem count visible in Fig. 6: these two stands have had a large number of trees smaller than 200 mm in breast-height diameter.
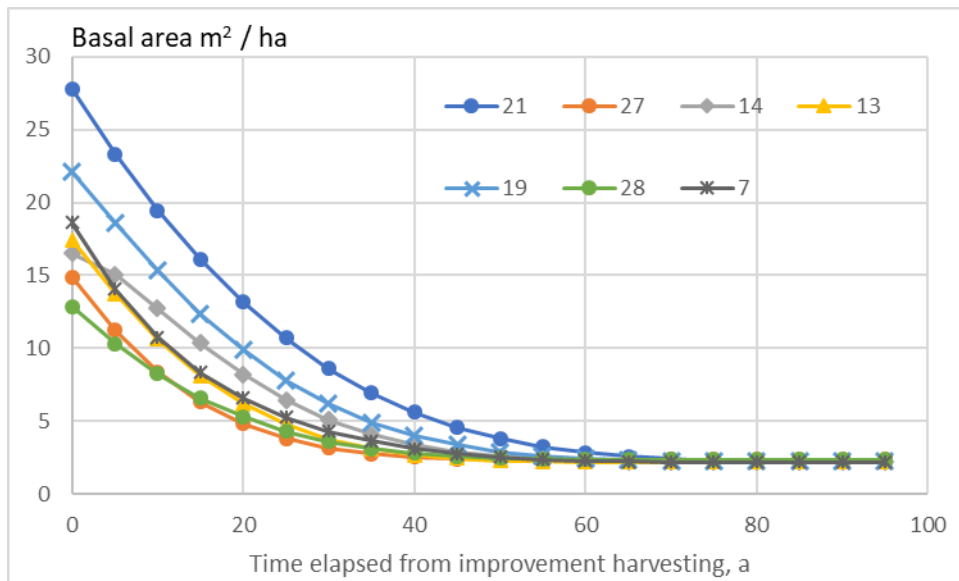
8

Fig. 5. Evolution of basal area within seven stands not previously thinned commercially. The leftmost point corresponds to the situation immediately after the improvement harvesting. Along with repeated diameter-limit cuttings, all stands approach a stationary state.
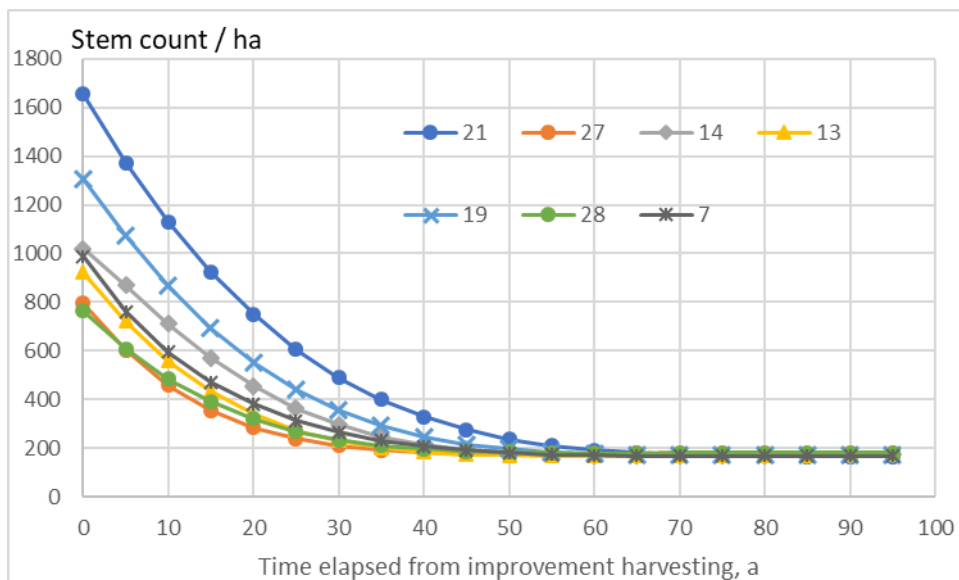

Fig. 6. Evolution of stem count within seven stands not previously thinned commercially. The leftmost point corresponds to the situation immediately after the improvement harvesting. Along with repeated diameter-limit cuttings, all stands approach a stationary state.

As there is a significant excess in basal area and stem count during the first decades after improvement harvesting, in comparison to the stationary state, there also is an excess in the harvesting yield (Fig. 7). In the stationary state, the harvesting yield is in the order of 7 m^3/ha

9

for any five-year period, the excess yield during the first decades after the improvement harvesting is rather significant. There is one example stand where the change in the harvest volume is non-monotonic. In that case, the mode value of tree size was well below the pulpwood-sawlogs transition size after the initial improvement harvesting.

It is worth noting that the five-year harvest yield 20 years after the improvement harvesting is in the order of 30 m^3/ha even if the basal area (after harvesting) is only 6 m3/ha (Figs. 5 and 7). The harvest yield mostly contains sawlogs.
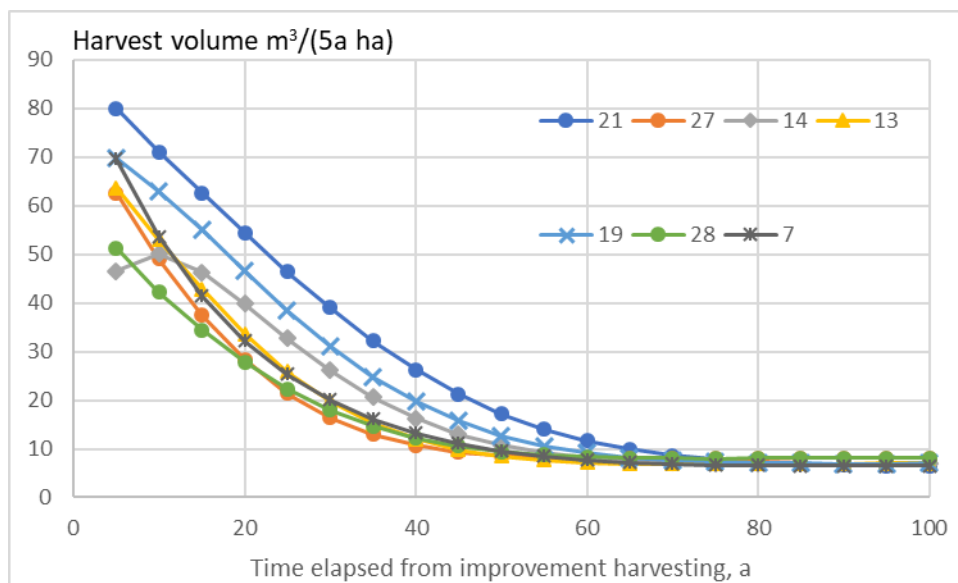

Fig. 7. Evolution of harvest volume / ha within any five-year period within seven stands not previously thinned commercially. The leftmost point corresponds to the situation five years after the improvement harvesting. Along with repeated diameter-limit cuttings, all stands approach a stationary state.

32. Stands previously thinned commercially

Annualized capital return rate after improvement harvesting, as a function of basal area, in the case of stands previously thinned commercially, is shown in Fig. 8. Again, the leftmost dot of any curve in Fig. 8 corresponds to the basal area of and capital return from trees of at most 150 mm of breast-height diameter. Further dots in any curve correspond to basal area and capital return from trees of at most 200, 250, 300, 350 and 400 mm of diameter. Again, we find that without any exception, the greatest capital return rate is gained if there is, in addition to removal

of trees of low quality, a diameter-limit thinning to 200 mm. Such stands, after the deliver annual capital return rates from 8,6% to 12,0%. Diameter-limit cutting to 150 mm would give capital return rate in the vicinity of 4%, which in general is greater than that achievable with gentle quality thinning only (Fig. 8).

It is worth noting that the greatest capital return rates are achieved in stands where the basal area is only 1,7…5,0 m^2/ha (Fig. 8). This is much less than in the case of the unthinned stands shown in Fig. 3, and again indicates that the stands in Fig. 8 have been thinned from below.
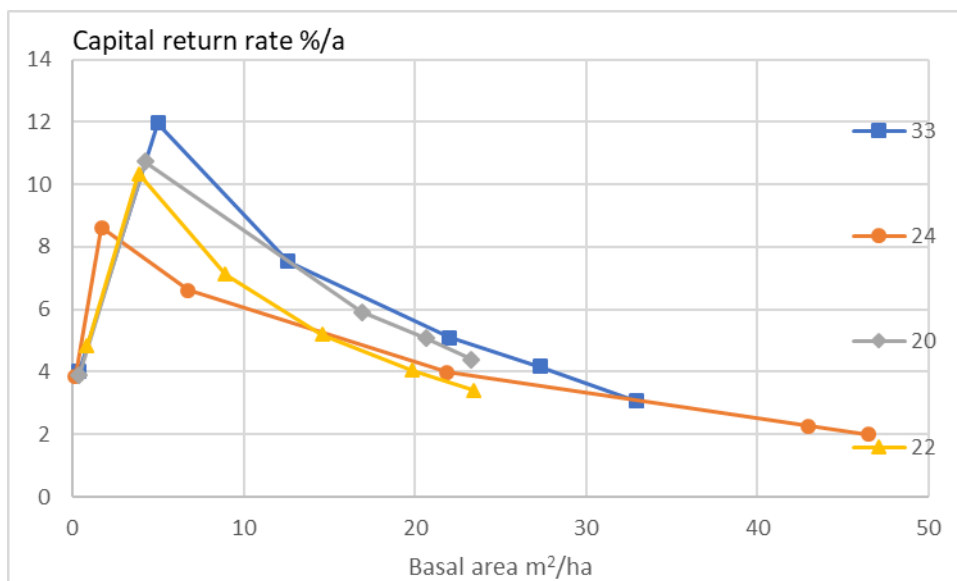

Fig. 8. Capital return rate and basal area of four stands not previously thinned commercially. The rightmost dot within any curve includes all trees determined to be of acceptable quality for further growing. The leftmost do within any curve corresponds to trees not larger than 150 mm in breast-height diameter. The diameter limit is increased by 50 mm for each step to the right.

Again, the stands will not be in any stationary state after diameter-limit cutting, combined with gentle quality thinning. Annualized capital return rate will evolve along with growth and further diameter-limit cuttings, implemented any five years after the improvement harvesting. We find from Fig. 9 that all stands approach a stationary state within a century, the stationary capital return rate approaching 8…9% (Fig. 4). There is some variation in the stationary capital return rate, due to somewhat varying site fertility. Again, all the capital return rates in Fig. 9 correspond to present time. In other words, the bare land value, as well as its appreciation rate, are taken as the present values. In other words, in Fig. 9, the improvement harvesting is assumed to have occurred in variably distant history.

There is an excess capital return during the early stages of development after the improvement harvesting, in relation to the stationary state (Fig. 9), with one exception. In the case of one stand only, the development of the capital return rate is monotonic, like in the case of Fig. 4. In three cases the capital return rate shows a depressed state 10…40 years after the improvement harvesting, in comparison to the stationary state. This obviously is due to a low number of trunks experiencing the pulpwood-sawlog transition.
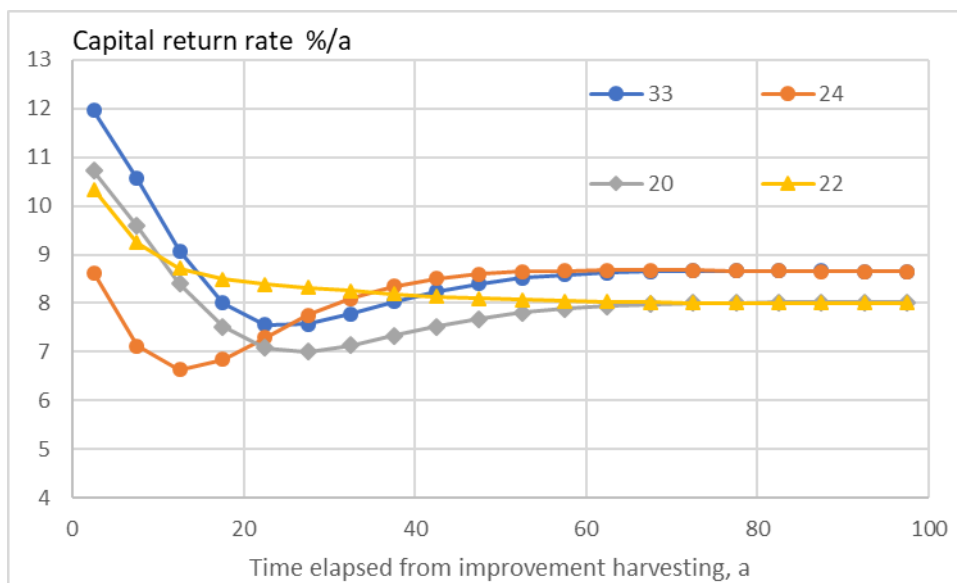

Fig. 9. Evolution of capital return rate within four stands previously thinned commercially. The leftmost point corresponds to the first five-year period after the improvement harvesting. Along with repeated diameter-limit cuttings, all stands approach a stationary state.

The experimental stands not being in any stationary state after the improvement harvesting, the capital return rate is not the only one of their features experiencing a transient. We find from Figs. 10 and 11 that the basal area, as well as the stem count per hectare again approach a stationary state. Only one of the four stands shows a monotonic decrement of the basal area and stem count. Three of the four stands show a depressed basal area and stem count after the improvement harvesting, in comparison to the stationary state. One of these three stands shows a depressed basal area and stem count right after the improvement harvesting (Figs. 10 and 11), even if the capital return rate is not depressed at that state (Fig. 9).
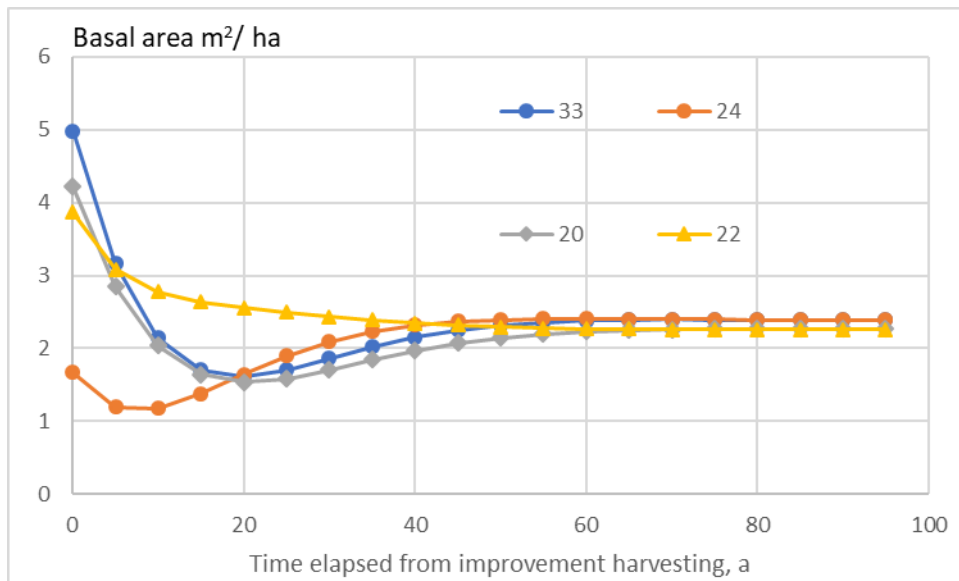
12

Fig. 10. Evolution of basal area within four stands previously thinned commercially. The leftmost point corresponds to the situation immediately after the improvement harvesting. Along with repeated diameter-limit cuttings, all stands approach a stationary state.
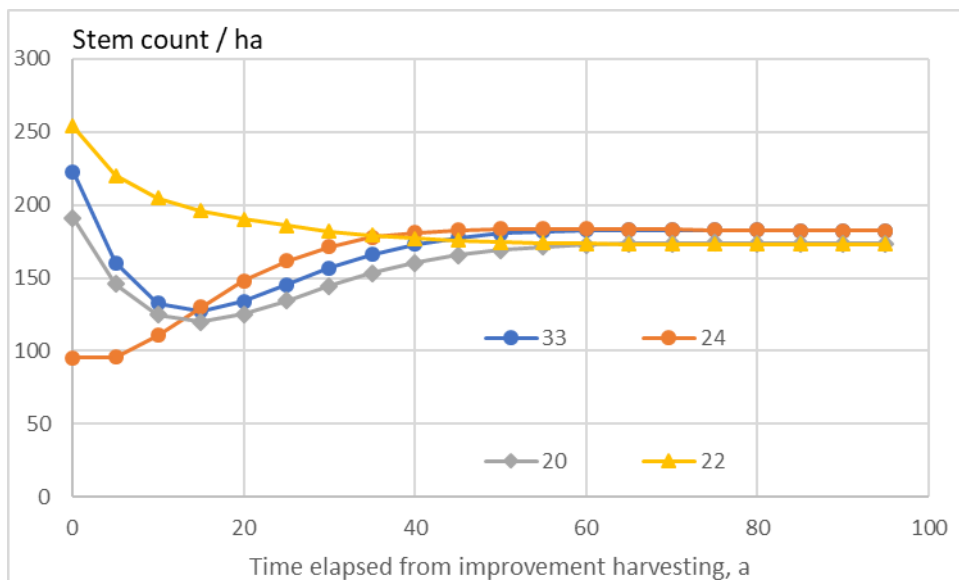

Fig. 11. Evolution of stem count within four stands previously thinned commercially. The leftmost point corresponds to the situation immediately after the improvement harvesting. Along with repeated diameter-limit cuttings, all stands approach a stationary state.

All the four stands show an excess five-year harvest volume after the improvement harvesting, in relation to the stationary state (Fig. 11). Again, the harvest volume decreases monotonically

13

only in one case, the other three cases showing a depressed harvest volume 10…40 years after the improvement harvesting.
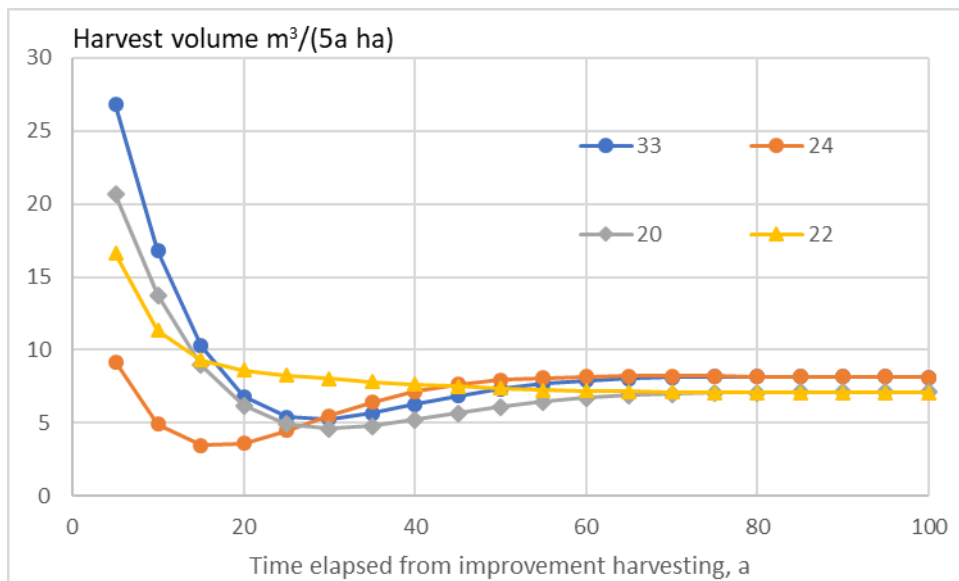

Fig. 12. Evolution of harvest volume / ha within any five-year period within four stands previously thinned commercially. The leftmost point corresponds to the situation five years after the improvement harvesting. Along with repeated diameter-limit cuttings, all stands approach a stationary state.

4. Discussion

In all the stands discussed above, there is a significant increment in the capital return rate by diameter-limit cutting to the transformation size of pulpwood to sawlogs, combined with quality thinning only (Figs. 3 and 8). Apart from that, two rather different sets of results have been introduced.

Stands not previously thinned commercially provide a significant capital return rate, basal area, stem count, and five-year harvest yield during several decades after the improvement harvesting. In fact, these are in excess of the level of the stationary state for a half century (Figs. 4, 5, 6 and 7). Interestingly, the cutting program displays many of the traits demonstrated as optimal by Kilkki and Väisänen [1], even if their objective function was a discounted net present value of revenues. A possible explanation for the similarity of the procedures was that the applied discounting rate accidentally was not far from the internal rate of return achievable in their example stands [1, 10].

14

Stands previously thinned commercially demonstrate a rather small basal area and stem count after the improvement harvesting (Figs. 8 and 11). The scarcity of pulpwood-sized trees results as a rapid decline in basal area, stem count, harvest yield, and capital return rate (Figs. 9, 10, 11 and 12). Such quantities even tend to stay in a depressed state, in comparison to the stationary state, for several decades (Figs. 9, 10, 11 and 12). One can, without doubt, argue that the productive capacity of these stands has been ruined by thinning from below.

According to Fig. 4, young stands after the improvement harvesting but without any previous commercial thinning show significant excess financial return, in comparison to the stationary case, during several decades. This, combined with excess harvest volume (Fig. 7), possibly suggests superiority of rotation forestry with repeated high thinnings, in comparison to stationary continuous-cover forestry.

One must raise a question regarding the capital return rate over the entire rotation, including the decades necessary to grow a young stand to a state where the improvement harvesting can be implemented. The present data does provide some tools for solving this question. Firstly, the characteristic tree age of the seven non-thinned stands discussed varied 31,,,45 years. Second, the computed stumpage value of trees to be collected in the improvement harvesting varied 2400…9200 Euros/ha. Third, the present bare land value, as well as the present level of artificial regeneration and young stand cleaning expenses are known. These can be discounted to the time of artificial regeneration and young stand cleaning. A natural discounting interest possibly equals the present bare land appreciation rate.

It has been recently shown that an accurate computation of a representative (expected) value of capital return rate requires knowledge of the details of the yield function [10]. However, an approximation can be gained simply as an internal rate of return [10]. Considering the numbers discussed in the preceding paragraph, the annual internal return rates up to the improvement harvesting appear to be 3,7…7,5%, with a mode value of 6,6%. This is less than the capital return rate in the stationary state (Fig. 4). However, considering the fact that there is a significantly elevated capital return rate during the first four decades after the improvement harvesting (Fig. 4), rotation forestry with repeated high thinnings apparently provides somewhat greater capital return rate as stationary continuous-cover forestry.

15

In the context of a comparison between rotation forestry with repeated high thinnings on the one hand and stationary continuous-cover forestry on the other, one possibly should discuss other factors, in addition to the capital return rate. Firstly, the harvest volume is much greater in rotation forestry (Fig. 7). Secondly, the low basal area and stem count in the stationary state (Figs. 5 and 6) may induce a significant risk of wind damage. An intense improvement harvesting in rotation forestry also may induce an elevated risk of wind damage [16, 17], but that risk can be reduced by implementing the improvement harvesting in stages, if necessary. Thirdly, risks involved in lengthy stationary forestry in terms of diseases and eventual loss of vigor are not fully known.

As stated above, stands previously thinned commercially demonstrate a rather small basal area and stem count after the improvement harvesting (Figs. 8 and 11). The scarcity of pulpwood-sized trees results as a rapid decline in basal area, stem count, harvest yield and capital return rate (Figs. 9, 10, 11 and 12). On the other hand, a significant increment of capital return rate can be achieved by partial diameter-limit cutting, or by thinning from above (Fig. 8). A larger cutting limit diameter obviously would increase the remaining basal area and harvest yield, at the expense of a lower capital return rate after the improvement harvesting (Fig. 8).

Fig. 13 shows the evolution of the capital return rate in previously thinned stands, but now with 250 mm cutting limit diameter. In comparison to Fig. 9 we find that the situation is clearly impaired. The initial values of capital return rate, gained after the improvement harvesting, are much lower, as already indicated in Fig. 8. The capital return rate in the stationary state also is lower with the higher cutting limit diameter (Fig. 13).

There are some benefits that are achieved at the expense of the lower capital return rate. The stem count, and in particular the basal area greater, and this corresponds to a greater volumetric harvest yield as is shown in Fig. 14, in comparison to Fig. 12. Not only the initial harvest volume, gained five years after the improvement harvesting, is greater, but the stationary harvest volume also is greater. Even if the capital return rate in Fig. 14 is clearly less than in Fig. 12, it is much greater than in the absence of any diameter-limit cutting in Fig. 8. This does, however, not change the fact that much of the financial productivity has been ruined by thinning from below, in comparison of Fig. 13 to Fig. 4.
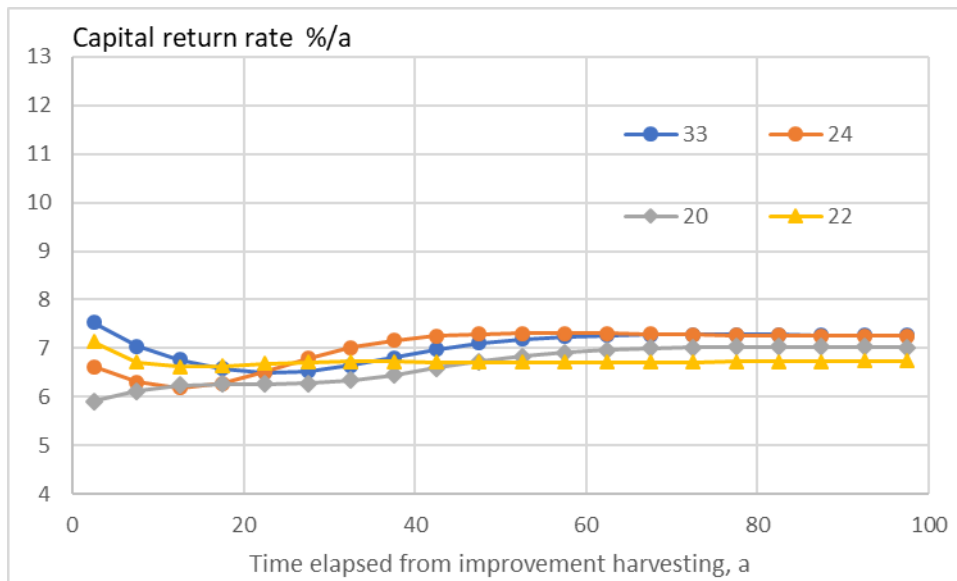
Fig. 13. Evolution of capital return rate within four stands previously thinned commercially. The leftmost point corresponds to the first five-year period after the improvement harvesting with cutting limit diameter 250 mm. Along with repeated diameter-limit cuttings, all stands approach a stationary state.
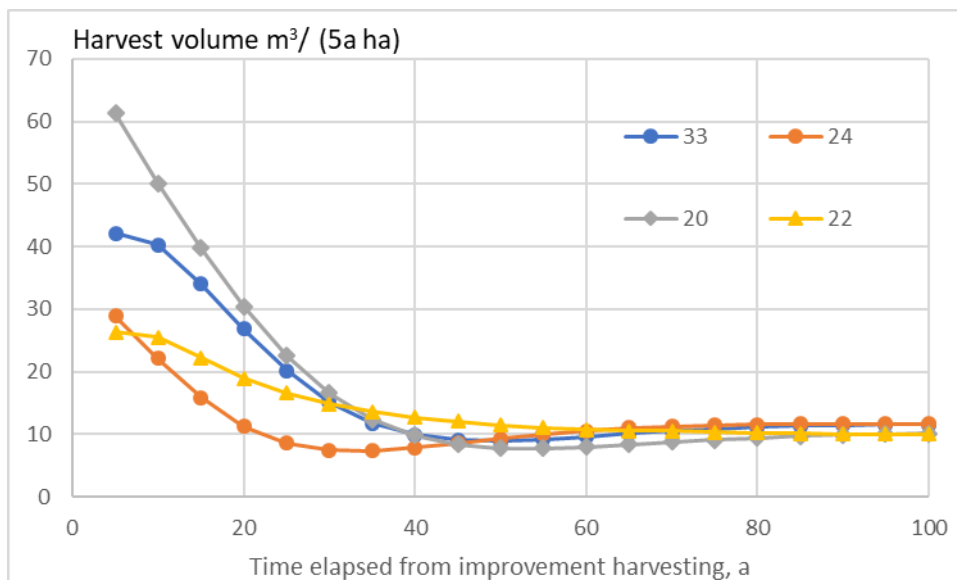

Fig. 14. Evolution of harvest volume / ha within any five-year period within four stands previously thinned commercially. The leftmost point corresponds to the situation five years after the improvement harvesting with cutting limit diameter 250 mm. Along with repeated diameter-limit cuttings, all stands approach a stationary state.

Several earlier studies indicate stationary continuous-cover forestry would be more profitable than rotation forestry [2, 3, 4, 8]. The results of this paper are contradictory. There are several

17

obvious reasons for the discrepancy. Firstly, the economic criteria differ. Most commonly, a discounted net present value of revenues has been maximized, using an external discounting interest rate [2, 18, 3, 4, 8]. It has been recently shown that maximization of net present value in general yields incorrect results from the viewpoint of wealth accumulation, particularly in the case of fertile stands [10]. Secondly, stationary continuous-cover forestry has been compared with clearcuttings, instead of a procedure of repeated high thinnings [2, 3]. It also is worth noting that sustainability has been secured by using a penalty function for declining stem counts [3]. Declining stem counts however are an essential feature of Fig. 6, and it is closely related to the excess capital return appearing in Fig. 4.

There are uncertainties in the growth model applied. The most uncertain submodel within the experimental model applied here is the recruitment model [11]. The recruitment model is crucial from the viewpoint of the amount of trees that can be maintained at the stationary state. The recruitment model is less essential in the case of rotation forestry containing artificial regeneration, improvement harvesting, and repeated high thinnings after the improvement harvesting.

It would be of interest to compare the present outcome with different growth modelings, as well as with different tree species, climates, and regions. Quite a few investigations have been published reporting recruitment, growth, and mortality [19, 20, 21, 22, 23, 5]. However, it appears that most of such modelings do not converge to any natural stationary state under a demographic stationarity criterion [13]. A common reason for such failure appears to be an inappropriate description of mortality: in case growth rate diminishes but mortality does not increase, a large number of trees accumulates to large diameter classes.

It remains to be investigated whether various growth models would produce coherent results under the boundary condition of frequently repeated diameter-limit cuttings. However, we have implemented some preliminary investigations using the growth model of Pukkala et al. [19]. Firstly, the greatest capital return rate is gained by diameter-limit harvesting to the transition diameter between pulpwood and sawlogs, regardless of the growth model. However, the rate of recruitment is faster in the model of Pukkala et al. [19], resulting as basal area, stem count and harvest volume larger than indicated for the stationary state in Figs. 5, 6 and 7. Secondly, the effect of spacing on diameter growth is stronger according to the model of Pukkala et al. [19], resulting as high growth rates in sparse stands. On the other hand, dense stands hardly

achieve basal area 45 m^2/ha within a century. Stands with basal area over 55 m^2/ha exist in the area, in agreement with the growth model of Bollandsås et al. [11].

Acknowledgement

References

1. Kilkki, P., Väisänen U. 1969. Determination of the optimum cutting policy for the forest stand by means of dynamic programming. *Acta For. Fenn.* **102**, 1-29.

2. Haight, R.G., Monserud, R.A. 1990. Optimizing any-aged management of mixed-species stands. II: effects of decision criteria. *For. Sci.* **36**, 125-144.

3. Pukkala, T., Lähde, E., and Laiho, O. 2010. Optimizing the structure and management of uneven-sized stands in Finland. *Forestry* **83**(2), 129–142. doi:10.1093/forestry/cpp037.

4. Tahvonen O., 2011. Optimal structure and development of uneven-aged Norway spruce forests. *Canadian Journal of Forest Research* **41**(12), 2389-2402.

5. Rosa R, Soares P, Tomé M., 2018. Evaluating the Economic Potential of Uneven-aged Maritime Pine Forests. *Ecological Economics* **143**, 210-217.

6. Tahvonen O. 2016. Economics of rotation and thinning revisited: the optimality of clearcuts versus continuous cover forestry. *Forest Policy and Economics* **62**:88-94.

7. Pukkala T., 2018. Instructions for optimal any-aged forestry, *Forestry: An International Journal of Forest Research*, cpy015, https://doi.org/10.1093/forestry/cpy015

8. Tahvonen O., Pukkala T., Laiho O., Lähde E., Niinimäki S., 2010. Optimal management of uneven-aged Norway spruce stands. *Forest Ecology and Management* **260**(1), 106-115. https://doi.org/10.1016/j.foreco.2010.04.006.

9. Jin X., Pukkala T., Li F., 2019. A new approach to the development of management instructions for tree plantations, Forestry: An International Journal of Forest Research, cpy048, https://doi.org/10.1093/forestry/cpy048

10. Kärenlampi P. P., 2018. Wealth accumulation in stationary rotation forestry - failure of the Net Present Value optimization? Preprints 2019, 2019010194 , https://www.preprints.org/manuscript/201901.0194/v1   doi: 10.20944/preprints201901.0194.v1

11. Bollandsås, O.M., Buongiorno, J., Gobakken, T., 2008. Predicting the growth of stands of trees of mixed species and size: A matrix model for Norway. Scand. J. For. Res. 23, 167–178.

12. Halvorsen, E., Buongiorno, J., Bollandsås, O.-M., 2015. NorgePro: A Spreadsheet Program for the Management of All-Aged, Mixed-Species Norwegian Forest Stands; Department of Forest and Wildlife Ecology: Madison, WI, USA. Available online: labs.russell.wisc.edu/buongiorno/files/NorgePro/NorgeProManual_4_24_15.doc (accessed on October 12, 2018).

13. Kärenlampi P. P., 2018. Stationary forestry with human interference. Sustainability 10(10), 3662.

14. Rämö, J. Tahvonen, O., 2015. Economics of harvesting boreal uneven-aged mixed-species forests. Can. J. For. Res. 45, 1102–1112.

15. Heinonen, J., 1994. Koealojen puu-ja puustotunnusten laskentaohjelma KPL. In Käyttöohje (Software for Computing Tree and Stand Characteristics for Sample Plots. User's Manual); Research Reports; Finnish Forest Research Institute: Vantaa, Finland. (In Finnish) https://doi.org/10.1139/x11-130

16. Wallentin C., Nilsson U., 2014. Storm and snow damage in a Norway spruce thinning experiment in southern Sweden. Forestry 87(2), 229-238.

17. Pukkala T., Laiho O., Lähde E., 2016. Continuous cover management reduces wind damage. Forest Ecology and Management 372:120-127.

18. Tahvonen, O., 2009. Optimal choice between even-and uneven-aged forestry. Nat. Resour. Model. 22, 289-321.

19. Pukkala, T., Lähde, E., Laiho, O., 2009. Growth and yield models for uneven-sized forest stands in Finland. For. Ecol. Manag., 258, 207–216.

20. Drössler, L., Nilsson, U., Lundqvist, L. 2014. Simulated transformation of even-aged Norway spruce stands to multi-layered forests: An experiment to explore the potential of tree size differentiation. *For. Int. J. For. Res.* **87**, 239–248.

21. Lundqvist, L., Spreer, S., Karlsson, C., 2013. Volume production in different silvicultural systems for 85 years in a mixed Picea abies–Pinus sylvestris forest in central Sweden. *Silva Fenn.* **47**, 897.

22. Trasobares, A., Tome, M., Miina, J., 2004a. Growth and yield model for Pinus halepensis Mill in Catalonia, north-east Spain. *For. Ecol. Manag.* **203**, 49–62.

23. Trasobares, A., Pukkala, T., Miina, J., 2004b. Growth and yield model for uneven-aged mixtures of Pinus sylvestris L. and Pinus nigra Arn. in Catalonia, north-east Spain. *Ann. For. Sci.* **61**, 9–24.