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ORIGINAL PAPER

Spruce forest stands in a stationary state

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Abstract We present stationarity criteria for forest stands, and establish embodiments using a Norwegian empirical stand development model. The natural stationary states only slightly differ from the outcome of long-term simulations previously implemented using the same empirical model. Human interference in terms of diameter-limit cutting is introduced. Consequently, stationary states differing from the natural one appear. Standing volume, growth and monetary value appear low but the financial return rate may be significant. Volume yield and financial return clearly contradict each other, the former arising from harvesting large trees, the latter from frequent removal of small trees. An exponential tree size distribution does not appear to comply with the stationarity criterion.

Keywords Growth · Plenterwald (selection cutting) · Recruitment · Stand development · Yield

Introduction

Forest trees often are produced in growth cycles, including terminal harvesting and artificial or natural regeneration (Kuusela 1961; Pearse 1967; Goodburn and Lorimer 1999). However, cyclical production is not the only option. It is also possible to maintain a continuous stand cover (Buongiorno et al. 1995; Pukkala et al. 2009, 2010; Pukkala 2016; Valkonen et al. 2017). Several studies have suggested that continuous-cover forestry has particular benefits (Hyytiäinen et al. 2004; Chang and Gadow 2010; Tahvonen 2011; Buongiorno et al. 2012). Financial sustainability has been investigated in terms of maximized net present value of future proceeds (Tahvonen 2016; Rämö and Tahvonen 2015, 2016; Tahvonen and Ramo 2016; Sinha et al. 2017). As a special case of continuous-cover process, a stationary system may appear which displays some kind of a demographic equilibrium (Schütz 1975, 1997, 2006; Brzeziecki et al. 2016). In principle, a stationary stand may develop naturally, provided the system has enough time for transient effects to level off. However in several cases, transient times may be long and it is not easy to find naturally developed stationary forests (Bollandsås et al. 2008; Aakala et al. 2009; Brzeziecki et al. 2016).

It has been postulated that in a natural state, the appearance frequency of trees would decrease exponentially as a function of tree size (de Liocourt 1898; Kerr 2014; Picard and Gasparotto 2016). However, we are not aware of any criterion of stationarity that would specifically produce exponential distributions. Exponential tree size distribution within a forest stand may be approached through specially designed harvesting schedules (Helliwell 1997; Pukkaa 2016; Schütz et al. 2016). However appears that such tailored systems are not stationary but in a kind of transient state (O'hara et al 2007).

In this paper, stationarity conditions for the size distribution of forest trees are established. Systems fulfilling a stationarity criterion are discussed because of their conceptual simplicity and practical implementability.

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The established steady-state equations are parametrized using a Norwegian empirical model for the growth and mortality of spruce trees, as well as recruitment of new trees (Bollandsås et al. 2008). Tree size distribution, total basal area, total volume as well as the financial value of trees in a natural stationary state are examined for three stand fertilities. Naturally dying trees and their financial value are discussed, provided they can be harvested.

We resist the temptation to implement any multi-objective optimization or any other treatment with limited tractability and comprehensibility. Instead, a few simple stationary harvesting patterns are introduced. Human interference affects size distribution, total basal area, total volume, as well as the financial value of the trees. Harvesting also produces a financial return. The interplay of harvest yield and financial return rate is discussed. Finally, the possibility of applying longer harvesting cycles, resulting as non-stationary states, is discussed.

Materials and methods

A stationary structure requires stationary distributions of population properties. Let us define stationary conditions on the basis of tree diameter ingrowth, diameter outgrowth, and mortality. The process of outgrowth obviously must be related to ingrowth into another diameter class. The size distribution can be stationary only if the sum of the number of individuals involved in the three processes equals zero. Consequently, a stationarity condition is:

$$Id5(D_{i-1})n(D_{i-1}) - Id5(D_i)n(D_i) - m(D_i)n(D_i) = 0 \quad (1)$$

where $n(D_i)$ is the number of trees in diameter class i, $Id5(D_i)$ is the probability that a tree survives and grows into the next diameter class, and $m(D_i)$ is mortality. Such a stationarity criterion is rather generic and appears in a variety of contexts. For forest stands, we established the criterion independently before finding out that it has been several times mentioned by Schütz, and applied by several researchers (Schütz 1975; Coomes et al. 2003; Kohyama et al. 2003; Schütz 2006; Muller-Landau et al. 2006).

Taking the indices i as positive natural numbers in Eq. (1), i–1 becomes ill defined with the smallest value i =1 because there is no description of existing trees smaller than those in the smallest diameter class. In other words, for the smallest diameter class, we need a boundary condition:

$$R - Id5(D_1)n(D_1) - m(D_1)n(D_1) = 0 \quad (2)$$

where the first term R corresponds to the number of trees recruited into the smallest diameter class

In order to solve the tree size distribution in a stationary state according to Eqs. (1) and (2), the three functions appearing in the equations have to be clarified. The empirical model of Bollandsås et al. (2008), Halvorsen et al. (2015) is utilized. The three functions become:

$$Id5(D_i) = \frac{a_1 + a_2 * D_i + a_3 * D_i^2 + a_4 * D_i^3 + a_5 * BAL(D_i) + a_6 * SI + a_7 * BA + a_8 * LAT}{\Delta} \quad (3)$$

$$m(D_i) = \frac{1}{1 + \exp\{-1 * [b_1 + b_2 * D_i * 10 + b_3 * (D_i * 10)^2 + b_4 * BA]\}} \quad (4)$$

$$R = \frac{c_1 * (BA)^{c_2} * (SI)^{c_3}}{1 + \exp\{-1 * [d_1 + d_2 * BA + 0.0655 * SI + d_3]\}} \quad (5)$$

where a_k , b_k , c_k and d_k are constants given in Bollandsås et al. (2008) and Halvorsen et al. (2015), and shown in the "Appendix". $BAL(D_i)$ is basal area of trees larger than D_i , SI is site index (dominant height at 40 years of age), BA is total basal area, LAT is latitude, and Δ is diameter increment from diameter class i–1 to class i.

Results

Properties of the stationary state

Figure 1 shows the number of trees within any diameter class in a stationary state in a spruce stand for three site fertility classes according to Eqs. (1)–(5). The only free parameter is latitude which is given a value of 61.9. The total number of trees > 50 mm dbh per hectare is 306, 343, and 381 for the tree fertility classes. The corresponding basal areas at breast height are 27.0, 32.2 and 37.1 m^2 ha^{-1}. An interesting feature is that the stationary size distributions are not monotonically decreasing in Fig. 1. In terms of Eqs. (1)–(5), with large trees, the growth rate related to Eq. (3) decreases as a function of increasing tree size. This induces crowding of appearance frequencies in large diameters. Crowding is partially compensated by increased mortality according to Eq. (4). Compensation is almost complete in the case of the highest fertility, but clearly incomplete with lower fertilities. However, in the largest diameter classes, mortality becomes high enough to reduce the appearance frequency of trees regardless of site fertility.

Stem diameter can be converted to trunk volume in a variety of ways. The relationship provided by Rämö and Tahvonen (2015) is applied for eutrophic spruce stands. The commercially utilizable trunk volume in trees of different diameter classes is given in Fig. 2. The total

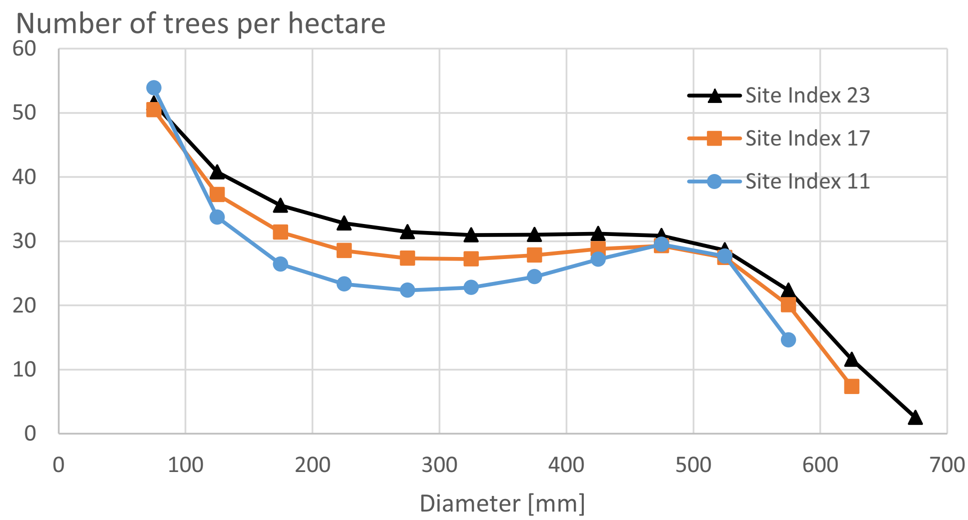

Fig. 1 Number of trees in 50 mm diameter classes in the stationary state according to Eqs. (1)–(5) for three site fertility classes

commercial stand volume per hectare is 237, 282 and 324 m^3 ha^{-1} for the three fertility classes.

The stumpage value of the standing trees is calculated on the basis of separate stumpage prices for pulpwood and sawlogs (Rämö and Tahvonen 2015). The total stumpage value per hectare is 12704, 15109, and 17381 Euros·ha^{-1} for the three fertility classes (Fig. 3).

According to Eq. (1), the number of dying trees within any diameter class corresponds to the number of trees growing out, the number of trees growing into the class subtracted. The total number of dying trees per hectare during a five-year period is 8, 11, and 14 for the three fertility classes (Fig. 4). In the stationary state, the total number of dying trees corresponds to the number of trees recruited into the smallest diameter class during the same period.

In a stationary state, the commercial trunk volume remains constant. Correspondingly, in the absence of harvesting, the reduction of the volume of living trees through death equals volumetric growth in Eq. (1). The stem volume in dying trees within any diameter class is shown in Fig. 5. The total amount of growth per hectare during a five-year period is 6, 12, and 20 m^3 for the three fertility classes. Correspondingly, the annual growth varies from 1.2 to 4.0 m^3 ha^{-1}.

In large-scale commercial forestry, a harvest yield of 6 to 20 m^3 ha^{-1} would be considered small. However, in small-scale forestry, such harvesting operations may well be feasible. In Fig. 6, the commercial stumpage value of trees dying within any five-year period is 336, 645, and 1092 Euros for the three fertility classes.

It is of interest to compare the stumpage values of dying trees to the total monetary value of standing trees. Provided the five-year growth can be technically harvested and then yields the expected stumpage value, the annualized return of the capital becomes 0.53%, 0.85% and 1.26% for the three different site fertility classes. Obviously, gaining the full stumpage value requires that the harvester is a professional capable of identifying dying trees before they suffer any deterioration in commercial value.

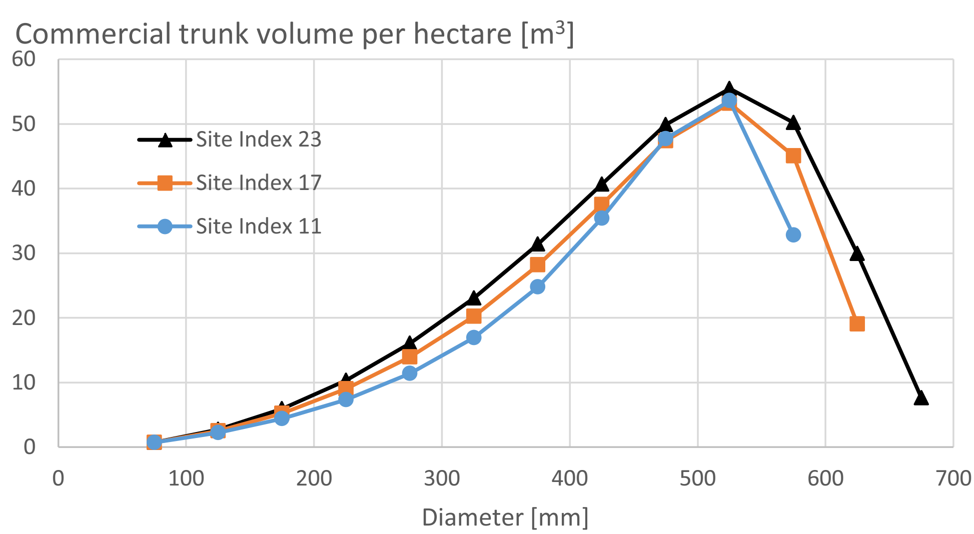

Fig. 2 Commercial volume by 50 mm diameter classes in the stationary state according to Eqs. (1)–(5) for three site fertility classes

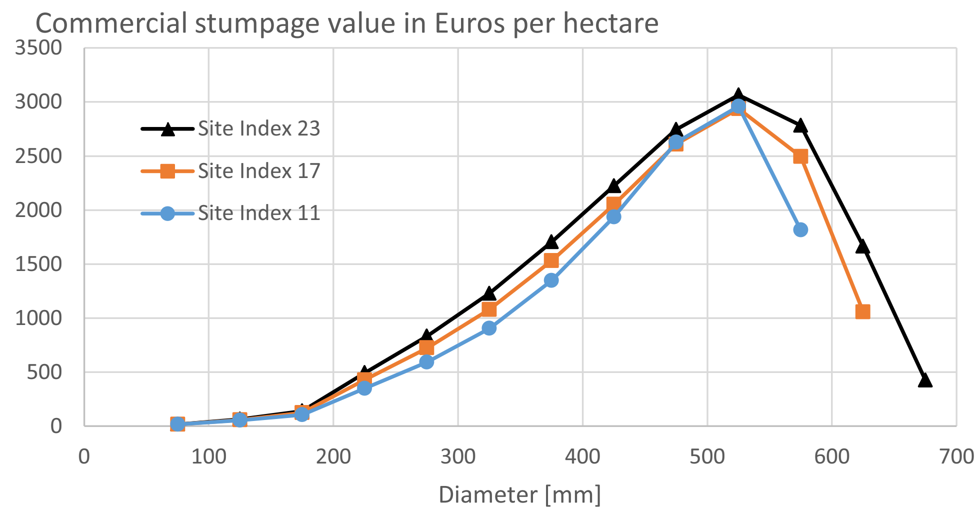

Fig. 3 Commercial stumpage values in 50 mm diameter classes in the stationary state according to Eqs. (1)–(5) for three site fertility classes

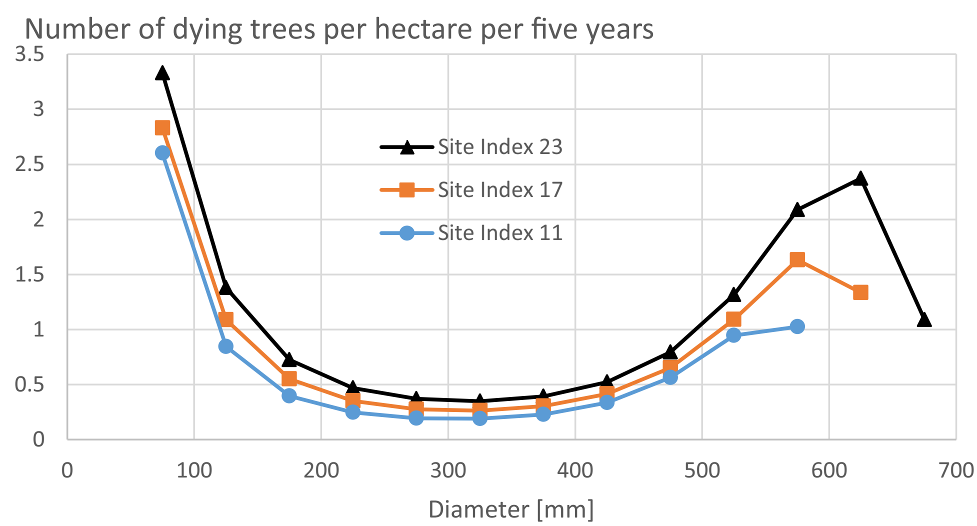

Fig. 4 Number of dying trees in 50 mm diameter classes in the stationary state during a five-year period according to Eqs. (1)–(5) for three site fertility classes

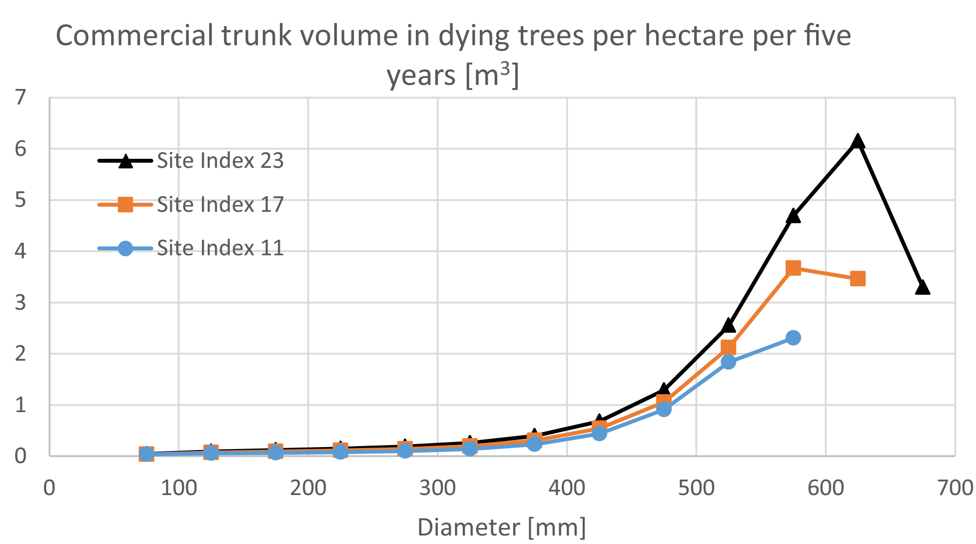

Fig. 5 Volumetric growth which equals the volume of dying trees in 50 mm diameter classes in the stationary state during a five-year period according to Eqs. (1)–(5) for three site fertility classes

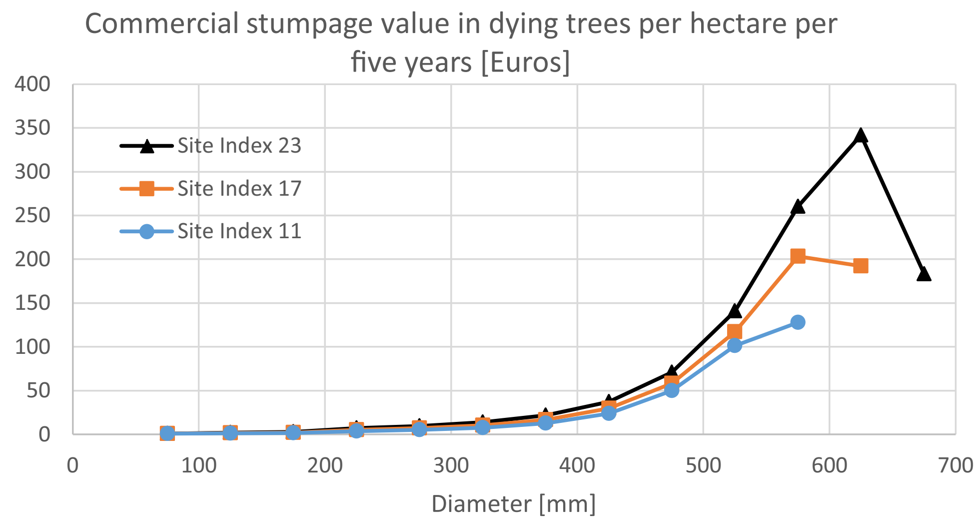

Fig. 6 Commercial stumpage value of dying trees in 50 mm diameter classes in the stationary state within any five-year period according to Eqs. (1)–(5) for three site fertility classes

Human interference

Consider an example where there is human interference in the stationary state through a harvesting program where trees larger than a particular diameter are periodically harvested. Equations (1) and (2) are still valid in other diameter classes but for the largest diameter class:

$$n(D_{Max}) = {}^1\!/_2 Id5(D_{Max-1})n(D_{Max-1}) \tag{6}$$

In Figs. 7, 8 and 9, the total number of trees exceeding the diameter of 50 mm, as well as basal area and total volume, increase as a function of cutting limit diameter. This occurs regardless of the fact that tree recruitment as well as mortality depend on total basal area according to Eqs. (4) and (5). The number of small trees is greater in Fig. 7 with a small cutting limit diameter than the number of small trees in the natural state illustrated in Fig. 1. The number of trees in Fig. 7 approaches the total number of trees appearing in Fig. 1 in the natural stationary state as the cutting diameter limit increases. The total volume of trees in Fig. 9 approaches the total volume appearing in Fig. 2 in the natural stationary state, as the cutting diameter limit increases.

There is a significant number of trees in Fig. 1 as well as in Fig. 7 in the case of a large cutting diameter limit. Similarly, the total volume is significant in Figs. 2 and 9 in the case of a large cutting diameter limit. However, at small cutting diameter limits, the number of trees, as well as the standing volume are rather low in Figs. 7 and 9. The same applies to basal area in Fig. 8.

The commercial volume harvested within any five-year period in diameter-limit cutting is shown in Fig. 10. It is assumed that in the context of diameter-limit cutting, dying trees are removed from all diameter classes. Figure 10 shows that when the cutting limit approaches the diameter of the largest trees, the harvesting pattern approaches the removal of naturally dying trees. With reduced cutting

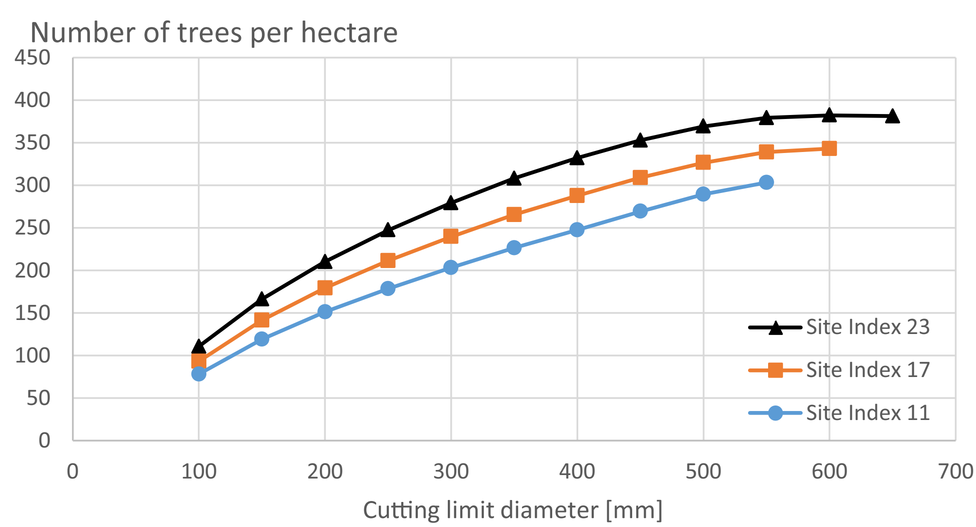

Fig. 7 Number of trees per hectare as a function of cutting limit diameter according to Eqs. (1)–(5) for three site fertility classes

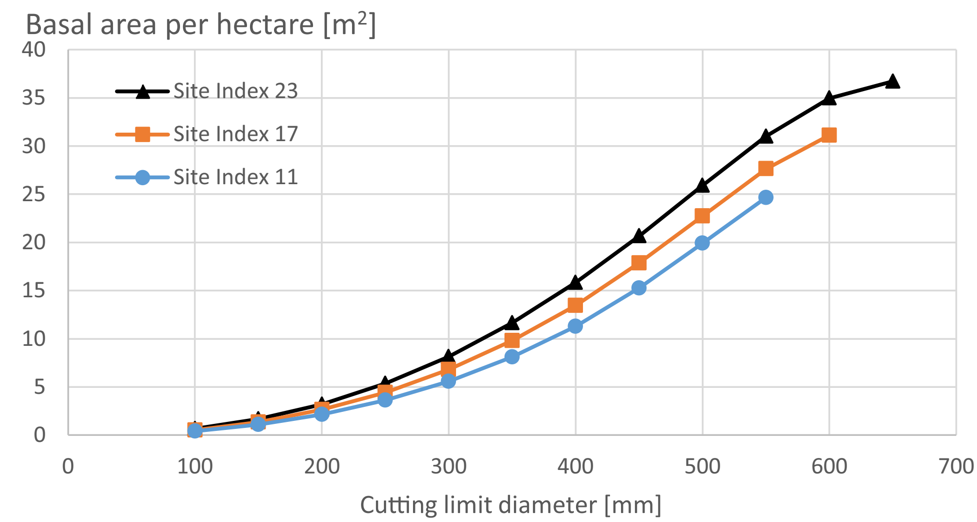

Fig. 8 Basal area per hectare as a function of cutting limit diameter according to equations (1)–(5) for three site fertility classes

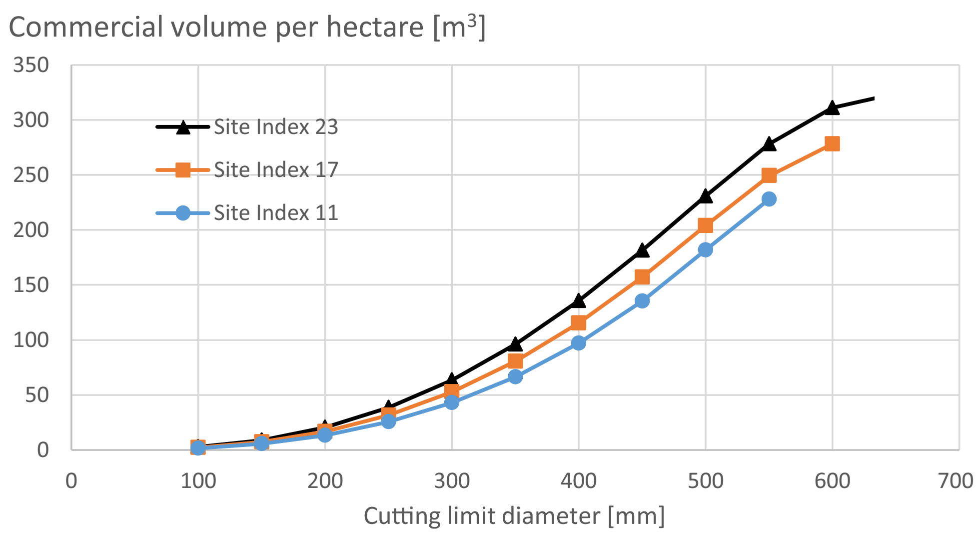

Fig. 9 Commercially viable trunk volume per hectare as a function of cutting limit diameter according to Eqs. (1)–(5) for three site fertility classes.

diameter limit, the proportion of harvesting volume from dying trees reduces rapidly. The greatest harvesting volume is gained at cutting limit 450 mm. With smaller diameter limits, the harvesting volume becomes reduced.

The highest commercial stumpage value of trees harvested in diameter-limit cutting within any five year period is reached with a cutting diameter limit of 450 mm (Fig. 11). As a function of cutting diameter limit, the largest increment is 150 to 200 mm, where sawlogs first appear in the harvesting yield, instead of merely only pulpwood.

The annualized capital return rate from diameter-limit harvesting is shown in Fig. 12. The stumpage revenue, which at the stationary state equals the value growth, is normalized by the total monetary value of the trees. The capital return rate has two minima and two maxima. A rather large annual rate is found with a cutting diameter limit of 100 mm (Fig. 12). An eventual problem with this cutting limit is that there are only 78–111 small trees per hectare at the stationary state, corresponding to volumes of 1.6 to 2.7 $m^3 \cdot ha^{-1}$, and yielding harvest volumes of only 1.3–3.0 m^3 ha^{-1} for any five-year period.

There is another local maximum in the capital return rate curve at a harvesting diameter limit of 200 mm. This also is restricted by a small number of stems (151–210 ha^{-1}), a small standing volume (13–20 m^3 ha^{-1}) and a small volumetric yield in harvesting within any 5-year period (4.4–10.2 m^3 ha^{-1}). With a harvesting diameter limit of 450 mm, the five-year yield would be greater (10.5–26.7 m^3 ha^{-1}) but the capital return rate much lower (1.7–3.1% per year).

Applications with longer harvesting intervals

Figure 10 shows that volumetric yields in harvesting repeated every five years are low, even in the case of the

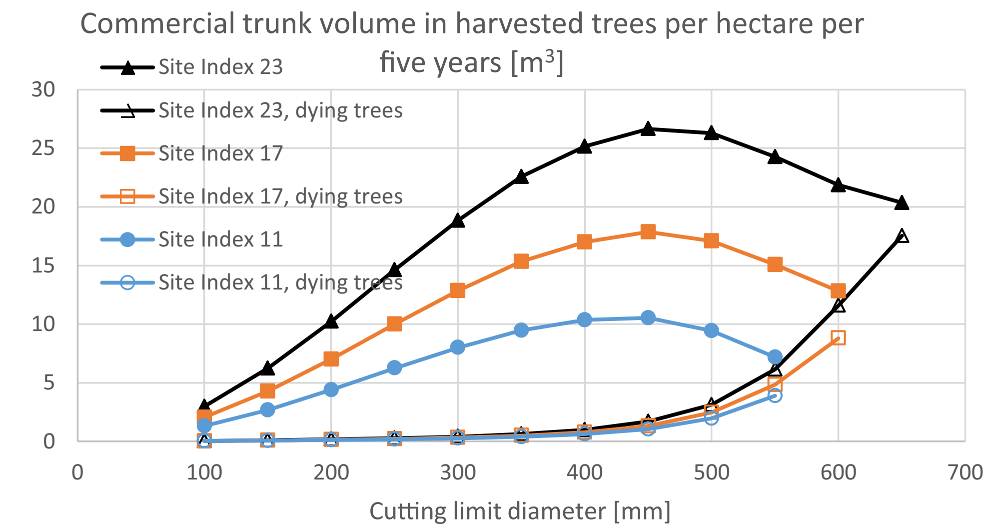

Fig. 10 Commercial trunk volume harvested in diameter-limit cutting within any five-year period, including dying trees from all diameter classes, according to Eqs. (1)–(5) for three site fertility classes.

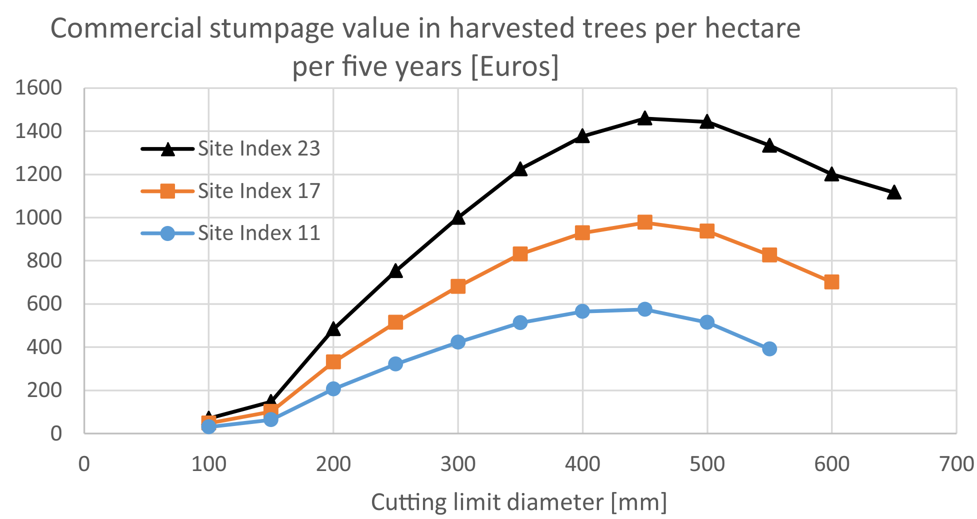

Fig. 11 Commercial stumpage value of trees harvested in diameter-limit cutting within any five-year period, including dying trees from all diameter classes, according to Eqs. (1–5), for three site fertility classes

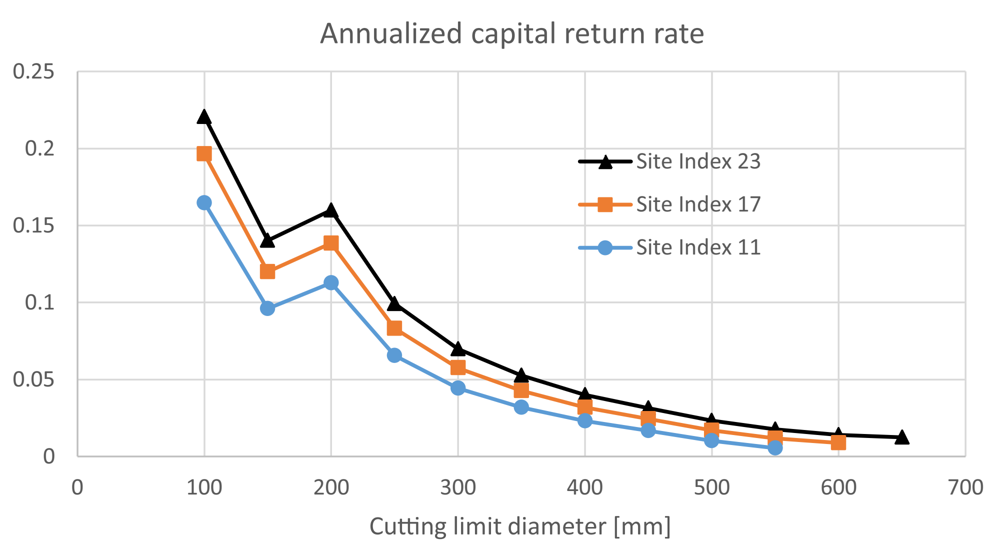

Fig. 12 Annualized capital return rate from diameter-limit cutting within any 5-year period, including dying trees from all diameter classes, according to Eqs. (1–5), for three site fertility classes

highest fertility and high cutting limit diameters. Therefore, it might be feasible to apply longer harvesting intervals. A question arises whether the forestry still can be considered stationary rather than periodic, and the obvious answer is "no". However, periodic harvesting may be a natural extension of stationary forestry.

Starting with a stationary state with the boundary condition that all trees greater than a particular cutting diameter limit are nonexistent, equations (1)–(5) are valid to determine the number of trees in any diameter class, with the exception that the number of trees in diameter classes above the diameter cutting limit is zero. If Eqs. (1) and (2) are then neglected, equations (3)–(5) may further modify the number of trees in any diameter class.

The development of standing commercially viable volume per hectare, beginning from a stationary state with stems over 200 mm of diameter not existing (Fig. 13). The initial state is stationary with the above boundary condition while consequent states are nonstationary. The total commercial volume and volume of trees exceeding 200 mm of diameter is shown in Fig. 13. The latter volume is zero at the initial state, and increases along with time. Also the total volume increases along with time. The total volume is 11–16 m^3 ha^{-1} at the initial state, and its further development strongly depends on site fertility. A volumetric harvesting yield of 20 m^3 ha^{-1} would require a harvesting interval from 8 to 18 years, depending on site fertility.

The distinction between total volume and volume in trees over 200 mm diameter is reduced with time, i.e., the volume of small trees is reduced (Fig. 13). This is due to reduced recruitment along with increasing basal area according to Eq. (5). Consequently, the system does not immediately return to the initial state at the instant of diameter-limit cutting.

Annualized capital return rate from diameter-limit cutting within any period of five years, initiating from the 200-mm diameter-limit cutting, is shown in Fig. 14. The capital return rate is here defined on financial grounds as the value of net growth in relation to the representative standing value. The value of annual net growth increases along with increasing capitalization but not in proportion to the capitalization. Thus, the momentary capital return rate becomes reduced with increasing capitalization. Initial annualized return in excess of 11 to 16%/year is reduced to 4 to 5%. This, to some degree, jeopardizes the benefit of longer harvesting intervals in terms of greater volume yield (Fig. 13). It is however, worth noting that the average capital return rate remains at 6 to 7% even if the harvesting interval would be 30 years (Fig. 14).

Figure 15 shows the development of standing commercially viable trunk volume per hectare, beginning from a stationary state with no trees over 300 mm of diameter is shown (Fig. 15). The commercial volume in stems exceeding 300 mm of diameter is also shown. The latter volume is zero at the initial state, and increases along with time. Also the total volume increases. The total volume is 39–55 m^3 ha^{-1} initially and its further development strongly depends on site fertility. A volumetric harvesting yield of 20 m^3 ha^{-1} would require harvesting interval from five to 13 years, depending on site fertility.

Annualized capital return rate from diameter-limit cutting, within any period of five years, initiating from the 300-mm diameter-limit cutting, is shown in Fig. 16. Now, the initial capital return varies between 4 and 7%, and declines to 2.5–3.2% within 25 years. In the case of such an extended harvesting interval, volumetric harvesting yield is rather significant (Fig. 15), whereas the capital return rate is not.

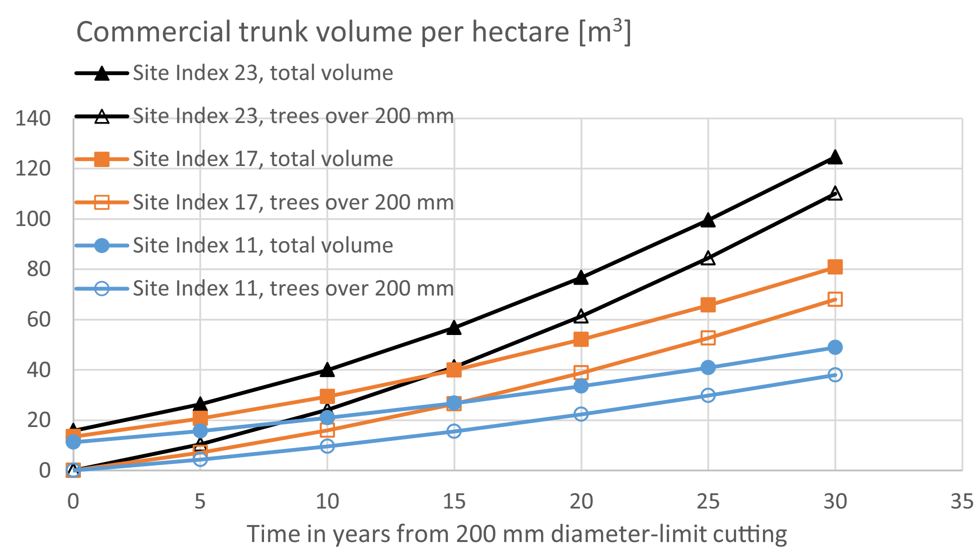

Fig. 13 Commercially viable volume as a function of time from diameter-limit cutting with a harvesting limit of 200 mm. Volume in trees exceeding the cutting limit diameter is shown separately

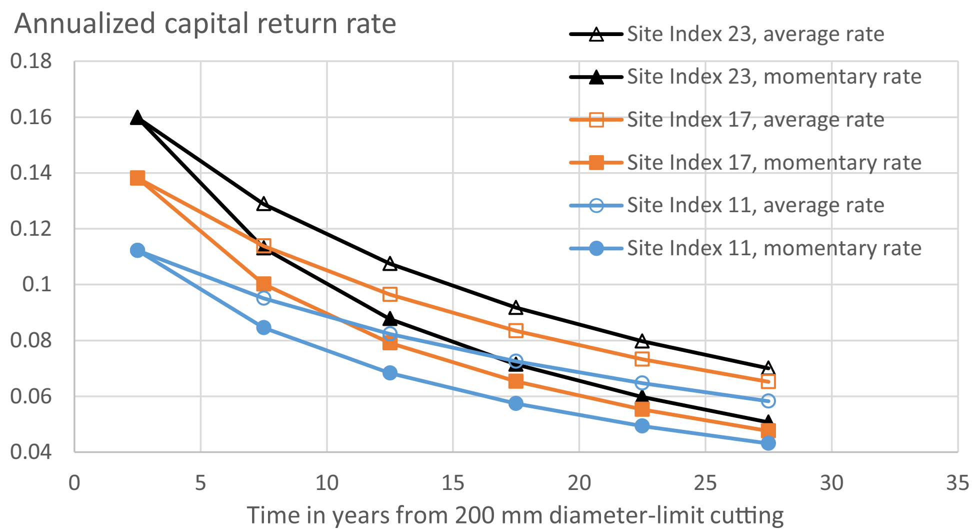

Fig. 14 Annualized capital return rate within any five-year period, after diameter-limit cutting with 200 mm harvesting limit. Also accumulated average capital return rate is shown.

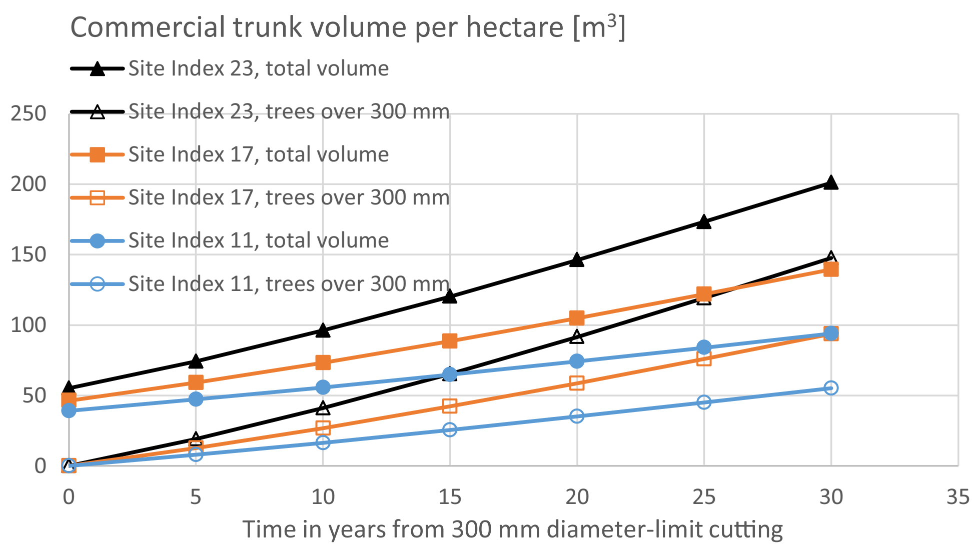

Fig. 15 Commercially viable stand volume as a function of time from diameter-limit cutting of 300 mm. Volume in trees exceeding the cutting limit diameter is shown separately

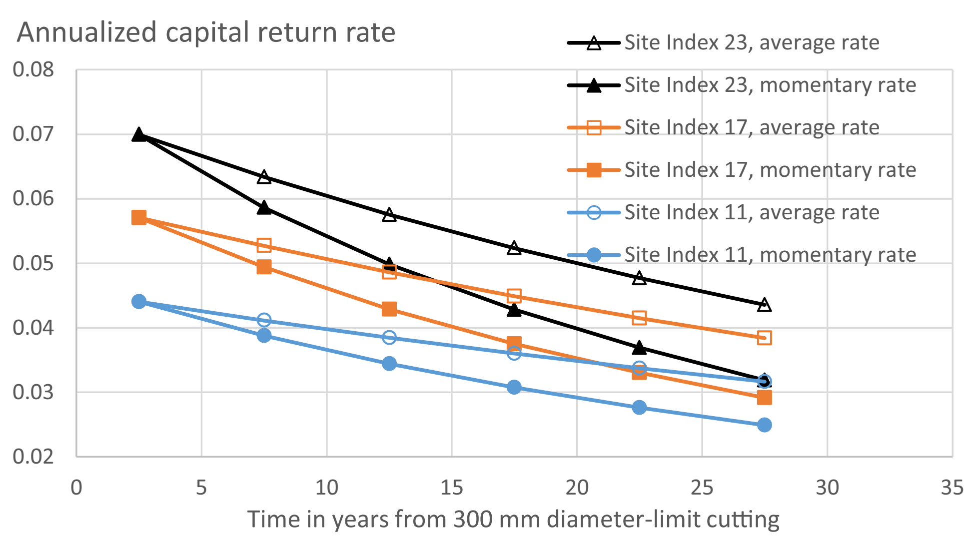

Fig. 16 Annualized capital return rate within any period of five years, initiating from 300 mm diameter-limit cutting.

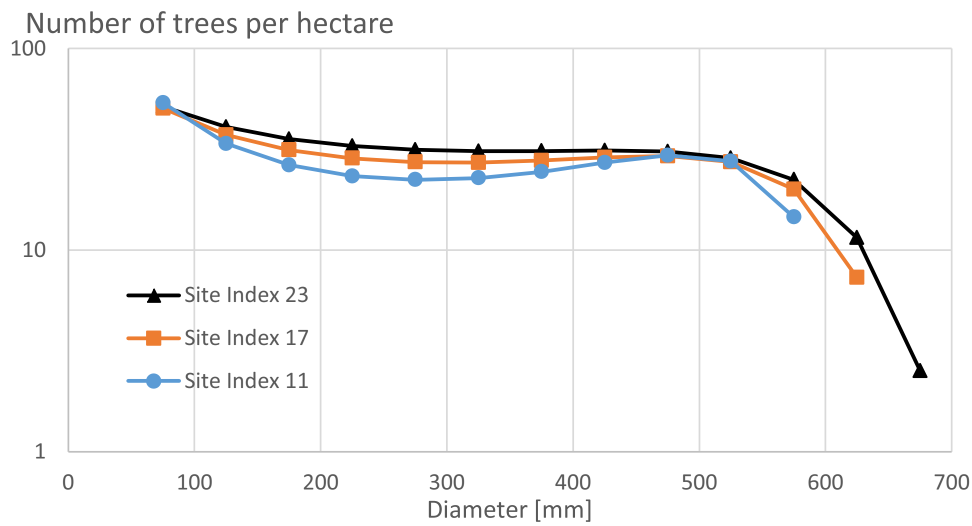

Fig. 17 Number of trees in 50 mm diameter classes in the stationary state according to Eqs. (1)–(5), for three site fertility classes, plotted on a semi-logarithmic scale.

Comparing Figs. 13 and 15 shows that the net growth rate is 40–50% higher if the cutting limit is 300 mm instead of 200 mm, with a boundary condition of 20 m^3 ha^{-1} harvesting yield. Considering also Figs. 14 and 16, the capital return rate is 100% higher with the 200 mm cutting limit, with the boundary condition of 20 m^3 ha^{-1} harvesting yield.

Discussion

The number of trees in a natural stationary forest appears small in comparison to non-stationary forest ecosystems (Figs. 1, 7; Pukkala 2006; Tahvonen 2011; Rämö and Tahvonen 2015; Lundqvist 2017; Sinha et al. 2017; Valkonen et al. 2017). The growth rate is less than that reported for comparative sites in non-stationary forests (Figs. 5, 10; Pukkala 2006; Tahvonen 2011; Lundqvist et al. 2013; Drössler et al. 2014; Rämö and Tahvonen 2015; Valkonen et al. 2017; Sinha et al. 2017; Lundqvist 2017). This is directly due to Eqs. (3)–(5). The recruitment rates given by Eq. (5) appear rather slow, inducing stationary systems with a small number of trees. On the other hand, the basal area and standing volume become significant, provided the stationary state is not disrupted (Figs. 2, 8, 9). Basal areas however, are less than those in long-term simulations (Bollandsås et al. 2008). This may be related to two issues of equations (1)–(5). Firstly, age does not contribute to mortality in Eq. (4). Secondly, Eqs. (1) and (2) have not been applied in long-term simulations, possibly resulting as a transient state at simulated high stand age.

Non-natural stationary states satisfying Eqs. (1) and (2) may develop under anthropogenic influences. One example is the boundary condition of repeated diameter-limit harvesting. Volumetric yield and financial return rate clearly appear to contradict each other. The highest financial return rates are achieved with frequent harvesting of small trees, resulting in a small amount of standing volume, along with rather small volumetric growth (Figs. 7, 8, 9, 10, 11, 12, 13, 14, 15, 16). On the other hand, a greater amount of capital in standing trees increases growth and yield but inevitably reduces capital return rate (Figs. 7, 8, 9, 10, 11, 12, 13, 14, 15, 16).

It is customary thinking within the field of forestry that trees should be grown as long as the capital return rate exceeds an external alternative rate of return or "opportunity cost". In the mind of the Author, this is incorrect. From a financial perspective, the capital return rate should be maximized within any production process. A justification is that an alternative practice within forestry itself, providing a higher capital return rate, may form an opportunity cost. The capital returns in this paper have been discussed in a purely operative basis. This is justified since bare land, not being a consumable, is not subject to amortizations. Proper allocation of capital between industries would require some kind of a scenario of real estate appreciation which is outside the scope of this study.

The empirical models (3)–(5) in this study describe growth, mortality and recruitment in a statistical sense. Significant scattering beyond modelled trends appears in any dataset (Bollandsås et al. 2008). Consequently, some amount of uncertainty in the present results is obviously related to the reliability of the models. However, qualitatively, the appearance of slow recruitment, in accordance with Eq. (5) appears to agree with several reports (Lundqvist 1993; Newbery et al. 2004; Pukkala et al. 2010; Vlam et al. 2016). There are also observations indicating a higher rate of recruitment (Lundqvist 1991; Lundqvist and Nilson 2007).

Few stationary structures have been found in old-growth forests (Newbery et al. 2004; Brzeziecki et al. 2016; Vlam et al. 2016). Recruitment often not being sufficient, the number of trees tends to decrease and the age of dominant trees to increase (Pukkala et al. 2010; Brzeziecki et al. 2016; Lundqvist 1993). Such a transitory situation apparently may endure several centuries, possibly close to a millennium (Aakala et al. 2009; Pukkala et al. 2010; Brzeziecki et al. 2016). During such a period, a variety of disturbances may appear, interfering with the development of a stationary state.

Obviously the recruitment of seedlings can be increased by artificial or seminatural regeneration (Busing 1994; Goodburn and Lorimer 1999; Pukkala 2006; Pyy et al. 2017). Such actions easily lead to periodic forestry, instead of stationary forestry. The prospects for high volumetric and monetary yield rates favor periodic forestry. The high financial return rate of capital bound within the process appears to be the significant benefit of stationary forestry.

It is interesting to consider the postulation of exponentially vanishing tree size distribution (de Liocourt 1898; Kerr 2014; Picard and Gasparotto 2016) from a viewpoint of stationarity. Replotting the size distribution of trees in Fig. 1 in a semi-logarithmic scale in Fig. 17 reveals that the size distribution of trees in the stationary state does not decay exponentially. In broad terms, the appearance density of trees is rather constant within the 225–475 mm diameter range. The reduction in the number of large trees does not show any linear section in the semi-logarithmic scale. The number of small trees in the stationary state is just slightly higher than that the constant frequency with medium-size trees, possibly corresponding to relatively slow recruitment (cf. Lundqvist 1993; Newbery et al. 2004; Pukkala et al. 2010; Vlam et al 2016).

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Appendix: The values of constants appearing in Eqs. (3), (4) and (5).

a1	17.839300	b1	− 2.491600	c1	43.14190	d1	− 2.2905
a2	0.047620	b2	− 0.020000	c2	− 0.15665	d2	− 0.0175
a3	− 0.000116	b3	0.000032	c3	0.36812	d3	0.0190
a4	0.000000	b4	0.030800				
a5	− 0.341160						
a6	0.906040						
a7	− 0.024140						
a8	− 0.267810						

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