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Two sets of initial conditions on boreal forest carbon storage economics

Petri P. Kärenlampi *

Lehtoi Research, Lehtoi, Finland

* petri.karenlampi@professori.fi

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Abstract

Two sets of initial conditions are used in the investigation of capital return rate and carbon storage in boreal forests. Firstly, a growth model is applied in young stands as early as the inventory-based model is applicable. Secondly, the growth model is applied to observed wooded stands. Four sets of thinning schedules are investigated in either case. The two sets of initial conditions yield similar results. The capital return rate is a weak function of rotation age, which results in variability in the optimal number of thinnings. Reducing the number of thinnings to one increases timber stock but induces a capital return rate deficiency. The deficiency per excess volume unit is smaller if the severity of any thinning is restricted by the removal of large trees only. Omission of thinnings best applies to spruce-dominated stands with stem count less than 2000/ha. Restricted thinning intensity applies to deciduous stands and dense pine stands. The albedo effect increases the benefits of restricted thinnings and increased clearcuttings instead of contradicting the carbon storage.

1. Introduction

There are two large sinks of atmospheric carbon on planet Earth: the oceans and the forests [1–4]. It is difficult to manipulate oceans, whereas forests can be managed. By definition, a carbon sink is a system with a positive time change rate of stored carbon. This paper discusses the microeconomics of boreal forests as a carbon sink.

A particular benefit of the boreal forest is carbon storage in the soil; the amount of soil carbon may exceed the carbon storage in living biomass [5–10]. However, living biomass produces litter resulting in soil carbon accumulation, and consequently, the rate of carbon storage depends on the rate of biomass production on the site. The biomass production rate is related to the amount of living biomass [6, 9, 11, 12]. As the time change rate of storage constitutes a sink, this paper focuses on changes in living biomass. In the case of trees, one of the most straightforward indicators of living biomass per surface area unit is the commercial volume of tree trunks.

The outcome of any process depends on the essential contributing mechanisms. Such mechanisms can often be described in terms of a process model. However, the outcome also depends on the occurring initial conditions, or more broadly, boundary conditions. In real-life applications, the initial conditions vary. Results of model-based investigations can be considered robust (or non-chaotic) if they are coherent under realistically varying sets of initial conditions [13].

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This paper investigates carbon storage in boreal forests using a growth model based on large inventory datasets [14]. To gain possibly robust results, two different sets of initial conditions are used. Both sets of initial conditions have been described in recent investigations [15–17], but have not been applied simultaneously in the clarification of any single problem.

The process model, together with the initial conditions, could produce an outcome. However, in this paper, there are more elements. There are objective functions. The objective functions are partially microeconomic, partially of a physical character. The microeconomic objective function is the capital return rate [16–20]. The physical objective functions are carbon storage area densities, discussed in terms of living biomass, and measured in area densities of commercial trunk volumes.

There is a hierarchy between the objective functions. Firstly, the capital return rate is maximized. Then, deviations are introduced, and the relationship of capital return rate deficiency to excess commercial volume is investigated. The deviations are introduced in terms of four additional sets of boundary conditions. These are constituted by four sets of restrictions applied to intermediate harvesting practices, or, in other words, thinning restrictions. Some of the restrictions may result in a favorable combination of carbon storage and capital return deficiency, in which case the deficiency could be compensated in terms of a carbon rent [21].

There are many previous investigations discussing the economic feasibility of thinning practices [22–30]. Some of them also discuss carbon storage features [31–35]. However, a few studies contain deficiencies restricting their applicability. Common deficiencies are unrealistic assumptions regarding the yield of various timber assortments, as well as pricing assumptions not adhering with reality [35–39]. It also appears that the optimal number of thinnings, thinning intensity, as well as selection between continuous-cover forestry and clearcuttings, depends on the applied discounting interest rate [22–30].

The capital return rate in forestry has been investigate sparsely [16–20, 40, 41]. Results regarding the relationship of capital return rate and carbon storage are still more sparse [16–20]. Again, some of the available results are deficient due to unrealistic yield assumptions [15, 19]. Others have used financial boundary conditions not considered appropriate in this investigation [16, 20]. There is one earlier study discussing capital return rate deficiency per excess volume unit appearing with the intent of carbon storage where the financial boundary condition meets that one here considered appropriate [17]. That study, however, did not discuss eventual thinning restrictions in detail [17].

2. Materials and methods

The two different sets of initial conditions have been described in three earlier investigations [15–17]. Firstly, a group of nine setups was created, containing three tree species and three initial sapling densities [17]. The idea was to apply the inventory-based growth model as early in stand development as it is applicable, to avoid approximations of stand development not grounded on the inventory-based growth model [14]. This approach also allowed an investigation of a wide range of stand densities, as well as a comprehensive description of the application of three tree species. The exact initial conditions here equal the ones recommended in [17], appearing there in Figs 8 and 9.

The second set of initial conditions is here reported in more detail. The tree species distribution was not accounted for in previous publications [15, 16]. Within the seven wooded, commercially unthinned sample plots of age from 30 to 45 years, located in Eastern Finland, the total stem count varied from 1655 to 2451 per hectare. A visual quality approximation was implemented. The number of stems deemed suitable for growing further varied from 1050 to 1687 per hectare. The distribution of the basal area (cross-sectional area of all trees at breast height) of these acceptable-quality trees into tree species is shown in Fig 1; the basal area of the acceptable-quality trees varied from 28 to 40 m^2/ha, in all cases dominated by spruce (*Picea abies*) trees.

The growth model—the process model acting on the initial conditions—used in this study has been established in 2008 by Bollandsås et al. [14], based on a comprehensive forest inventory in Norway. The growth model has been applied in a variety of earlier investigations [15, 17, 42]. In this study, it is used exactly in the same form as in [17].

To clarify the capital return rate, a financial treatment is needed. We apply a procedure first mentioned in the literature in 1967, but applied only recently [16–20, 40, 41]. Instead of discounting revenues, the capital return rate achieved as relative value increment at different stages of forest stand development is weighed by current capitalization, and integrated. The procedure applies to forest estates of any distribution of site properties, but the result is stationary in time only if the stand age distribution within the forest estate is even. Assumption of even age distribution of stands within an estate corresponds to the "normal forest principle" [43], where any established stand setup or observed sample plot serves as a "normal stand" of an estate [16, 17, 19, 20]. Regeneration expenses are capitalized at the time of regeneration and amortized at the end of any rotation [17].

It is, however, not necessary to adopt the "normal forest principle" in the application of the financial theory [16–20, 40, 41]. This fundamental viewpoint is here presented as an addition to the theory. Instead of discussing an estate with a constant-valued density function of stand ages, let us discuss a single stand, observed at an arbitrary time. The momentary capital return rate is

$$r(t) = \frac{d\kappa}{K(t)dt}, \tag{1}$$

where κ in the numerator considers value growth, operative expenses, interests and amortizations, but neglects investments and withdrawals. In other words, it is the change of

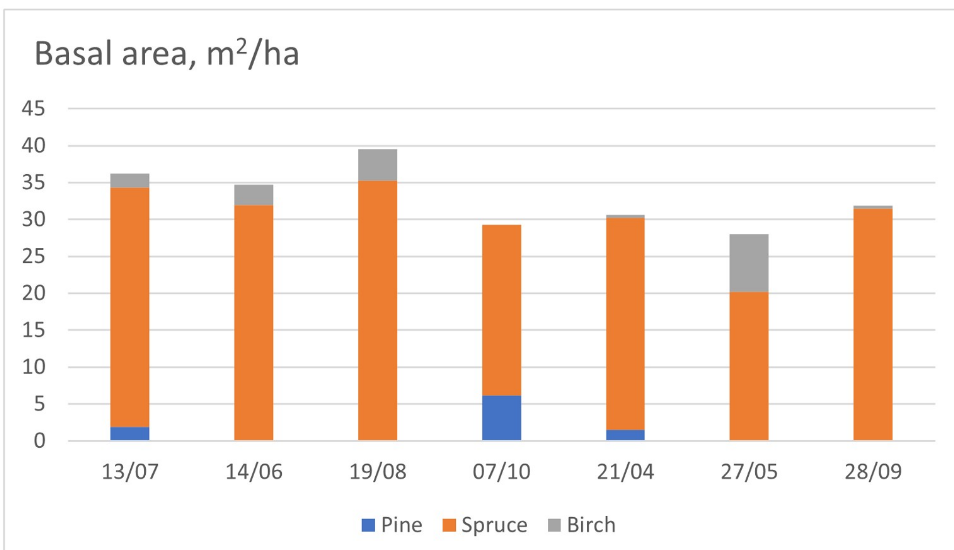

Fig 1. Distribution of basal area of acceptable-quality trees into tree species at seven sample plots.

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capitalization on an economic profit/loss basis. K in the denominator gives capitalization on a balance sheet basis, being directly affected by any investment or withdrawal.

One single observation of the stand at an arbitrary time however does not represent the expected value of the capital return rate within the stand. The expected value can be produced by integrating over the rotation as

$$\langle r(t)\rangle = \frac{\langle \frac{d\kappa}{dt}\rangle}{\langle K\rangle} = \frac{\int_0^\tau p(a)\frac{d\kappa(a,t)}{dt}da}{\int_0^\tau p(a)K(a,t)da} = \frac{\int_0^\tau p(a)K(a,t)r(a,t)da}{\int_0^\tau p(a)K(a,t)da}, \tag{2}$$

where a is stand age (or time elapsed since the latest regeneration harvesting), and τ is rotation age. Now, however, time proceeds in a linear manner. Consequently, the probability density function p(a) is constant within the interval [0, τ]. Then, it becomes canceled from Eq (2). Further assuming real-valued prices and expenses, as well as growth functions, to be time-independent, the expected value of capital return rate becomes independent of time as

$$\langle r\rangle = \frac{\int_0^\tau \frac{d\kappa(a)}{dt}da}{\int_0^\tau K(a)da} = \frac{\int_0^\tau K(a)r(a)da}{\int_0^\tau K(a)da}. \tag{3}$$

In other words, Eq (3) does not require the application of the "normal forest principle".

Finally, as the initial conditions and the growth process function have been established, as well as the objective function as the expected value of capital return rate, four sets of operative boundary conditions are applied. First, intermediate harvesting events (thinnings) are designed for any normal stand to maximize the capital return rate, without any restriction. Second, the number of thinnings is restricted to one. Third, the severity of any thinning is restricted by removing large trees only. A breast-height diameter limit of 238 mm is used. The fourth boundary condition consists of the omission of commercial thinnings.

The three latter of the four boundary conditions defined above in general result as a deficient capital return rate, in comparison to the first (with no restriction). However, at the expense of a capital return deficiency, the magnitude of carbon storage may be increased.

3. Results

Fig 2 shows that in the case of pure spruce stands (Fig 2a), the capital return rate is maximized by one, two, or three thinnings, depending on the initial sapling density [17]. Increased sapling density increases the number of thinnings, as well as rotation time, regardless of the tree species (Fig 2a). Silvicultural practices giving the greatest capital return rate correspond to a rotation age of 89 years. However, the capital return rate, especially in the case of high sapling densities, is a weak function of the rotation age, and correspondingly, a reduction in the number of thinnings (Fig 2b) would change the capital return rate only moderately. Restricting thinnings to the removal of trees thicker than 237 mm would result in only two of the nine data series (setups) being thinned (Fig 2c). Omission of thinnings reduces rotation times significantly but capital return rates only moderately (Fig 2d). There is a significant difference

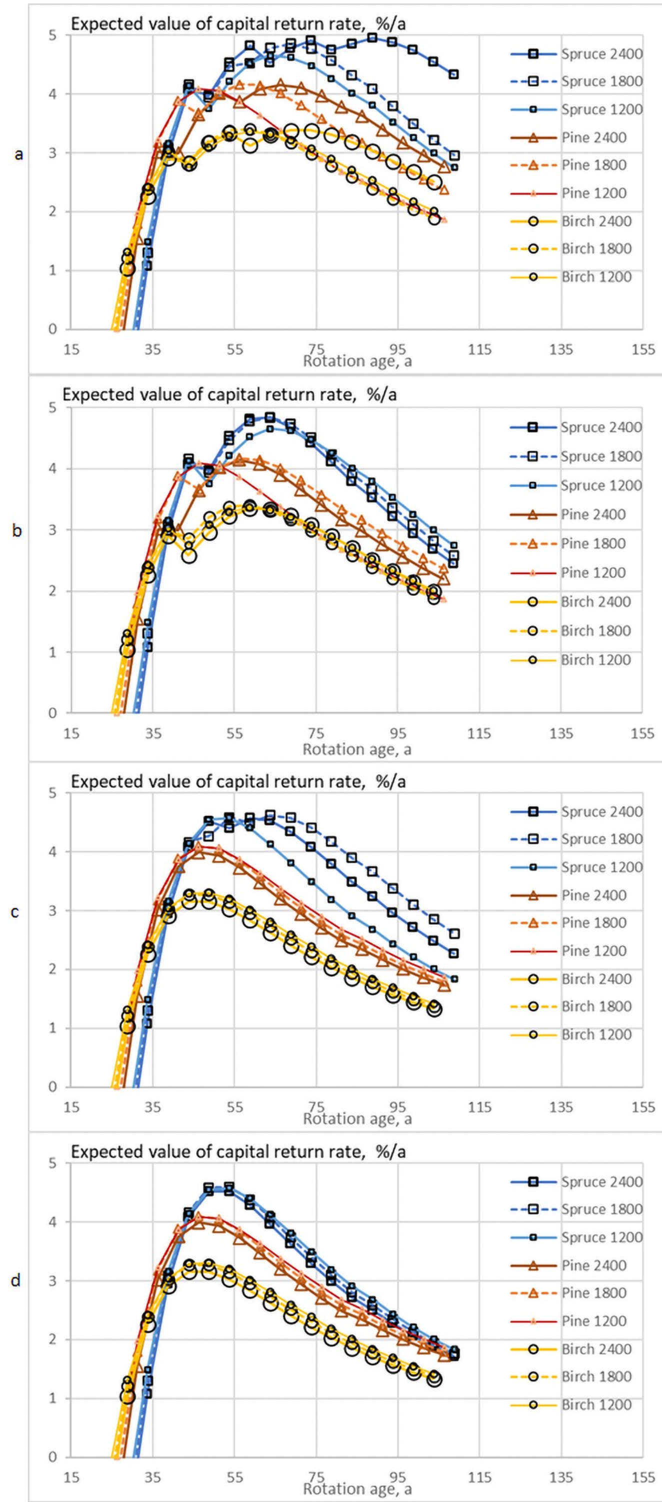

Fig 2. The expected value of capital return rate, as a function of rotation age, when the growth model is applied as early as possible. (a) no restrictions on thinning treatments (b) number of thinnings restricted to at most one (c) thinning restricted to removal of trees thicker than 237 mm (d) thinnings omitted.

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between tree species, which however does not differ much between the applied thinning restrictions.

The seven wooded normal stands (Fig 3) somewhat differ in terms of the number of thinnings. In five normal stands, the greatest capital return rate is gained with one thinning, whereas two thinnings are required in the remaining two cases (Fig 3a). Optimal rotation ages are 62, 50, 50, 80, 77, 53, and 53 years. On the other hand, there is some resemblance to Fig 2a. In the case of stands thinned more than once, the capital return rate is a weak function of rotation age (Fig 3a). The same would happen in the case of stands thinned only once if additional thinnings would be introduced.

Restricting the number of commercial thinnings to one (Fig 3b) naturally would affect only the two normal stands where two thinnings would take place according to Fig 3a. Restricting thinnings to the removal of trees thicker than 237 mm would induce one thinning in five normal stands and two in two normal stands (Fig 3c), always reducing the rotation time in relation to Fig 3a. Omission of thinnings further reduces rotation times but reduces capital return rate only moderately (Fig 3d).

Any deviation from the procedures corresponding to the maximum capital return rate induces a deficiency in capital return rate. Annual monetary deficiency per hectare can be gained by multiplying the deficiency in percentage per annum by current capitalization per hectare.

Any deviation from the procedures corresponding to the maximum capital return rate also changes the expected value of the volume of trees per hectare. In case the volume is greater than that volume corresponding to the maximum capital return rate, there is a positive expected excess volume (also a negative excess volume may appear). The annual monetary deficiency per hectare can be divided by the excess volume to yield a measure of the financial burden of increasing the timber stock.

Silvicultural practices giving the greatest capital return rate in Fig 2a correspond to an expected value of stand volume of 139 m^3/ha. This is achieved with a relatively long rotation time of 89 years. Fig 4 shows the capital return rate deficiency per excess volume unit as a function of positive excess volume. It is found that without any restriction to thinning practices, possibilities for increasing timber storage are limited (Fig 4a). Restricting the number of thinnings to at most one provides much higher excess volumes with a lower expense (Fig 4b). Restricting thinnings to the removal of trees thicker than 237 mm would further increase achievable excess volumes and reduce the corresponding capital return deficiencies (Fig 4c). This restriction results in only two of the nine data series becoming thinned (Figs 1c and 4c). Omitting all thinnings after young stand tending still increases achievable excess volumes and also reduces the corresponding capital return deficiencies (Fig 4d). However, at moderate excess volumes, the lowest capital return deficiencies in the case of the spruce stand with high initial stem count are gained by restricting thinnings to the removal of trees thicker than 237 mm (Fig 4c and 4d).

In Fig 4, the capital return rate deficiency, as well as the excess volume were shown in comparison to the stand setup providing the best available capital return rate. However, there are three alternative tree species and three sapling densities investigated. Any of these nine setups is likely to have dynamics of its own. Fig 5 shows the setup-specific capital return rate deficiency per excess volume, as a function of setup-specific excess volume. We find from Fig 5a that within any setup, excess volume can be gained by extending rotation time, with a moderate capital return rate deficiency. However, in the case of spruce cultivation with the highest initial sapling density, the achievable excess volume is not large (Fig 5a). Restricting the number of thinnings to one increases the available excess volume within a few setups. In the case of the spruce stand with the highest initial stem count, the capital return rate deficiency is

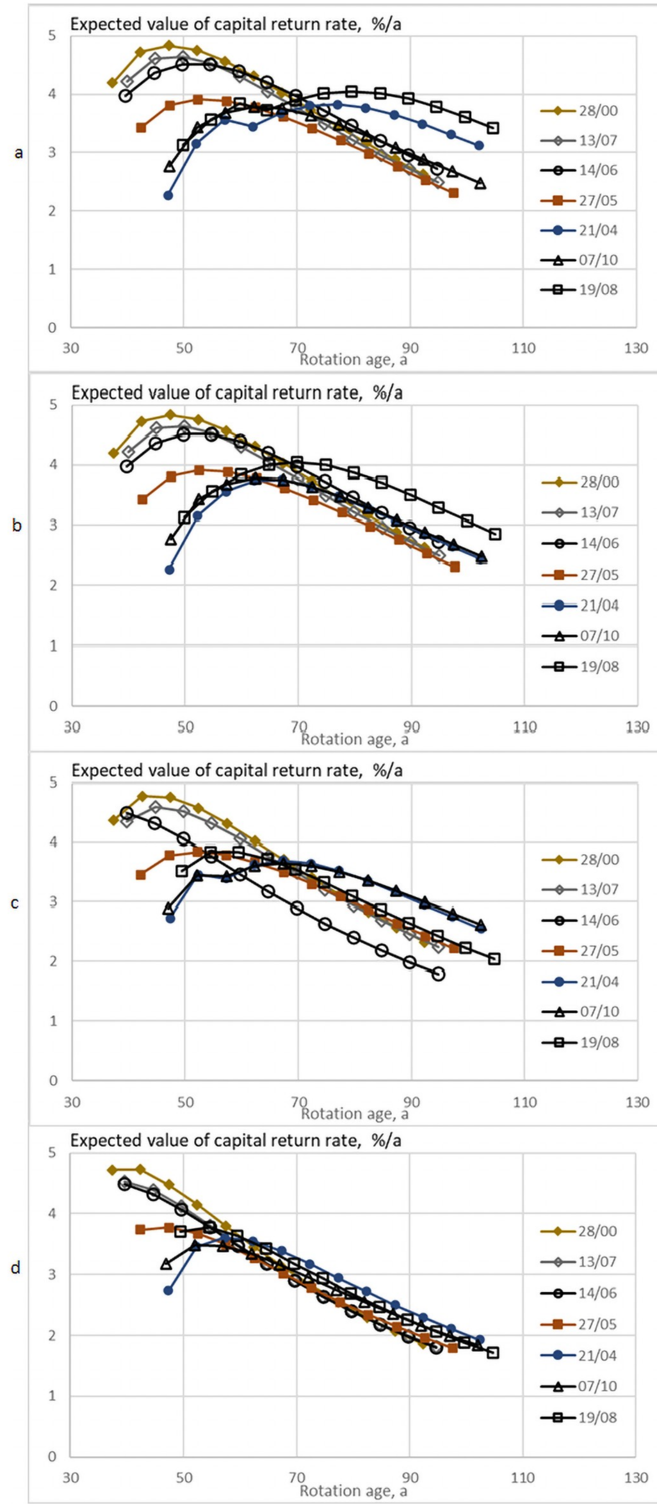

Fig 3. The expected value of capital return rate, as a function of rotation age, when the growth model is applied to observed wooded stands. (a) no restrictions on thinning treatments (b) number of thinnings restricted to at most one (c) thinning restricted to trees thicker than 237 mm (d) thinnings omitted.

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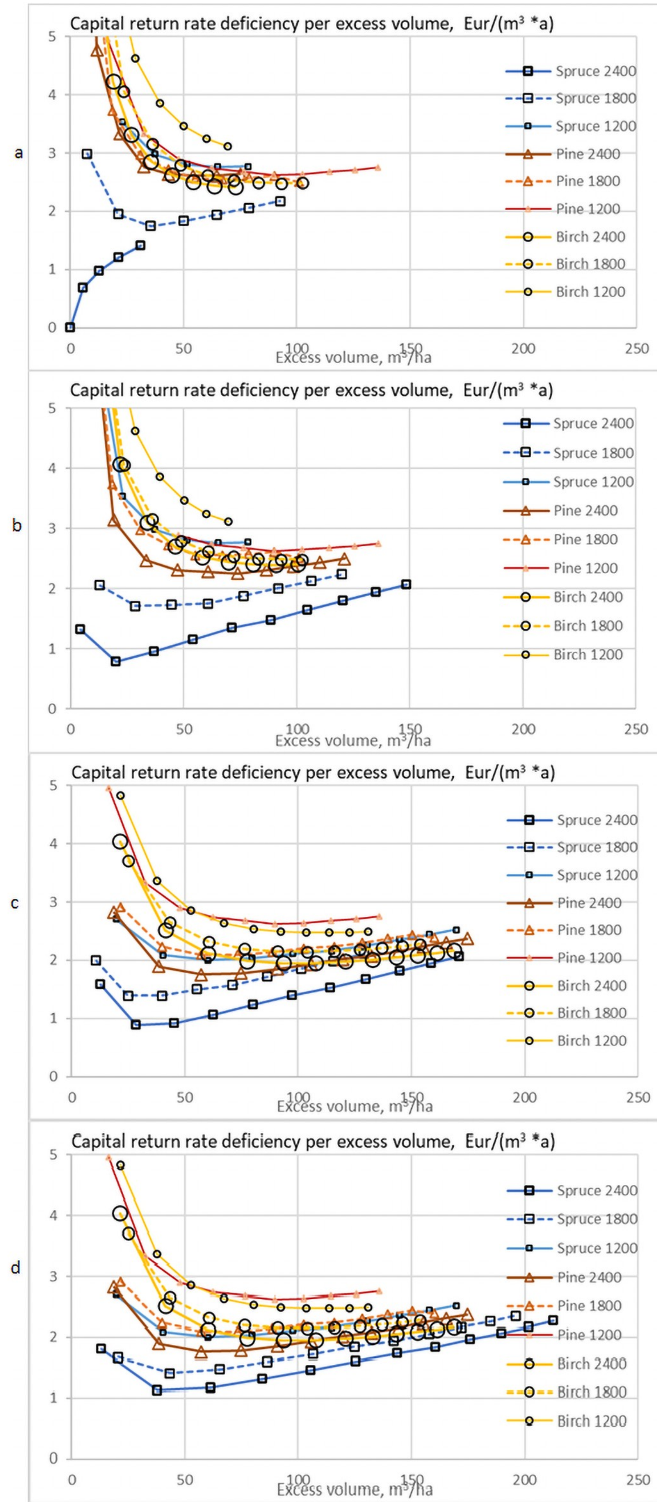

Fig 4. Capital return rate deficiency per excess volume unit, as a function of excess volume, when the growth model is applied as early as possible. (a) no restrictions on thinning treatments (b) number of thinnings restricted to at most one (c) thinning restricted to trees thicker than 237 mm (d) thinnings omitted.

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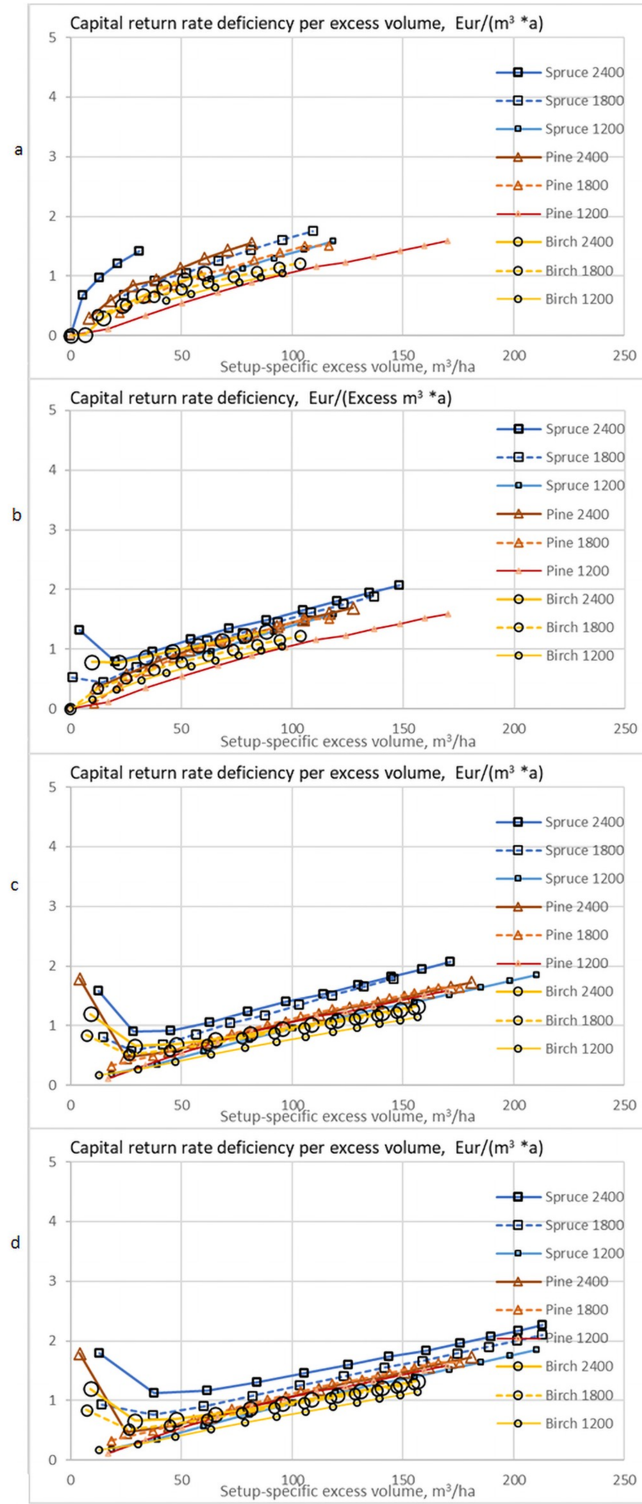

Fig 5. Setup-specific capital return rate deficiency per excess volume unit, as a function of setup-specific excess volume, when the growth model is applied as early as possible. (a) no restrictions on thinning treatments (b) number of thinnings restricted to at most one (c) thinning restricted to trees thicker than 237 mm (d) thinnings omitted.

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reduced (Fig 5b). Restricting thinnings to the removal of trees thicker than 237 mm further increases achievable excess volume and decreases the corresponding capital return rate deficiency in all cases (Fig 5c). Omission of thinnings in Fig 5d changes the situation in the case of the two setups that would experience thinning in Fig 5c: available excess volume increases, and capital return rate deficiency per excess volume is reduced.

The expected values of stand volumes corresponding to the maximum capital return rate in the case of the seven wooded stands used as normal stands (Fig 3) are 104, 117, 102, 111, 120, 103, and 104 m^3/ha. Fig 6 shows capital return rate deficiency per excess volume as a function of excess volume for these seven cases. We find from Fig 6a that within any case, excess volume can be gained by extending rotation time, with a moderate capital return rate deficiency. Restricting the number of thinnings to one (Fig 6b) increases the available excess volume within those normal stands thinned twice in Fig 6a (cf. Fig 2a). Restricting thinnings to the removal of trees thicker than 237 mm increases achievable excess volume and decreases the corresponding capital return rate deficiency in all cases (Fig 6c). Omission of thinnings in Fig 6d increases available excess volumes and further reduces corresponding capital return rate deficiencies per excess volume unit.

4. Discussion

The two independent sets of initial conditions appear to yield similar results. The capital return rate is a weak function of rotation age, which results in variability in the optimal number of thinnings. Reducing the number of thinnings to one increases timber stock but induces a capital return rate deficiency. The deficiency per excess volume unit is smaller if the severity of any thinning is restricted by the removal of large trees only. Omission of thinnings best applies to spruce-dominated stands with stem count less than 2000/ha. The similarity of the results in different datasets indicates repeatability.

It was claimed above that introducing further thinnings in Fig 3 would show that the capital return rate is a weak function of rotation age. However, a fact is that optimal rotation ages in Fig 3 are shorter than in Fig 2. It is of interest to consider the origin of this difference.

It was found that the timber stock and corresponding capitalization on stands observed in the field and appearing in Fig 3 were greater than the corresponding measures on computer-grown stands appearing in Fig 2. Obviously, the observed stands had been more productive than predicted by the growth model, resulting in shorter rotation times.

An interesting observation is that the rate of value growth in the stands appearing in Fig 2 is rather low at the youngest ages. The youngest stands do not accumulate any sawlogs, and the proportion of timber not fulfilling pulpwood dimensions is large. Regeneration expenses anyway are carried in the balance sheet, resulting a low capital return rate.

The capitalization consists of bare land, capitalized investments, and the value of trees. Even if the immediate sales value of small trees is small, one can expect that they will rapidly grow in value when getting bigger. This kind of additional expectation value is often used in the valuation of young forests in the geographic reference area. Total capitalization, including such an additional expected value, could be approximated by some kind of a smoothing function. One possibility could be

$$k(a) = \frac{1}{\tau - a} \int_{a}^{\tau} K(t) \exp\{r(t)(a - t)\} dt. \tag{4}$$

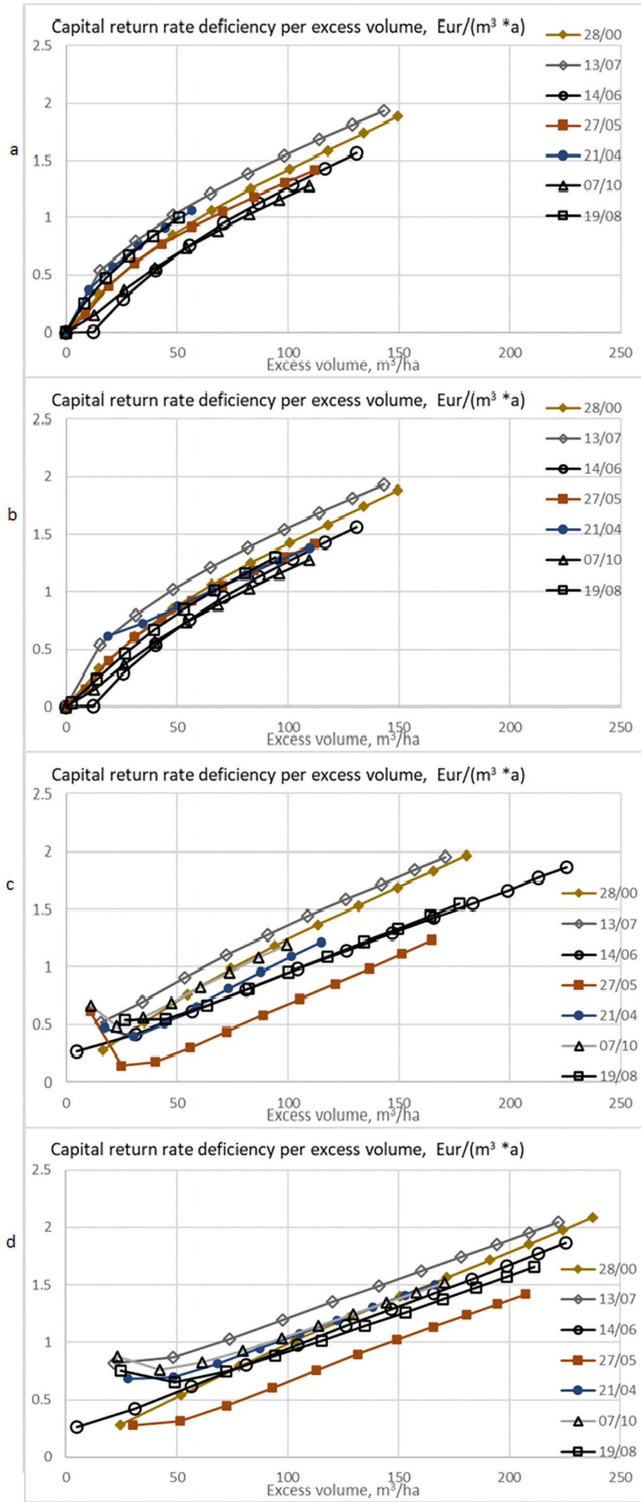

Fig 6. Capital return rate deficiency per excess volume unit, as a function of excess volume, when the growth model is applied to observed wooded stands. (a) no restrictions on thinning treatments (b) number of thinnings restricted to at most one (c) thinning restricted to trees thicker than 237 mm (d) thinnings omitted.

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where $r(t)$ is the capital return rate at stand age t. A simpler version would be

$$k(a) = \frac{1}{\tau - a} \int_a^\tau K(t) \exp\{\langle r \rangle (a - t)\} dt. \tag{5}$$

It is worth noting that either of the above Equations can be used only after the determination of the capital return rates, which depend on the applied silvicultural practices. The capital return rates also depend on capitalization, which requires Eqs (4) or (5) (or the like) to be applied iteratively with Eq (3). Both of the above Equations converge to terminal capitalization $k(\tau) = K(\tau)$, regardless of the capital return rate $r(t)$ or $\langle r \rangle$. However, there is no guarantee of any definite convergence in a newly established stand. Such convergence $k(initial) = K(initial)$ could be approached by fitting such an internal rate of return i which provides convergence. That would correspond to assuming that the bare land value includes any additional expectation value for a newly established stand, resulting as

$$k(a) = \frac{1}{\tau - a} \int_a^\tau K(t) \exp\{i(a - t)\} dt. \tag{6}$$

Again, Eq (6) has to be applied iteratively with Eq (3). At least in principle, Eq (6) as such cannot be used to maximize the internal rate of return, since Eq (3) considers different capital return rates at different development stages and weighs them by capitalization.

It might be possible to determine capitalization indirectly by discounting revenue. This would result as

$$k(a) = BL + \int_a^\tau R(t) \exp\{p(a - t)\} dt, \tag{7}$$

where BL denotes bare land value, and $R(t)$ net revenue at time t. Again, the discount rate p shall be fitted for convergence $k(initial) = K(initial)$.

The functionality of Eqs (6) and (7) is investigated in Fig 7, in the case of spruce stand established with 1800 saplings/ha, and wooded stand 13 observed at the age of 35 years. The former shows a positive additional expectation value of trees for young stands and after thinnings. If such additional values would be considered, microeconomically optimal rotation ages would become shorter and carbon storage less. However, Eq (6) results as the additional value being negative before the first thinning. It is not known how the negative additional expectation value should be considered in forest management. Within the wooded stand observed at 35 years of age, the additional expectation value of trees of young stands according to Eq (6) would be negative, being slightly positive only after thinning. Eq (7) would indicate zero additional value before thinning, and somewhat negative after thinning.

The applicability of an eventual additional value accounting for further growth obviously depends on silvicultural practices. It can also be manipulated with computational procedures. Fig 8 shows that if 1%, 3%, and 4% discount rates are applied, instead of the internal rate of return, there would be additional expectation values in the case of young stands and thinned stands. However, the examined discount rates are arbitrary, and capitalization now does not converge to the capitalization of a newly established stand.

Indeed, Fig 7(a) indicates that in the case of the early application of the growth model, internal rate of return—based interpolation could be useful in the determination of young stand

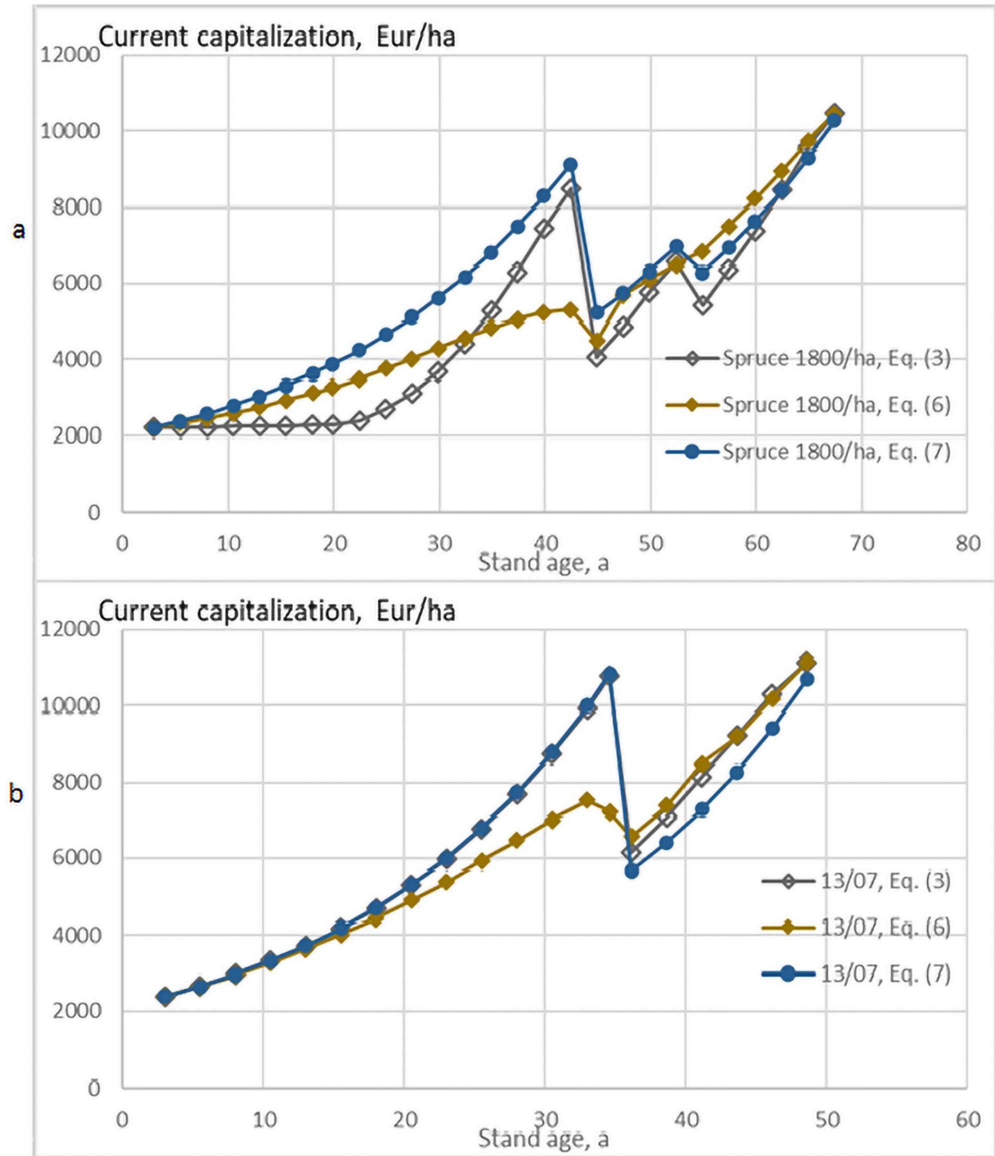

Fig 7. Capitalization, as appearing in Eq (3), as well as smoothed capitalization according to Eq (6), in the case of two example stands.

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capitalization. After such adjustment, it is straightforward to proceed with Eq (3) by simply substituting $k(a)$ from Eq (7) in place of $K(a)$.

On the other hand, in the case of Fig 7b, interpolation of capitalization appears irrelevant. A natural reason is that the stand has been first observed at the age of 35 years. The capitalization from stand establishment to the time of observation already has been approximated by exponential interpolation. Correspondingly, results based on the observations of wooded stands are not in the need of any further interpolation, and that set of results possibly should be better trusted. However, in this paper, results originating from the two sets of initial conditions were similar, with the exceptions of shorter rotation times and smaller carbon storage based on the observation of wooded stands (Figs 2 and 3).

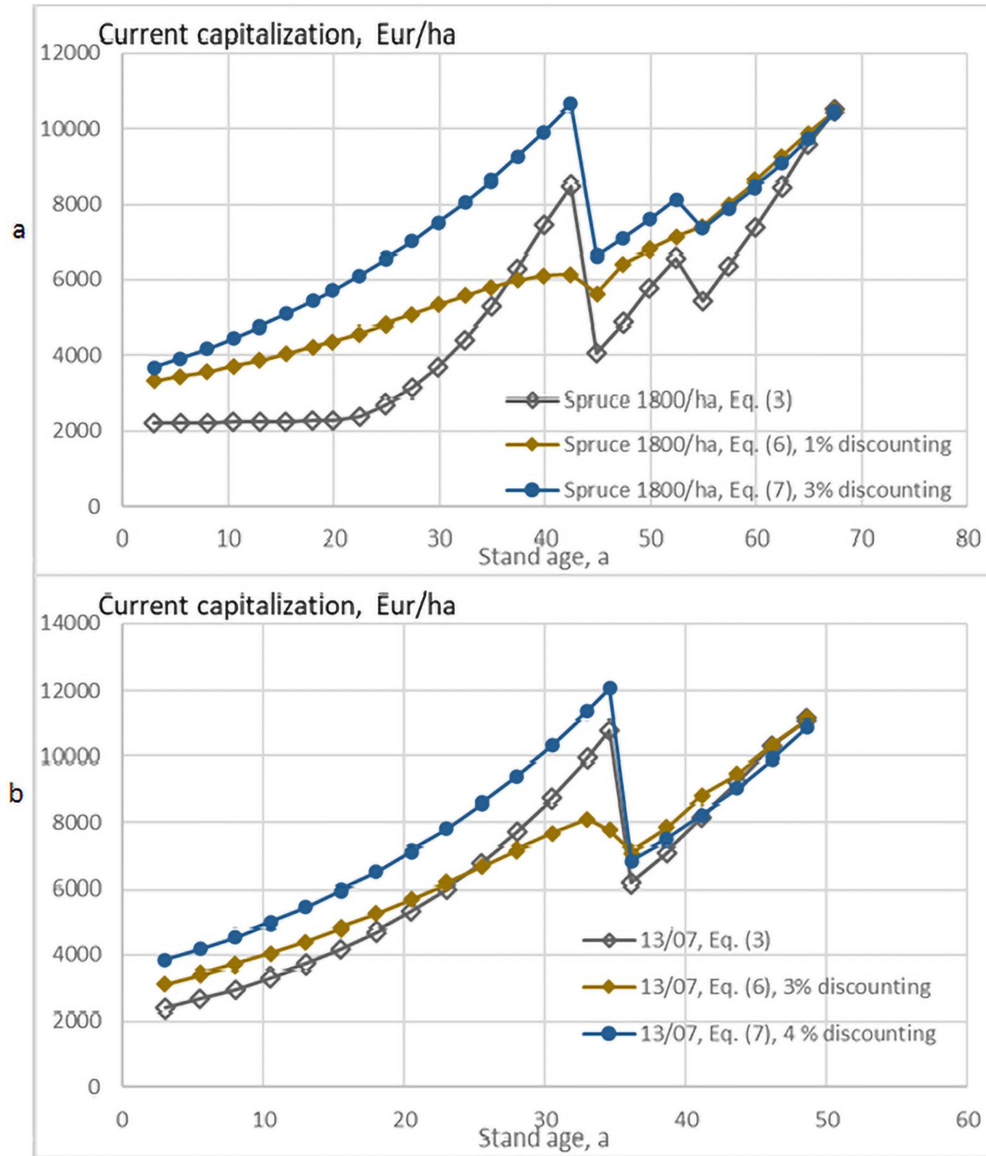

Fig 8. Capitalization, as appearing in Eq (3), as well as smoothed capitalization according to Eqs (6) and (7), in the case of two example stands. However, 1%, 3%, and 4% discount rates are used, instead of an internal rate of return.

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If one would smoothen the value creation along the rotation time, one possibly should consider amortization of investments more evenly, instead of full amortization at the end of the rotation.

It appears that restriction or omission of thinnings is a cost-effective way of enhancing carbon sequestration in boreal forestry. Implementation of thinnings is microeconomically profitable, but a moderate carbon rent would motivate to omit thinnings and consequently sequester carbon. Within the boreal region, omission of thinnings would make most productive forest sites unthinned within 40 years. If this would increase carbon storage by 40%, the annual increment would be in the order of 1% of the present carbon stock. This would correspond to at least a ton of CO_2 per hectare, or at least 10 million tons for 10 million hectares, as *additional* sequestration due to omission of thinnings. At the global 2018 emission level, the additional sequestration would compensate for the emissions induced by two million humans, or about one million in developed countries [44, 45]. It is worth noting that these tonnage estimates are minimum estimates; an increment of necromass and soil carbon level may further increase the additional amount of sequestration due to omission of thinnings [5–10]. The corresponding expense, in terms of carbon rent, would be very small (in the order of one Euro per hectare) in the beginning and increase about 40 times during the sequestration process [21].

It is of interest to compare the 40% carbon storage increment achievable by restriction or omission of thinnings to carbon storage increments achievable by other means. One opportunity obviously would be fertilization. Fertilization increases the growth of coniferous boreal forests [46, 47], but it is economically profitable in the case of stands where most of the additional growth rapidly increases sawlog yield. Let us first write the expected value of commercial stand volume per hectare

$$\langle V \rangle = \frac{1}{\tau} \int_0^\tau V(t)dt. \tag{8}$$

Let us then write the momentary volume as the sum of volume in the absence of fertilization and additional volume due to fertilization:

$$\langle V \rangle = \frac{1}{\tau} \int_0^\tau (V_0(t) + \Delta V(t))dt. \tag{9}$$

Now, the relative increment of the expected value of volume due to fertilization is

$$\frac{\langle V \rangle}{\langle V_0 \rangle} = 1 + \frac{\int_0^\tau \Delta V(t)dt}{\int_0^\tau V(t)dt}. \tag{10}$$

On the right-hand side of Eq (10), the numerator of the second term is in the order of 50–100 m^3/ha. However, the denominator is in the order of 5000–10 000 m^3/ha. Correspondingly, the increment of the expected value of the commercial volume is in the order of 1%, corresponding to an excess volume of 1–2 m^3/ha. The situation would change if the fertilization would happen decades before final harvesting. However, even if fertilization would happen 20 years before harvest, the numerator would be in the order of 200 m^3/ha, and the expected value of volume increment in the order of 3%.

A question arises, whether there are adverse effects for the society or the economy. How would restricted thinnings affect the wood supply of forest-based industries?

The wood supply question primarily concerns how restricted thinnings contribute to the production rate of wood raw materials. This can be clarified since the growth model [14] yields the expected values of the net growth rate of commercial timber. Fig 9 shows the relative growth rate as a function of excess volume for the nine combinations of tree species and sapling density, the growth model applied as early as it is applicable. The expected value of the net growth rate is given in relation to the growth rate corresponding to the maximal capital return rate within any setup.

a
b
c
d

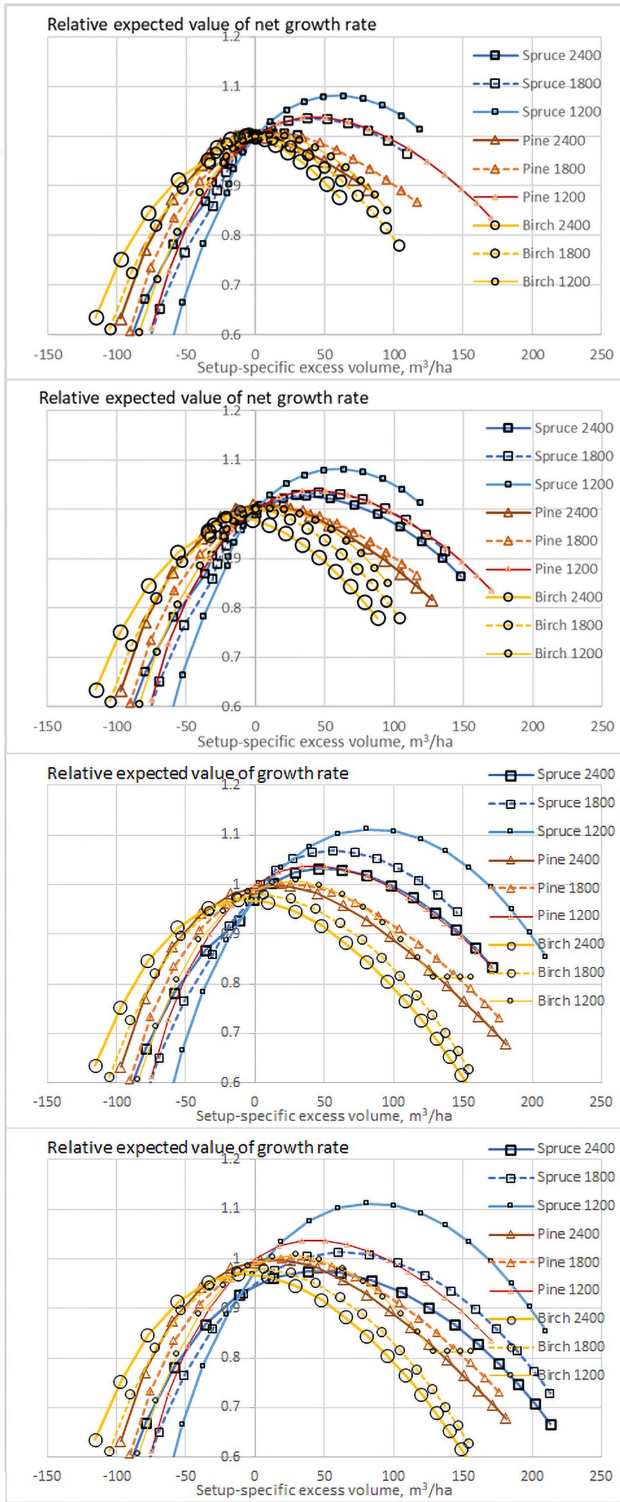

Fig 9. Setup-specific expected value of relative annual net growth rate of commercial timber, as a function of setup-specific excess volume when growth model is applied as early as possible. The growth rate is given in relation to the growth rate appearing when the capital return rate is maximized without restrictions (co-ordinate (0,1) in Fig 9a). (a) no restrictions on thinning treatments (b) number of thinnings restricted to at most one (c) thinning restricted to trees thicker than 237 mm (d) thinnings omitted.

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Fig 9a shows that simply extending rotation times increases the growth rate in the case of spruce stands and pine stands of low sapling density. It reduces the growth rate in the case of birch stands and dense pine stands. The effects are the same when the number of thinnings is restricted to one, except for a clearer growth increment in dense spruce stands (Fig 9b). Restricting thinnings to the removal of trees thicker than 237 mm amplifies not only the excess volume but also the growth rate increments (Fig 9c). Omission of thinnings, however, reverses the net growth rate increment of commercial timber in the case of dense spruce stands (Fig 9d).

The seven observed wooded normal stands show slight or moderate increments in growth rate when the rotation age is increased (Fig 10a)). Reduction of the number of thinnings to one induces almost the same (Fig 10b). Restricting thinnings to the removal of trees thicker than 237 mm, combined with a moderate excess volume, increases the growth rate in all cases (Fig 10c). Omission of thinnings, with a moderate excess volume, leaves the growth rate unaffected in two cases and increases it in five cases (Fig 10d).

One can summarize that restricting or omitting thinnings for carbon sequestration increases the supply of commercial timber in the spruce-dominated forests, as well as in pine forests of low stem count (Figs 9 and 10). In birch forests, as well as on dense pine stands, the net growth of commercial timber is reduced.

Another question is, how the omission of thinnings contributes to different wood-based industries. Within southern and central boreal regions, thinnings mostly yield pulpwood, while clearcuttings yield sawlogs and plywood logs [48]. The proportion of sawlogs and plywood logs appears as 35–40% of the total yield [48]. An unknown proportion of the sawlogs is used in pulping, instead of sawmilling. Omission of commercial thinnings directly reduces the supply of pulpwood but increases the pulpwood content in clearcuttings. However, the growth model applied in this study indicates that the total sawlog yield does not collapse, but rather is retained [17]. This requires that young stand tending and eventual precommercial thinning are properly implemented, leaving at most 2000 stems per hectare [17].

Restriction or omission of thinnings significantly reduces harvesting expenses [49].

The eventual adverse effects of the omission of thinnings do not solely depend on the growth rate. Practical macroscopic consequences depend on macroscopic boundary conditions. As such, increment of timber stock might periodically reduce wood supply, while increased growth (in spruce-dominated forests) would increase it in the longer term. However, present timber stocks may exceed microeconomically optimal levels [48]. In such a case, a carbon storage compensation would prohibit an expected timber stock reduction in the future, again increasing wood supply in the long term.

It is worth noting that while the omission of thinnings reduces rotation times (Figs 2 and 3), age-related risks are likely to be reduced. Omission of thinnings naturally reduces thinnings-related risks like wind damage [50–53].

Last but not least, restriction or omission of thinnings and the corresponding reduction of rotation times increases the proportion of areas not covered by dense vegetation. This increases the albedo effect: radiation is reflected from open surfaces [54–59]. A portion of the reflected radiation is able to exit the atmosphere [54, 57]. Some results indicate deciduous forests would reflect more than coniferous [55, 56]. The albedo effect apparently is of somewhat smaller magnitude than the carbon sequestration, but greater than the substitution effect of fossil fuel emissions by biomass [54, 57]. Several earlier studies have claimed the albedo effect counteracts carbon storage ambitions; carbon storage would require longer rotation times, whereas albedo enhancement would benefit from a greater proportion of open areas [56, 57, 60]. This paper indicates the contrary: restricted thinnings are related to reduced rotation times (Figs 2 and 3), which again relates to positive albedo effects.

a

b

c

d

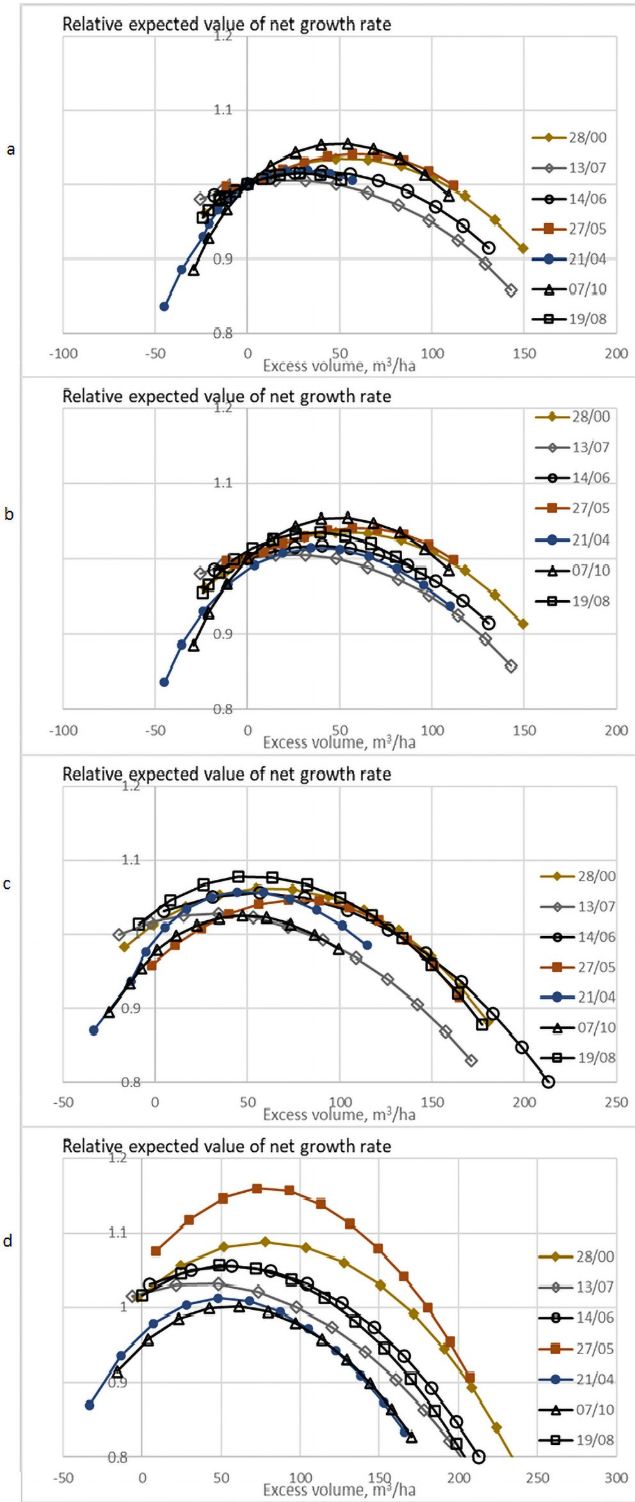

Fig 10. The expected value of relative annual growth rate, as a function of excess volume, when the growth model is applied to observed wooded stands. The growth rate is given in relation to the growth rate appearing when the capital return rate is maximized without restrictions (co-ordinate (0,1) in Fig 10a). (a) no restrictions on thinning treatments (b) number of thinnings restricted to at most one (c) thinning restricted to trees thicker than 237 mm (d) thinnings omitted.

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The operative outcome of this paper is possibly affected by the albedo consideration in the selection of tree species. In Fig 4c and 4d, deciduous stands show a greater capital return rate deficiency per excess volume unit than coniferous stands. Correspondingly, they require a higher carbon rent. However, a greater carbon rent may be justified by the greater albedo effect [55, 56].

5. Conclusions

The results above indicate that restricting thinnings may result in significant additional carbon storage at a capital return deficiency in the vicinity of a Euro per excess commercial cubic meter of standing timber storage. Such a level of carbon rent [21] would be well in concert with the 2021 European carbon emission prices in the vicinity of 50 Eur per ton of CO_2. Naturally, such climate benefits are achievable only if the carbon rent arrangements can be materialized.

From the viewpoint of the society, an important finding is that restriction of thinnings as a means of increasing carbon storage does not jeopardize the wood supply of the relevant industries.

Supporting information

S1 Table. Measurement data of trees on wooded stands. Koealan säde = experimental plot radius. Tila = estate name. Koealanro = experimental plot number. BA = basal area. Numerical tree species codes: 1 = Pinus sylvestris, 2 = Picea abies, 3 = Betula pendula, 4 = Betula pubescens, 5 = Populus tremula, 6 = other species.
(XLSX)

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Author Contributions

Conceptualization: Petri P. Kärenlampi.

Data curation: Petri P. Kärenlampi.

Formal analysis: Petri P. Kärenlampi.

Funding acquisition: Petri P. Kärenlampi.

Investigation: Petri P. Kärenlampi.

Methodology: Petri P. Kärenlampi.

Project administration: Petri P. Kärenlampi.

Resources: Petri P. Kärenlampi.

Software: Petri P. Kärenlampi.

Supervision: Petri P. Kärenlampi.

Validation: Petri P. Kärenlampi.

Visualization: Petri P. Kärenlampi.

Writing – original draft: Petri P. Kärenlampi.

Writing – review & editing: Petri P. Kärenlampi.

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