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Economic Performance of Genetically Improved Reforestation Material in Joint Production of Timber and Carbon Sequestration: A Case Study from Finland

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Received: 15 June 2020; Accepted: 2 August 2020; Published: 5 August 2020

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Abstract: Genetically improved material has been proven to financially outperform unimproved material in timber production according to various studies. Genetic improvements in carbon sequestration are also promising, implying a possibility for further financial gains. Research Highlights: Including carbon pricing (i.e., timber production combined with carbon sequestration) with genetically improved material improves financial performance compared to pure timber production. Furthermore, the proportion of carbon benefit (%) of absolute bare land value fluctuates between 27% and 42%, indicating a substantial role of carbon sequestration to financial performance. Background and Objectives: Until now, economic analyses of the impact of tree improvement have mainly dealt with growth performance: volume yield or height growth. Yet planted forests can have a significant contribution to carbon sequestration, which will play a major role in carbon markets. This study focuses on comparing the financial performance between genetically improved and unimproved reforestation material when stand management is optimized according to timber production or to joint production (timber and carbon sequestration together). Another goal is to reveal possible differences in financial performance related to climatic conditions along the south–north gradient. Materials and Methods: The stand projections are based on simulations with and without genetic gains for joint production (timber + carbon) and merely timber production in eight locations in Finland. Stand-level optimization is applied for financial analyses. Results: Genetically improved reforestation material considerably enhanced financial performance when the joint production of timber and carbon was applied, regardless of the climatic region. Conclusions: If carbon pricing became a reality, there would be a distinctive shift in bare land values, which is further boosted by a genetic gain.

Keywords: stand-level optimization; genetic gains; carbon pricing; joint production; Scots pine

1. Introduction

Fast-growing reforestation materials from tree improvement programs have significantly increased the productivity of planted forests [1,2]. In the Nordic countries, the present level of genetic gains in volume growth range between 10% and 25% [3]. Several studies have demonstrated that shorter rotations due to improved material can considerably increase the financial profitability of forestry [4–7].

Thus far, economic analyses of tree improvement have focused on gains in volume yield and wood properties and paid little attention to the carbon sequestration (for a review, see [8]). There is an evident need to take a closer look at the carbon sequestration ability of trees, since planted forests may play a major role in carbon markets in the future.

In general, policymakers and the concerned public have emphasized the need for carbon emission mitigation programs to address climate change resulting from the global use of fossil fuels [9]. With regard to practice and implementation, two approaches, namely carbon markets and carbon offsets, have received the most attention. Carbon markets would establish and sell a supply of tradable emission permits among industrial users of fossil fuels, while a forest carbon offset program would allow forest landowners to sell carbon emission permits in return for altering their forest area and/or its management in ways to sequester and store additional carbon. Carbon offset sales are of particular interest among forest policymakers because they would, in theory, provide financial incentives to owners to retain land in forest cover rather than convert it to non-forest and developed uses with attendant losses of an array of ecosystem services [9,10]. Furthermore, a recent case study (Western Oregon, USA) indicated that silvicultural methods would become simpler (e.g., less thinnings to be conducted and elimination of uneven-aged management) and planting instead of natural regeneration would be employed under a carbon offset program [11].

Since tree breeding has played an integral role in increasing tree growth and productivity [2,3,12], an intriguing question arises: Would landowners gain extra benefits from genetically improved reforestation material in the presence of carbon pricing? Although many studies have addressed the issue of optimal stand management in relation to carbon credits and carbon storage [13–16], this particular question has drawn little attention so far. Earlier studies in radiata pine [17] and loblolly pine [12] suggested that benefits from carbon sequestration due to tree improvement might be substantial.

The main objective of this study was to compare the financial performance of different types of reforestation materials (unimproved versus improved) when stand management is optimized either for timber production (hereon referred to as TP) or jointly for timber production and carbon sequestration (TP-CS). The secondary objective was to determine whether the financial performance would be affected by climatic conditions. The study focuses on Scots pine (*Pinus sylvestris* L.), which is commercially the most important Eurasian tree species and is widely used in artificial reforestation on the temperate and boreal climatic zones [1,18,19].

2. Materials and Methods

2.1. Stands

The study was performed using eight simulated pine stands at locations along the latitudes 61° and 63° in Finland (Figure 1). In this region, genetically improved material from Scots pine seed orchards is commonly used in reforestation.

2.2. The Optimization Problem

The goal was to maximize bare land value (also known as land expectation value, see, e.g., [20,21]) under the TP and TP-CS management. Both scenarios were simulated assuming regeneration either with unimproved or improved stock in even-aged stands (rotation forestry, RF); since improved material can be applied only for RF in uneven-aged management (continuous cover forestry, CCF), stand establishment takes place through the seeding of natural trees. Two levels of genetic gains were applied to volume growth: 10% and 15%. Both values fall into the range of genetic gains estimated for improved Scots pine stands in Finland [7].

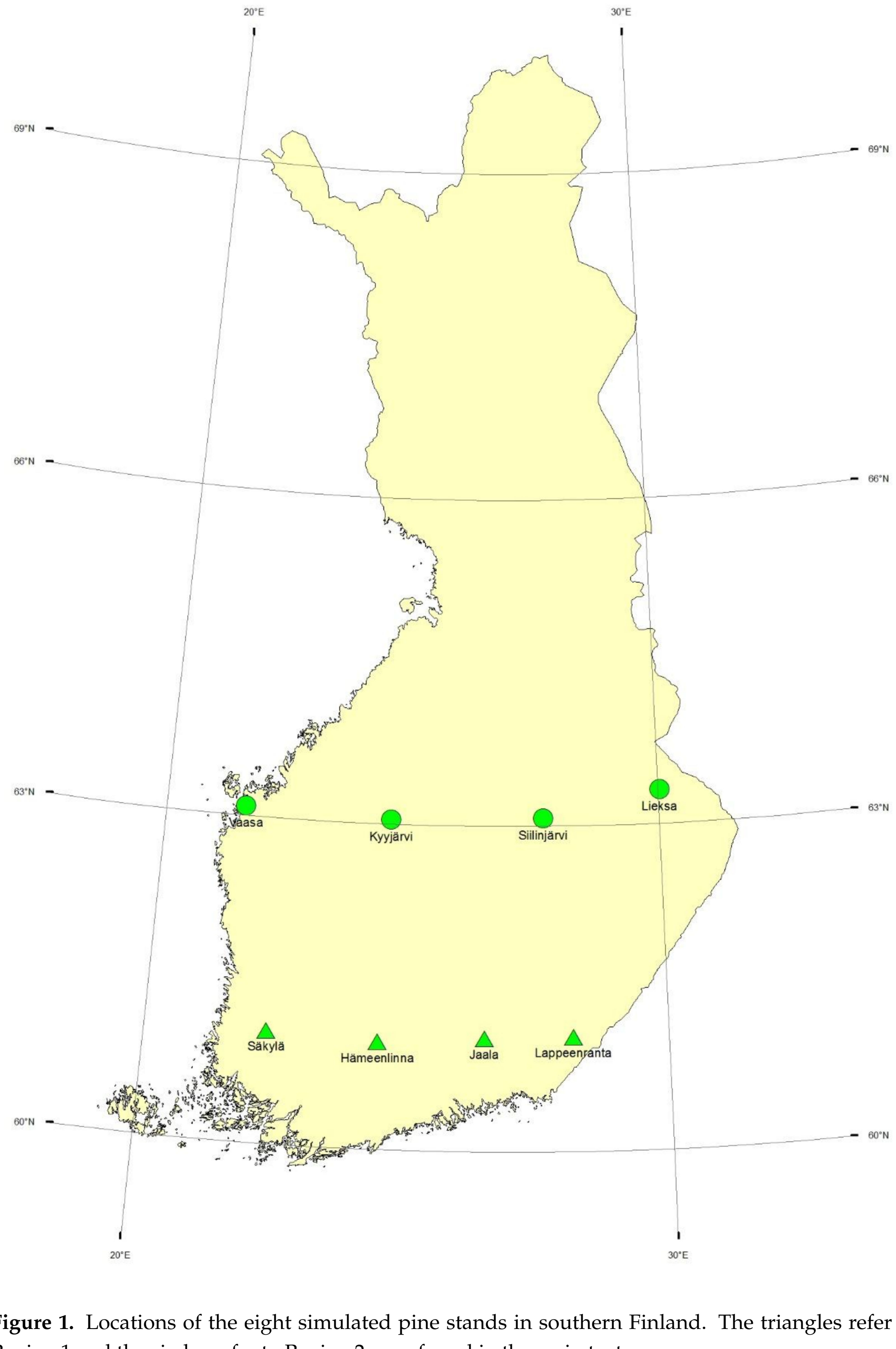

Figure 1. Locations of the eight simulated pine stands in southern Finland. The triangles refer to Region 1 and the circles refer to Region 2, as referred in the main text.

The optimization problem was presented as a discrete-time system of state and control variables [22]. Let Z_{t_i} denote standing volume ($m^3 ha^{-1}$) before the i^{th} thinning at age t_i, i= 0, ... T (t_0 and t_T denote the beginning and the end of rotation, respectively), k denote timber assortments (k = 1, ... , K) and p_k denote the stumpage price (€ m^{-3}) of each timber assortment. Let b be the discount factor *s.t.* $b = 1/(1 + r)$, where r is the interest rate in real terms (here 2%). The removal (in m^3) of each timber assortment k in i^{th} thinning is denoted by h_{ki}. The removal depends on stand state, thinning intensity, and timing. Thinning intensity (removal relative to the growing stock) in i^{th} thinning is g_i, and for improved trees, the removal is also affected by genetic gain, $\boldsymbol{\eta}$. The control variables include the timings for thinnings, total number of thinnings, the intensity of each thinning, and the timing for clearcut (i.e., rotation period). Using this notation, the maximum net present value of bare land, $MaxLEV_{gg}$, regarding timber production for improved trees can be expressed as:

$$MaxLEV_{gg} = \frac{\sum\limits_{i=0}^{T} b^{t_i} \sum\limits_{k=1}^{K} p_k h_{ki}\left(Z_{t_i}, g_i, \eta\right) - \sum\limits_{l=0}^{M} b^{t_l} \sum\limits_{s=1}^{S} sc_{st_l}^{gg}}{1 - b^{t_T}} \tag{1}$$

where $sc_{st_l}^{gg}$ indicates a cost of a silvicultural action s associated with improved trees at stand age t_l so that M refers to time when the last silvicultural measure takes place within a rotation, € ha^{-1}. Note that the use of improved seed material in direct seeding generates an extra cost of 70 € ha^{-1} compared to unimproved material [5]. Then, $M < T$ and $t_i \neq t_l$. The maximum net present value of bare land, $MaxLEV_n$, regarding timber production for an unimproved stand is assessed according to:

$$MaxLEV_{n} = \frac{\sum\limits_{i=0}^{T} b^{t_i} \sum\limits_{k=1}^{K} p_k h_{ki}\left(Z_{t_i}, g_i, \eta\right) - \sum\limits_{l=0}^{M} b^{t_l} \sum\limits_{s=1}^{S} sc_{st_l}^{n}}{1 - b^{t_T}} \tag{2}$$

where $sc_{st_l}^{n}$ is the cost (€ ha^{-1}) of a silvicultural action s for unimproved reforestation material at stand age t_l so that M' refers to the time when the last silvicultural measure takes place within rotation, € ha^{-1}. In principle, $t_T < t_{T'}$ indicates the fact that the improved growth rate shortens the length of the optimal rotation period, as shown in earlier studies [4,5]. Furthermore, $M \neq M'$ indicates different timings for silvicultural measures associated with improved and unimproved cases, and $g_i \neq g_i{}'$denotes the different thinning intensity of improved and unimproved case.

For TP-CS, new variables are introduced into the equations. First, let $c_i{}^{gg}$ and $c_i{}'$ denote the quantity of stored carbon (tCO_2, ton of carbon dioxide) at stand age t_i for improved and unimproved reforestation material, respectively. The carbon price (€/tCO_2) is denoted as p_c for both cases. The maximum net present value of bare land, $MaxLEV_{gg}{}^{j}$, from the joint production of timber and carbon sequestration of improved trees can be expressed as:

$$MaxLEV_{gg}^{j} = \frac{\sum_{i=0}^{T} b^{t_i} \sum_{k=1}^{K} p_k h_{ki}\left(Z_{t_i}, g_i, \eta\right) + \sum_{i=0}^{T} b^{t_i} p_c c_i^{gg}\left(Z_{t_i}, g_i, \eta\right) - \sum_{l=0}^{M} b^{t_l} \sum_{s=1}^{S} sc_{st_l}^{gg}}{1 - b^{t_T}} \tag{3}$$

where the variables are identical to those presented in Equation (1), and $c_i{}^{gg}$ denotes the quantity of stored carbon (tCO_2) at stand age t_i, the price of carbon (€/tCO_2) being p_c. Then, the maximum net present value of bare land, $MaxLEV_n{}^{j}$, for the joint production (timber and carbon) of an unimproved stand is assessed according to:

$$MaxLEV_{n}^{j} = \frac{\sum_{i=0}^{T'} b^{t_i} \sum_{k=1}^{K} p_k h_{ki}\left(Z'_{t_i}, g'_i\right) + \sum_{i=0}^{T'} b^{t_i} p_c c'_i\left(Z'_{t_i}, g'_i\right) - \sum_{l=0}^{M'} b^{t_l} \sum_{s=1}^{S} sc_{st_l}^{n}}{1 - b^{t_{T'}}} \tag{4}$$

where the variables are identical to the terms in Equation (2), and $c_i{}'$ denotes the quantity of stored carbon (tCO_2) at stand age t_i when the price of carbon (€/tCO_2) is p_c.

A genetic algorithm PIKAIA was used to search the maximum value of the objective function (Equations (1)–(4)) [23,24]. In general, genetic algorithms [25] simulate the evolutionary process based on natural selection, combining the survival of the fittest with genetic operators abstracted from nature [25,26]. PIKAIA seeks to maximize a user-defined function $f(x)$ in a bounded n-dimensional space $X \equiv (X_i, X_2, \ldots, X_n), X_k \in [0.0, 1.0] \forall k$ where it spans the entire range [0.0, 1.0] of control variables in all the n dimensions. The PIKAIA algorithm has been previously used in many stand-level analyses in boreal conditions (see, e.g., [4,5,27,28]).

2.3. Stand Projections

The initial values of state and control variables for the PIKAIA algorithm (Equations (1)–(4)) were provided by the stand simulator Motti [29–31]. The procedure was similar to that applied in [32–34]. The stand simulations were performed for each scenario (TP with unimproved or genetically improved material; TP-CS with unimproved or improved material) in the eight locations (Figure 1). The site type was assumed to be dryish, nutrient poor sites typical for Scots pine (*Vaccinium* type in the Finnish classification system; see [35]). All the simulations were started from bare land, and the regeneration method was direct seeding [5]. The development of improved stands was modeled by incorporating the genetic gains for early-rotation height and diameter growth as genetic multipliers in in the Chapman–Richards growth function used to model individual tree growth in Motti [4,5,36]. In this study, two levels of genetic gain were applied: +10% or +15% in volume growth, compared to unimproved reforestation material. Both values fall into the range observed in a recent article reporting projected gains in the growth of genetically improved Scots pine stands in Finland [7].

In brief, the Motti stand simulator consists of two sets of models: stand-level and individual-tree level models, which are both based on an empirical–statistical modeling approach [31]. Stand-level growth models are used until ca. 7 m dominant height, after which individual-tree level models are applied (for technical details of the Motti stand simulator, see [27], Supplementary data). The growth models require tree species, diameter at breast height, height, and the number of trees per hectare as initial variables.

The carbon stock was calculated based on the above-ground living biomass of trees [31]. The technical procedure of assessing the carbon compartments as well as the share of carbon in dry weight of biomass and the conversion coefficient between carbon and carbon dioxide are presented in detail in [27] (pp. 117–118). Only the above-ground carbon content was considered in this study, since the volume of this part of the tree biomass is the easiest to assess for carbon payments [16,27]. Furthermore, the above-ground part is also directly affected by the forest management. Carbon storages in wood products as well as possible substitution effects from the use of wood products were not considered, since both of them are driven by demand for products rather than decisions made by a landowner [37,38].

2.4. Financial Data

The stumpage prices and per unit silvicultural costs were based on the latest 5-year statistics covering the 2014–2018 period for stumpage prices and the 2013–2017 period for silvicultural costs (original values available at http://statdb.luke.fi). These were converted to real prices through deflation (applying the cost-of-living index of Statistics Finland 2019; http://www.stat.fi/til/khi/index_en.html), after which arithmetic averages were calculated. The averages stumpage prices for Scots pine saw logs (pulpwood in parenthesis) were € 58.24/m^3 (18.27), € 49.02/m^3 (15.37), and € 40.08/m^3 (12.08) in the final felling, intermediate thinnings, and the first thinning, respectively. For Norway spruce, the corresponding prices were: € 59.25/m^3 (19.33), € 49.64/m^3 (15.72), and € 41.72/m^3 (11.71). For other tree species (mainly birch), the prices were: € 44.92/m^3 (17.75), € 37.88/m^3 (14.79), and € 33.03/m^3 (11.85). The following per-hectare costs were used: clearing of regeneration areas € 189.9/ha, ploughing € 239.2/ha, seeding € 230.9/ha (for improved seed material: +€ 70/ha, totaling € 300.9/ha). The costs of early cleaning and tending of seedling stands and precommercial thinning were based on time consumption models with a fixed hourly rate of € 35/hour [31].

For carbon credits, we applied a permanent unit price of € 35/tCO_2, which corresponds to the social cost of carbon introduced in [39]. However, the permanent unit price p_∞ was translated into an instant price according to $P_c = P_\infty\left(1 - \frac{1}{1+r}\right)$, where p_c is the instant price and r is the discount rate. With a 2% discount rate and p_∞ equaling € 35/tCO_2, the instant price is € 0.686/tCO_2; for details, see [27] (pp. 117–118). The translation of permanent price into instant price was required for technical procedures applied in the stand-level optimization framework.

2.5. Sensitivity Analysis

The interest rate plays a crucial role in economic analyses, particularly in boreal forestry with long time horizons [40–42]. Thus, we also used a 4% interest rate in half of the sites and compared the results to those obtained with 2% interest. When the permanent unit price, € 35/tCO_2, was converted to an instant price, a 4% interest rate was applied instead of the original 2%, which resulted in a higher instant price, € 1.346/tCO_2 (originally € 0.686/tCO_2).

3. Results

3.1. Main Results

In Region 1, the optimization for TP postponed the first thinning regardless of the type of reforestation material (Table 1). Thinning removals were larger with genetically improved material and with TP-CS compared to TP (Table 1). Genetically faster-growing material obviously resulted in the highest mean annual increments (MAI) (Table 1). TP-CS led to higher MAI regardless of the genetic gains, but the increase was not more than 5% compared to TP.

Table 1. Resulting values of relevant variables in stand-level optimizations with the objective function of timber production (TP) or joint production of sequestered carbon and timber (TP-CS). See Figure 1 for the locations of Regions 1 and 2. Social cost of carbon €35 tonCO_2; discount rate 2%. "GG" refers to genetic gain.

Variable	Scenario	Region 1 Unimproved	Region 1 GG 10%	Region 1 GG 15%	Region 2 Unimproved	Region 2 GG 10%	Region 2 GG 15%
Timing of the first thinning, yrs	TP	46.3 (5.0) [a]	38.3 (5.0)	36.3 (5.0)	38.0 (1.8)	41.3 (4.4)	35.3 (1.9)
	TP-CS	49.0 (0.8)	46.5 (0.6)	42.3 (2.5)	55.8 (5.0)	52.0 (3.5)	50.3 (1.5)
Number of thinnings	TP	3.8 (0.5)	4.5 (0.6)	2.0 (0.0)	4.0 (0.0)	4.3 (0.5)	4.3 (0.5)
	TP-CS	2.0 (0.0)	2.0 (0.0)	3.3 (0.5)	2.0 (0.0)	2.5 (0.6)	2.5 (0.5)
Average removal in thinnings	TP	78.8 (4.3)	80.5 (3.9)	85.1 (3.9)	62.4 (4.3)	72.7 (3.9)	69.8 (2.9)
	TP-CS	83.1 (8.3)	87.8 (3.7)	92.4 (4.5)	74.0 (1.4)	80.8 (2.8)	81.8 (2.8)
Rotation period	TP	93.8 (8.0)	92.8 (2.6)	88.5 (3.0)	97.3 (5.7)	94.0 (4.9)	91.5 (2.1)
	TP-CS	81.1 (8.3)	87.8 (3.7)	92.4 (4.5)	98.8 (8.1)	99.5 (1.7)	91.3 (3.8)
MAI (m^3 ha^{-1} yr^{-1})	TP	5.4 (0.1) [62%] [b]	6.3 (0.1) [65%]	6.9 (0.2) [65%]	4.4 (0.3) [58%]	5.2 (0.2) [60%]	5.6 (0.3) [63%]
	TP-CS	5.6 (0.2) [63%]	6.6 (0.1) [64%]	7.0 (0.2) [67%]	4.7 (0.6 [61%]	5.3 (0.2 [66%]	5.7 (0.2) [64%]
Carbon benefit [c]	TP	0 [d]	0	0	0	0	0
	TP-CS	33%	29%	27%	42%	34%	32%

[a] Values in parenthesis indicate standard deviation, S.D., [b] a percentage in brackets indicates the average proportion of saw logs in mean annual increments (MAI), [c] Carbon benefit illustrates the discounted carbon incomes as a proportion of MaxLEV, % (the remaining proportion refers to discounted cutting incomes from timber), and [d] for timber production, there are no carbon incomes (0).

In Region 2, stand management optimized for TP-CS resulted in fewer thinnings than TP, also indicating a higher growing stock (Table 1). The rotation period was shorter for TP than for TP-CS. The rotation shortened with increasing genetic gain for TP. For TP-CS, in turn, the longest rotation period was associated with the lower of the two genetic gains, 10% (Table 1). Improved reforestation material led to a higher MaxLEV in both regions and stand management scenarios (Figure 2). For instance, in Region 1 and the TP scenario, MaxLEV increased as much as 51% when 15% genetic gain was applied (Figure 2a). For TP-CS, the relative increase was 39% (Figure 2a).

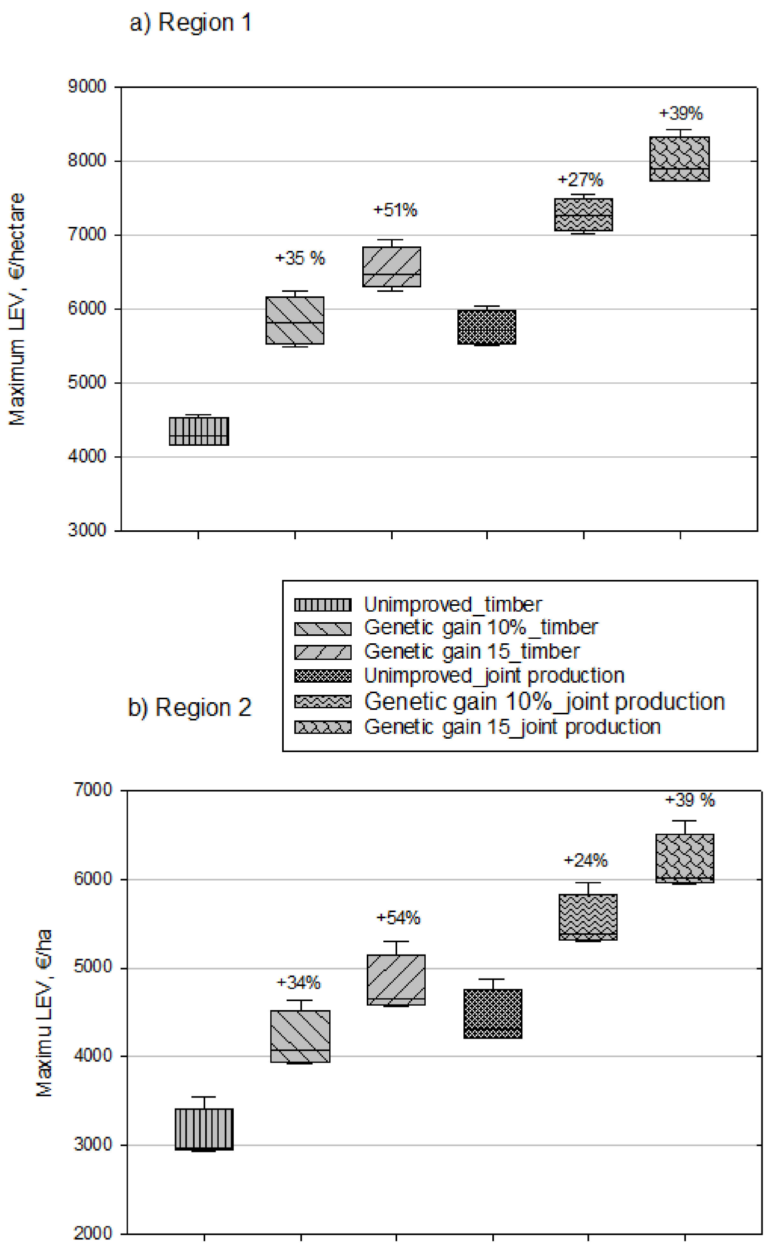

Figure 2. Maximum LEVs in Region 1 and 2, € ha^{-1}. Boxplots of maximum bare land value (€/ha), discount rate 2%. Bottom edge of each box illustrates the 25th percentile, the upper edge illustrates the 75th percentile, a line within a box marks the median, and the whiskers of the boxplots indicate the 10th and 90th percentiles. Percentages above the boxplots represent the relative increase compared to unimproved reforestation material when timber production or the joint production of timber and carbon is applied in the stand-level optimization, (**a**) Region 1, (**b**) Region 2 (for Region 1 and 2, see Figure 1).

In the slightly colder climate of Region 2, the relative increases in MaxLEV due to improved reforestation material were similar to those in Region 1 (Figure 2b). With 10% genetic gain, the MaxLEV of the TP-CS scenario was about 25% higher compared to the unimproved material (Figure 2b). The relative increase in MaxLEV due to genetic gain was slightly less for TP-CS than for TP in both regions (Figure 2a,b). However, the difference between the scenarios was small. The absolute MaxLEV was always higher for TP-CS than for TP (Figure 2a,b).

3.2. Sensitivity Analyses

The discount rate had a great impact on MaxLEV. For instance, at a 2% discount rate in Region 1, the MaxLEV of TP with unimproved material was 4334 €/ha, whereas at a 4% discount rate, MaxLEV was only 477 €/ha. In Region 2, the MaxLEV of TP-CS with 10% genetic gain was on average 5507 €/ha and 1995 €/ha with 2% and 4% discount rates, respectively. A higher instant carbon price (€ 1.346/tCO_2) resulted in a significant increase in MaxLEV. In Region 1, TP-CS with 15% genetic gain yielded MaxLEV 8000 €/ha with an instant carbon price of € 0.686/tCO_2, while with a higher instant carbon price (€ 1.346/tCO_2), MaxLEV rose to 10,160 €/ha, assuming a 2% discount rate (Table 2). With 4% discounting, the effect of different instant carbon prices became even more notable—e.g., in Region 2, TP-CS with 10% genetic gain yielded MaxLEV 1 995 €/ha when the instant carbon price was € 0.686/tCO_2, whereas with an instant carbon price of €1.346/tCO_2, MaxLEV increased to 4068 €/ha (Table 2).

Table 2. Effect of discount rate and carbon pricing on the MaxLEVs, €/ha. Shading refers to carbon price 1 with 2% and 4% discount rates.

Discount Rate	Instant Carbon Price Applied [a]	Region 1	Region 2
2%	1	Unimproved-TP: 4 334 (191) [b] Genetic gain 10%-TP: 5 846 (332) Genetic gain 15%-TP: 6 540 (293) Unimproved-TP-CS: 5 753 (238) Genetic gain 10%-TP-CS: 7 280 (223) Genetic gain 15%-TP-CS: 8 000 (321)	Unimproved-TP: 3 109 (295) Genetic gain 10%-TP: 4 179 (325) Genetic gain 15%-TP: 4 796 (341) Unimproved-TP-CS: 4 426 (306) Genetic gain 10%-TP-CS: 5 507 (308) Genetic gain 15%-TP-CS: 6 158 (340)
	2	Unimproved-TP-CS: 7 680 (232) [c] Genetic gain 10%-TP-CS: 9 425 (261) Genetic gain 15%-TP-CS: 10 160 (303)	Unimproved-TP-CS: 6 099 (430) Genetic gain 10%-TP-CS: 7 229 (438) Genetic gain 15%-TP-CS: 8 028 (381)
4%	1	Unimproved-TP: 477 (78) [d] Genetic gain 10%-TP: 932 (19) Geneticgain15%-TP:1164(41) Unimproved-TP-CS: 2 100 (45) Genetic gain 10%-TP-CS: 2 694 (51) Genetic gain 15%-TP-CS: 2 942 (69)	Unimproved-TP: 56 (21) Genetic gain 10%-TP: 430 (35) Genetic gain 15%-TP: 628 (39) Unimproved-TP-CS: 1 611 (69) Genetic gain 10%-TP-CS: 1 995 (42) Genetic gain 15%-TP-CS: 2 217 (35)
	2	Unimproved-TP-CS: 4 231 (59) [d] Genetic gain 10%-TP-CS: 5 035 (97) Genetic gain 15%-TP-CS: 5 374 (99)	Unimproved-TP-CS: 3 530 (138) Genetic gain 10%-TP-CS: 4 068 (84) Genetic gain 15%-TP-CS: 4 401 (98)

[a] The same social cost of carbon, € 35/tCO_2 was further translated into an instant price according to two interest rates: 2% and 4%, resulting in two instant prices of carbon: price 1 is 0.686 and price 2 is 1.346 €/tCO_2, respectively, [b] value in parenthesis represents standard deviation, S.D., [c] Note that carbon pricing affects only TP-CS, [d] When MaxLEV was assessed according to a 4% discount rate, only two stands were included into the analysis: for Region 1 Säkylä and Jaala, and for Region 2, Vaasa and Lieksa (see Figure 1 for locations).

4. Discussion

Including carbon sequestration into the analysis of optimized stand management seems to result in a prolonged rotation period, which is the result that agrees with earlier studies (e.g., [13,14,27,43,44]). The MAI also showed a slight increase when carbon sequestration was included as a goal of stand management. The two management alternatives (TP and TP-CS) schemes compared seem to differ at most at the timing of the first commercial thinning. Regardless of the climatic region and the level of genetic gain, the first commercial thinning occurred considerably earlier in TP than in TP-CS. This observation might have some impact on silvicultural guidelines.

If carbon pricing became a reality, that would mean a major increase in bare land values. These could be boosted further by regeneration with improved seed or plant material. We found the additional financial benefits due to the inclusion of genetic gains to be slightly smaller for TP-CS than for TP, even though the absolute bare land values from TP-CS always outperformed those from TP. The estimated carbon price (the social cost of carbon, € 35/tCO_2) used in this study can be considered to be on a high side given the history on carbon prices in the EU Emission Trading System (https://sandbag.org.uk/carbon-price-viewer/). On the other hand, recent papers [45,46] indicate that the carbon price might rise considerably in the future.

The discount rate applied in the main analyses was 2%, whereas in the sensitivity analysis, we used 4% discounting. The choice to apply a 2% interest rate is a compromise between fluctuating time spans (associated with optimum rotation periods ranging from 82 to 105 years) and recent studies on applicable interest rates in forestry [40–42]. Price [42] illustrated the discount schedules for three countries (UK, Norway, and France): the suggested discount rates fluctuated between 2% and 4% when the time horizon is from 30 to 200 years. A debate on social discount rates to be applied in e.g., climate–economic models has been going on for some time [47–50]. Arguments have been presented both for lower [49] and higher [47,48] discount rates. Furthermore, a recent theoretical paper [51] shows that a reduction in carbon emissions and an equal-sized increase in carbon sequestration will affect future generations differently, which even complicates the issue of applicable discount rates.

The results are to some extent conditional to the choice of growth simulators and optimization algorithms and thus, they warrant some caution (see, e.g., [52–54]). The Motti stand simulator and PIKAIA optimization algorithm have earlier been used in a similar context [5,36] but not as extensively as here. We wish that these results will be tested using other growth simulators and optimization algorithms as well as with different growth conditions and tree species.

The study scope focuses solely on the economic performance of timber production and combined timber production and carbon sequestration in the presence and absence of genetic gains, and many other aspects deserve to be studied in the future. For instance, the impact of tree breeding on carbon assimilation should be studied thoroughly. Here, we assume that a higher volume growth of timber obtained by tree breeding corresponds to higher carbon assimilation. The assumption should be studied further. Breeding for increased growth may cause decreased wood density (e.g., [55]), which may cause a lower carbon content of wood. However, variation in carbon rich lignin, not density, explains the difference in carbon between softwoods and hardwoods [56]. Lignin concentrations are higher in early wood than late wood in Scots pine [57], and since increased growth in improved genetic material has been found to be mainly due to larger earlywood proportion [58], tree breeding should not have negative effects on carbon assimilation. While some shifts in carbon allocation due to breeding are evident (e.g., thinner branches and thicker logs), increased volume growth above ground does not necessary mean decreased below-ground allocation [59]. Thus, our general assumption that genetically improved trees that produce more biomass bind more carbon than unimproved trees at the stand level seems to be correct.

There are two other aspects this study has omitted by design. First, we have not considered ecosystem services related to forests (such as water purification, biodiversity, recreational opportunities, and flood regulation, see e.g., [10]). However, taking into account more ecosystem services in the financial assessments would have required a totally different approach (cf. [60]). On the other hand, it would be fascinating to calculate trade-offs between different ecosystem services in the presence of enhanced tree growth compared to the absence of genetic gains. Second, any substitution effect from the use of wood products [61,62] was ignored, since substitution effects are generally considered to be driven by demand for products rather than decisions made by a landowner [37,38] such as forest management decisions. Including the substitution effects into the financial analysis calls for further research in the near future.

Finally, the methodology introduced here, particularly Equations (3) and (4), are generalizable to be used with other stand simulators as well. However, to our knowledge, there are only a few stand simulators that include the effect of genetic gains on tree growth [4,5,63].

5. Conclusions

In summary, our study demonstrated that tree improvement can considerably improve bare land value compared to the case without any improvement, i.e., unimproved seed material. However, tentative results indicate that in the presence of genetic gains, pure timber production seems to be relatively more attractive than a joint production of timber and carbon sequestration compared to an unimproved case, i.e., without any genetic gain. On the other hand, with the moderate social cost of carbon (€35/tCO_2), carbon benefit for a private forest owner constituted approximately one-third of the total present value of bare land, when discounting with 2%. Such a proportion creates a financial incentive that might alter the way forests are managed in the future.

Author Contributions: Conceptualization by A.A., K.K., J.H. and M.H.; methodology, A.A. and R.A.; stand-level optimizations were done by R.A. (supervised by A.A.).; formal analysis conducted by A.A. and R.A.; original draft was written by A.A., and K.K., J.H. and M.H. contributed to reviewing and editing; project administration was handled by K.K. and J.H.; K.K. and J.H. took part in funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the European Union H2020 Programme under Grant [773383-B4EST].

Acknowledgments: We'd like to thank our employer, Natural Resources Institute Finland (Luke) for providing an inspiring and dynamic working environment. Then, Leena Yrjänä (at Luke) is warmly appreciated for generating an illustrative map, Figure 1.

Conflicts of Interest: The authors declare no conflict of interest

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