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ABSTRACT
To date there are no studies comparing RF and CCF on peatlands with stand-level optimization. This study fills this gap and introduces the effect of genetic gain into analyses, covering different locations and two site types on peatlands. Two different data sets are applied: (1) six experimental plots which had been treated by conducting thinnings from below (RF management) and (2) identical locations and site types to those six plots representing bare land cases. A stand-level optimization was applied to achieve maximum net present value according to CCF and RF. The results demonstrated the superiority of RF with genetic gains to other options: RF without genetic gain and CCF when the starting point was an ongoing rotation. The results were valid regardless of location (southern, northern Finland), site type (Vaccinium myrtillus type I, herb-rich) and interest rate (3%, 5%). When starting from a bare land in northern Finland CCF became financially more profitable than RF (with or without genetic gain) with a 5% interest rate. This is mainly due to poorer growth potential in northern compared to southern Finland and the fact that the stand establishment costs associated with RF differ only slightly between southern and northern Finland.

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Stand-level optimization; peatlands; rotation forestry; continuous cover forestry; spruce; genetic gain

Introduction

Peatlands have a globally important role in sustaining biodiversity and providing a variety of ecosystem services such as carbon storage, timber, recreation, natural products, and improved water quality (Tanneberger et al. 2021; Yu 2012; Zedler and Kercher 2005). Internationally, around 15 million hectares of peatlands and wetlands have been drained for forestry in the temperate and boreal regions, particularly between the 1960s and the late 1980s (Palviainen et al. 2016). Especially in Finland, drained peatlands are an integral part of operational forestry, covering about 25% (4.7 Mha) of the total forest land area (Nieminen et al. 2018). The rationale for drainage is to maintain or even enhance forest growth in areas suitable for timber production (e.g. Hökkä et al. 2021), and the drainage itself can be considered as an act to increase nutrient supply (Lauren et al. 2021). However, despite the enhancing impact of drainage on tree growth, digging ditches creates negative side effects: a pulse of suspended solids (SS), nutrients (mainly phosphorus and nitrogen), and organic carbon are discharged into receiving surface waters (Finér et al. 2021). In addition, once the organic soil is drained, the stored carbon is permanently released as CO_2 to the atmosphere until the whole peat layer is decomposed (Sommer and Frank 2024). This creates carbon dioxide (CO_2) emissions from soil (e.g. Nieminen et al. 2018) which might – particularly in the most nitrogen-rich sites (see Ojanen et al. 2013) – lead to situations where drained peatland forests become net sources of CO_2 to the atmosphere. Further, clear-cutting (an essential element of rotation forestry, RF) tends to increase these emissions, particularly on nutrient-rich peatland forests (Korkiakoski et al. 2023).

Thus far, rotation forestry (RF) with clear-cutting and drainage has been the prevailing management practice on peatlands in Nordic conditions (Nieminen et al. 2018). An alternative to RF, continuous cover forestry (CCF) has been observed to offer several favorable features such as higher resistance against natural hazards, better adaptation potential to climate change (Gauthie et al. 2015), and higher environmental, esthetic, recreational, and cultural values (O'Hara 2014). Furthermore, a recent study (Ekholm et al. 2022) demonstrated CCF to enhance short-term biodiversity in managed forests. One drawback of CCF might be a lower timber output compared to RF (Tahvonen and Rämö 2016; Bianchi et al. 2020). On the other hand, CCF has been reported in numerous studies to financially outperform RF on mineral soils, particularly with interest rates above 2% (to name a few, Tahvonen and Rämö 2016; Parkatti et al. 2019; Parkatti et al. 2023). To date, there are no studies based on stand-level optimization focusing on the financial comparison between RF and CCF on peatlands (cf. Juutinen et al. 2021 which does not apply optimization).

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

The purpose of RF is to achieve a nearly coeval cohort of trees, to harvest and regenerate the forest by clear-cutting followed by soil preparation and artificial regeneration (either sowing or planting), rarely using natural regeneration with seed-trees. In the Nordic conditions, RF involves intermediate thinnings from below to improve the growth and vitality of the remaining dominant trees (Mäkinen and Isomäki 2004). Further, in RF ditch network maintenance (DNM) operations are recommended every 20–40 years to sustain and improve tree growth through drainage (Sikström and Hökkä 2016). CCF on the other hand relies on natural regeneration avoiding clearcutting (Pommerening and Murphy 2004). In CCF only a subset of the trees is harvested, while a sufficient number of trees is retained to maintain forest cover (Appelqvist et al. 2021). Maintaining a continuous tree cover with adequate evapotranspiration capacity could reduce, or even exclude, the need for regular DNM operations (Sarkkola et al. 2010, 2013). This could result in a more stable water table level than in rotation forestry, which, in turn, is favorable from a water quality perspective (Nieminen et al. 2018; Leppä et al. 2020). As it is possible to manage water table level with CCF and concurrently diminish soil disturbance (compared to RF), the cascading effects of water level controlling may positively influence greenhouse gas emissions and biodiversity as well (Laudon and Hasselquist 2023).

Before assessing trade-offs between economic returns from marketed and non-marketed public goods provided by peatlands (see Juutinen et al. 2020 for an approach), the financial performance of both management systems (RF and CCF) needs first to be compared in a theoretically sound framework (Amacher et al. 2009). One such framework is stand-level optimization based on a tree growth simulator incorporated with optimization algorithms (see Cao 2010 and Parkatti 2021 for alternative growth modelling approaches and optimization algorithms applied). In brief, a tree growth simulator (consisting of numerous individual growth models) provides the objective function values for the optimization algorithm in return for decision variables (e.g. Niinimäki et al. 2012; Arias-Rodil et al. 2015; Ahtikoski and Hökkä 2019). In this study a stand simulator Motti was incorporated with the PIKAIA optimization algorithm (for technical details, see e.g. Ahtikoski and Hökkä 2019).

To date, there is a lack of knowledge on the financial comparison between CCF and RF on peatlands so the effect of genetic gain is included in the financial performance of RF. In brief, tree breeding generates genetic gains which are further deployed in practice through seed orchards (Haapanen et al. 2016). The genetic gains translate to e.g. enhanced tree growth (compared to the absence of genetic gains), and this enhanced tree growth can further be modeled into individual growth models by applying e.g. genetic-gain multipliers (see, e.g. Carson et al. 1999; Ahtikoski et al. 2012). Genetic gains apply for RF since improved forest reproductive material (FRM) is used only in artificial regeneration; either planting or sowing (Serrano-León et al. 2021). In this study CCF and RF on spruce-dominated peatlands were compared with regard to financial performance. The assessments were based on stand-level optimization for both CCF and RF, and the effect of genetic gains associated with RF was also taken into account. Finally, the impact of growth conditions (location and temperature sum) was investigated by adopting two separate geographical locations representing south–north gradient in Finland.

Material and methods

Stands, ongoing rotation

The stands for the analyses were derived from experimental plots located in southern (geographical center of the plots: N 60° 21′; E 25° 0′) and northern (N 65° 1′; E25 ° 50′) Finland (Figure 1). The plots were further divided into three stand structures: suitable, intermediate and unsuitable for CCF. The division into stand structures was based on stand characteristics and diameter distributions representing trees of various sizes (Table 1, Figure 1). According to e.g. Brunner et al. (2025) a multilayer stand structure with falling diameter distribution is characteristic to stands managed by the CCF. Thus, a suitable stand structure for CCF includes an adequate number of naturally regenerated saplings as well as medium-sized and large trees to guarantee good productivity and produce seed material in the future. The rationale was to discover whether the division would serve as a tool to beforehand find suitable stands for CCF. An unsuitable stand structure for CCF has a large number of average-sized trees indicating a lack in the "regeneration engine", i.e. too few saplings and/or large trees to provide seeds for future saplings (Figure 2). For the intermediate case, the diameter distribution is between the two so that there is an abundant spruce advance growth under the dominant tree canopy layer. The stem number also falls between suitable and unsuitable cases (Table 1). For instance, in southern Finland (Ruotsinkylä) the suitable stand structure for CCF has a significant number of saplings in diameter classes 2.5–7.5 cm and enough large trees for future seeding while in the unsuitable

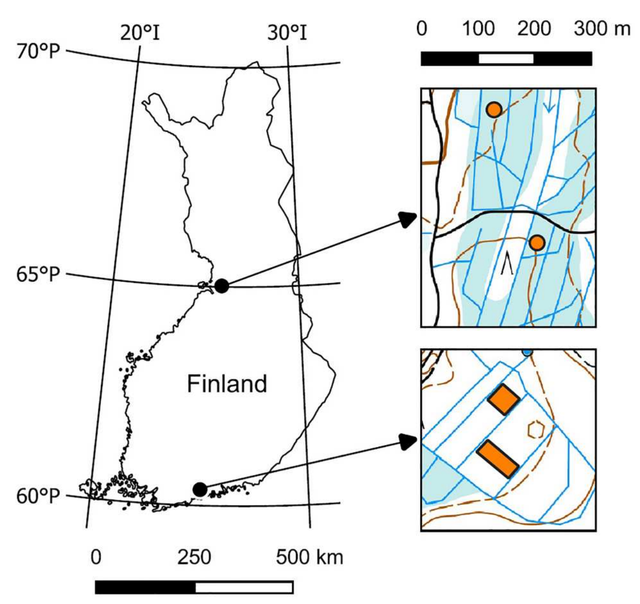

Figure 1. Locations of experimental plots. Ruotsinkylä in southern and Asmonkorpi in northern Finland. "P" stands for northern latitude and "I" for eastern longitude.

Table 1. Stand characteristics of the study stand at the beginning of the simulation period.

	Asmonkorpi			Ruotsinkylä		
Variable	suitable	intermediate	unsuitable	suitable	intermediate	unsuitable
N, trees ha^{-1}	1090	572	655	3249	510	328
BA, m^2 ha^{-1}	23.7	31.5	37.7	39.8	39.6	30.6
D_a, cm	14.2	24.5	26.4	10.5	27.7	33.8
D_w, cm	24.5	30.5	29.2	18	42.2	35.6
D_a/D_w	0.58	0.80	0.90	0.58	0.65	0.95
H_a, m	12.1	18.0	20.0	10.7	22.3	28.7
H_w, m	17.5	21.1	21.1	15.7	30.0	28.7
V, m^3ha^{-1}	195.2	299.7	363.7	312.2	501.8	401.4
Birch, %	4.7	2.6	9.6	1.4	3.9	3.2
Pine, %	0.0	7.5	0.0	0.0	19.3	0.0

Abbreviations: *N,* Number of stems per hectare; *BA*, stand basal area; D_a, arithmetic mean diameter at breast height; D_w, basal area weighted mean diameter at breast height; D_a/D_w, the ratio of D_a to D_w; H_a, arithmetic mean diameter height; H_w, basal area weighted mean height; *V*, stand volume; *Birch*, birch proportion of volume; *Pine*, pine proportion of volume.

stand structure, there are no saplings at all (Figure 2(a,b)). Further, in northern Finland (Asmonkorpi) the unsuitable stand structure for CCF only has saplings less than 10% of the total stem number (Figure 2(d)). Ruotsinkylä experimental plot represents an herb-rich type and Asmonkorpi is of Vaccinium myrtillus type I (for Finnish drained peatland site types see Laine et al. 2012).

Bare land cases

When simulations start from bare land, stand characteristics are irrelevant. Then only location and site type are required for simulating. In other words, ingrowth and tree growth are both generated by a stand simulator according to the models incorporated into the simulator. In this study we applied the identical locations (see Figure 1) and site types (herb-rich and *Vaccinium myrtillus type I*) associated with Ruotsinkylä and Asmonkorpi experimental plots when starting the analyses from bare land.

Stand projections of rotation forestry (RF)

Tree growth was simulated according to stand projections generated by the Motti stand simulator (Salminen et al. 2005; Hynynen et al. 2015). Motti is a stand-level decision-

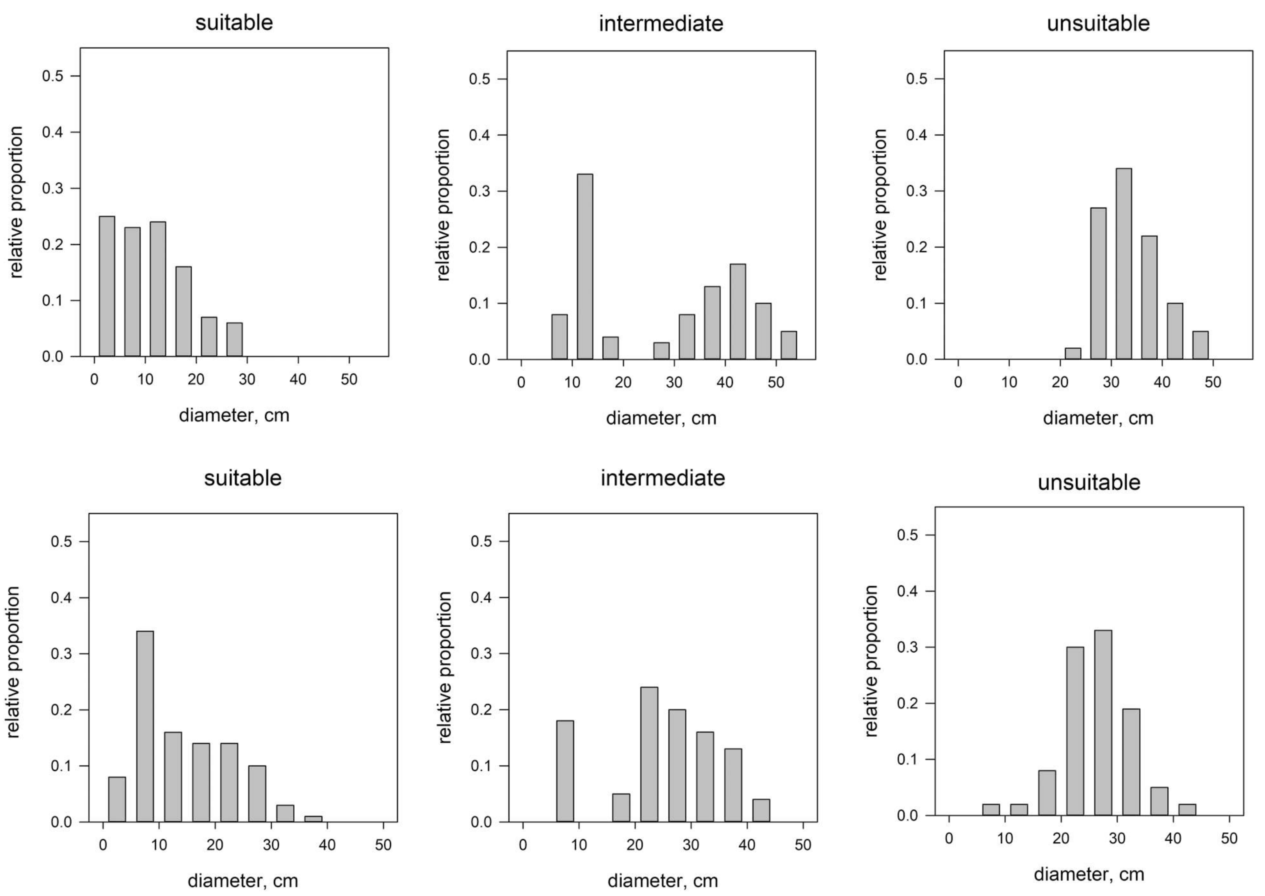

Figure 2. Diameter distributions at the onset of the simulations. Suitable, intermediate and unsuitable cases in Ruotsinkylä (upper graphs) and Asmonkorpi (lower graphs) presented.

support tool for assessing the effects of forest management on stand dynamics (Salminen et al. 2005; Juutinen et al. 2018; Ahtikoski and Hökkä 2019). Motti includes stand-level and individual-tree-level distant-independent models. Both the stand-level and individual-tree-level models are based on empirical-statistical modelling approach with a huge body of long-term inventory data covering Finland (Matala et al. 2003; Hynynen et al. 2014). The original inventory data consisted of repeated thinnings from below and clear-cutting, i.e. rotation forestry. Stand-level models are applied for natural regeneration and early growth while individual-tree-level models are used to predict growth for mature trees, Hdom > ca. 8 m (for technical details on growth modeling related to Motti, see Hynynen et al. 2014). Thus far Motti stand simulator has been widely applied both at stand-level (to name a few, Hynynen et al. 2005; Haapanen et al. 2016; Ahtikoski and Hökkä 2019) and landscape-level analyses (e.g. Mönkkönen et al. 2014; Hynynen et al. 2015; Ahtikoski et al. 2023).

Incorporation of genetic gains

Improved FRM in RF enables the potential of genetic gains. The development of a stand established with improved FRM was here technically modeled by incorporating genetic gains in height and diameter growth into the asymptote parameter of Chapman-Richards growth function (see Ahtikoski et al. 2012; Haapanen et al. 2016). Genetic gain estimates were derived from progeny trials, representing 12.8% genetic gain in height and 13.5% genetic gain in diameter over unimproved trees (Haapanen 2020). In seedling stands, the development is described using age-dependent models for stand characteristics (Siipilehto 2006a). The genetic gains are used as multipliers, namely 1.128 for the predicted mean height and 1.135 for the predicted mean diameter. The new growth model with genetic gains was included in the Motti stand simulator for testing its logical behavior, comparing the simulation results against field measurements (e.g. Deng et al. 2020) and finally producing stand projections with genetic gains for optimization problems.

Stand projections of continuous cover forestry (CCF)

First, in CCF the stand is assumed to be regenerated merely naturally. Then, stand projection of uneven-aged stands for CCF included: (1) establishment of new seedlings, (2) growth and mortality of seedlings until the threshold size (Hdom = 6 m), (3) growth and mortality of the advanced trees. The seedling establishment was predicted using models by Eerikäinen et al. (2007) while the height growth of Norway spruce seedlings was predicted by Eerikäinen et al. (2014) and for broadleaves Eerikäinen et al. (2007). The seedling establishment information included height distributions for Norway spruce, birch and aspen. The increasing stand basal area restricted both the establishment and growth of seedlings (Eerikäinen et al. 2007, 2014). As seedling establishment was better on peatlands compared to mineral soils (Miina and Saksa 2013; Siipilehto 2021), the number of established seedlings predicted by models of Eerikäinen et al. (2007) was multiplied by 1.4. In the Motti simulator, we sampled two percentile trees (h50 and h95) representing median (50%) and dominant tree (95%) for each 5-year growth step and followed the development (growth and survival) of those two sampled trees until the threshold value of 6 m dominant height was reached. Thereafter, the Weibull distribution was recovered from two percentiles (Dubey 1967; Bailey and Dell 1973; Siipilehto 2006b) and a systematic sample of n trees representing species-specific distributions was taken depending on the number of survived saplings per ha (N): $n = 1$ if $N < 3$, $n = 3$ if $4 < N < 10$, and $n = 5$ if $N \geq 10$. The diameter of a tree was predicted by the model of Eerikäinen et al. (2007) based on tree height. Survival of the small seedlings was predicted using height and basal area as the driving variables (Eerikäinen et al. 2007) and thereafter, when diameter > 2 cm, using models based on tree diameter and basal-area-of-larger trees as the driving variables (Pukkala et al. 2009).

Motti is initially designed for RF, which means that also the individual tree-level growth models have been developed and tested mainly based on data from even-aged stands (Hynynen et al. 2014). Motti has separate growth models for mineral soil sites and peatlands RF stands. For peatlands, Motti predictions are based on the tree-level growth models published in Repola et al. (2018). For growth simulation of uneven-aged stands, the diameter and height growth models of Motti have been tested with empirical CCF data of 20 Norway spruce permanent sample plots with a 20- to 25-year monitoring period in southern Finland (Lee et al. 2024). Based on the verified biases of the tree-level growth predictions, correction models for diameter and height growth of Norway spruce growing in CCF stands have been developed as a function of the variables indicating tree size, tree- and stand-level competition, uneven-aged stand structure, and time after the last selection cutting (Lee et al. 2024). These correction models were incorporated into the Motti to obtain a more reliable tree-level prediction of tree diameter and height growth in uneven-aged Norway spruce stands.

Objective function

Since this study compares CCF and RF systems (further, RF including genetic gains) the objective function is complicated. For rotation forestry (RF) the optimization problem is presented as a discrete-time system of state and control variables (see Blot and Naïla 2014). Let Z_{t_i} denote standing volume (m^3 ha^{-1}) before the ith thinning at age t_i, $i = 0, \ldots T$ (t_0 and t_T denote the beginning and the end of rotation, respectively), k denotes timber assortments ($k = 1, \ldots, K$) and p_k the stumpage price (€ m^{-3}) of each timber assortment. Let b be the discount factor, $b = 1/(1 + r)$ where r is the interest rate in real terms. A cost of a silvicultural measure l is w_l, € ha^{-1}. The removal of each timber assortment k in ith thinning is denoted by h_{ki}, expressed in m^3. Thinning intensity in ith thinning is g_i, expressed relative to growing stock. Then, the removal is a function of stand state, thinning intensity, timing and genetic gain, $\boldsymbol{\eta}$ (for improved FRM $\boldsymbol{\eta} > 1$, otherwise

0). The control variables include the timings of thinnings, total number of thinnings, the intensity of each thinning, the timings of silvicultural actions and the timing of clearcut (i.e. rotation period). The maximum net present value of bare land (interchangeably land expectation value), *Max LEV_{RF}* of timber production for rotation forestry can be expressed as:

$$\text{Max LEV}_{\text{RF}} = \frac{\sum_{i=0}^{T} b^{t_i}[\sum_{k=1}^{K} p_k h_{ki}(Z_{t_i}, g_i, \eta) - \sum_{l=1}^{L} w_{lt_i}]}{1 - b^{t_T}} \quad (1)$$

Then, the present value to be maximized in RF (Max NPV_{RF}) with standing timber is calculated by discounting the net revenues from the remaining part of the ongoing rotation and the discounted maximum net present value of bare land (see Hyytiäinen and Tahvonen 2001 for analogy):

$$\text{Max NPV}_{\text{RF}} = \sum_{i>0}^{T} b^{t_i - n}\left[\sum_{k=1}^{K} p_k h_{ki}(Z_{t_i - n}, g_i, \eta) - \sum_{l=1}^{L} w l_{t_i}\right] + b^{t_T - n}(\text{maxLEV}_{\text{RF}}) \quad (2)$$

where n is the stand age at the onset of simulations.

For continuous cover forestry (CCF) the net present value to be maximized included two parts: conversion and steady-state (see, e.g. Tahvonen and Rämö 2016). Regardless of the initial state (either a bare land or existing stand) the CCF management starts with a conversion phase (interchangeably transition phase) in which the cutting cycles and harvest intensities vary (Rämö and Tahvonen 2017), but gradually the time between harvests converges toward a steady-state cycle with a fixed removal of trees in each cycle (Tahvonen and Rämö 2016, Parkatti and Tahvonen 2020). Thus, the present value to be maximized is:

$$\text{Max NPV}_{\text{CCF}} = \sum_{s=0}^{S} b^{t_s} \sum_{k=1}^{K} p_k h_{ks}(Z_{t_s}, g_s) + \frac{p_k h_{km}(Z_{t_m}, g_m)}{1 - b^{t_m}} * b^{t_S} \quad (3)$$

where t_S is the duration of transition phase (in years), p_k stumpage price for timber assortment k (€ m^{-3}), h_{ks} the removal of timber assortment k in sth thinning during the transition phase (m^3 ha^{-1}), Z_{t_s} denotes standing volume during transition phase, g_s is the thinning intensity in sth thinning during the transition phase, h_{km} is the removal of timber assortment k in steady-state phase, Z_{t_m} represents standing timber at steady-state, g_m is the thinning intensity at steady-state, steady-state takes t_m years and b is the discount factor, $b = 1/(1 + r)$ where r is interest rate in real terms. In this study g_i, g_s and g_m were set to represent thinning intensities exceeding the absolute value of 30 m^3 ha^{-1}. This was to avoid repetitive thinnings with removals resulting in non-profitable loggings (cf. Laitila et al. 2010 for applying a minimum of 25 m^3 ha^{-1}; see Ahtikoski et al. 2021 for overall profitability of thinnings in Finnish conditions).

Optimization algorithm

For numerical optimization PIKAIA algorithm (see Charbonneau and Knapp 1995; Metcalfe and Charbonneau 2003) was applied, the objective function being the maximization of Max LEV_{RF}, Max NPV_{RF} or Max NPV_{CCF}, Equations (1), (2) or (3), respectively. Practically the procedure was the following: the Motti stand simulator produced the objective function values (i.e. stand projections) for the PIKAIA algorithm to solve in return for decision variables (see Niinimäki et al. 2012; Arias-Rodil et al. 2015). Optimization was solved as a mixed-integer nonlinear programming problem (e.g. Sinha et al. 2017), but without convexity assumptions (see Rämö and Tahvonen 2017). The PIKAIA optimization belongs to genetic algorithms which use computer programs to simulate the evolutionary process combining an artificial survival of the fittest with genetic operators abstracted from nature (e.g. Holland 1975; Goldberg 1989; Das et al. 2017). The main advantages of genetic algorithms are their high precision and shorter calculation times (Li et al. 2010) and the ability to avoid local optima (Hadi and Gonzalez-Andujar 2009).

Technically, the PIKAIA internally seeks to maximize a user-defined function *f(x)* in a bounded *n*-dimensional space $x \equiv (x_i, x_2, \ldots, x_n)$, $x_k \in [0.0, 1.0] \forall k$ by spanning the range [0.0, 1.0] in all dimensions. The parameter space of this study represents multidimensional, multimodal function with decision variables for RF such as the timing and intensity of thinning(s) and timing for a clearcut, and for CCF the intensity of harvests both in conversion and steady-state phase and the length of a cutting cycle in steady-state. In this study, we applied 100 generations (instead of the default, 500) and population size 50 (instead of 100) for compromising between the computing time and eminence of the results. For technical details on PIKAIA default values and their modifications applied in forestry assessments, see Ahtikoski et al. (2012) and Juutinen et al. (2018). The Motti stand simulator incorporated with the PIKAIA algorithm has been applied in various stand-level analyses in boreal forests (to name a few, Ahtikoski et al. 2013, 2019, 2021). To speed up computing a specific bat file was created. The bat file was executed to launch multiple executables and further linking the tasks into chains solved in time sequence. Considerable time savings in computing time (up to 70%) could be achieved with the above-mentioned procedure utilizing the full capacity of multi-processor design. On average computing time varied between ca. 15 and 35 min in RF and 25 and 45 min in CCF.

Economic data

Nominal unit costs of silviculture (Luke Statistics database 2023a, Silvicultural and forest improvement work) and stumpage prices (Luke Statistics database 2023b, Volumes and prices in roundwood trade) were obtained from annual statistics covering the latest 5-year time series. In practice, the time series for both unit costs and stumpage prices included calendar years from 2018 to 2022. We consider the underlying time series to be long enough to include both peak and bottom prices and costs experienced within a business cycle. The nominal unit costs and stumpage prices were further deflated according to the cost-of-living index (Statistics Finland 2023) to convert them into real terms. Original time series covered both southern and northern Finland

Table 2. Stumpage prices (€ m^{-3}) and silvicultural costs (€ ha^{-1}) in real terms. For CCF stumpage prices according to only Thinning were applied whereas for RF all three stumpage price options (First thinning, Thinning and Regeneration felling) were used in the analyses for Ruotsinkylä (southern Finland).

Felling method	Pine logs[a]	Spruce logs	Birch logs	Pine pulp[b]	Spruce pulp	Birch pulp
Regeneration felling (RF)	68.44 (66.88)	71.27 (69.95)	48.86 (50.64)	21.32 (21.95)	24.12 (23.68)	21.02 (20.96)
Thinning (RF, CCF)	60.08 (56.77)	61.85 (58.84)	42.55 (43.48)	19.17 (18.59)	19.65 (19.13)	18.51 (18.02)
First thinning (RF)	49.73 (44.89)	51.88 (47.27)	39.44 (37.49)	14.77 (14.45)	15.10 (14.49)	14.36 (14.17)
Silvicultural measures in RF, €/ha						
Mounding 483.7 (454.5)						
Manual planting 824.0 (797.8)[c]						
Early pre-commercial thinning 404.2 (425.4)						
Pre-commercial thinning 531.5 (514.1)						
Ditch network maintenance 396.8 (281.8)						

Note: Values in parenthesis applied for Asmonkorpi (northern Finland). In CCF stand regenerated naturally and no silvicultural measures were applied.
[a]Logs for saw logs.
[b]Pulp for pulpwood.
[c]Planting costs are identical with unimproved and improved seed material, see Antola et al. (2023).

separately. Silvicultural unit costs and stumpage prices in real terms are presented in Table 2. In this study, 3% and 5% real interest rates were applied. The lower interest rate, 3% reflects the study by Price (2018) suggesting that interest rates between 2% and 4% applied in forestry (UK, Norway, France) are relevant when the time horizon ranges from 30 to 200 years. The higher interest rate, 5% corresponds to the 6% interest rate applied in assessing the profitability of transformation to CCF for Sitka spruce in Great Britain (Davies and Kerr 2015). Applying 5% rather than 6% is due to the poorer average tree growth of spruce in Finland compared to Great Britain.

Results

Growth and yield

In southern Finland (Ruotsinkylä) with unsuitable stand characteristics at the onset, it took ca. 80 years in optimum CCF to achieve a steady-state with 3% interest rate (Figure 3(a)). An intriguing detail was that the optimal management of RF without genetic gain did not include any intermediate thinnings when a 3% interest rate was applied (Figure 3(a)). In northern Finland (Asmonkorpi) it took 88 years in optimum CCF to achieve a steady-state (with a 15-year cutting cycle) with a 5% interest rate (Figure 3(b), Table 3). When starting from a bare land the optimal rotation period in northern Finland in RF was 49 or 54 years, depending on whether improved FRM was used or not, the interest rate being 5% (Figure 3(b), Table 3). When starting form bare land the mean annual increment (MAI) associated with CCF steady-state was 61%-83% of the MAI associated with RF without genetic gain, depending on the interest rate (3% or 5%) and location, Ruotsinkylä or Asmonkorpi (percentages derived from Table 3). In the optimal solutions of CCF majority of the thinnings (excl. early transition) were thinnings from above whereas in RF majority of the thinning (excl.thinning preceding final cut) were thinnings from below.

Financial performance

Regardless of the initial stand structure (suitable, intermediate or unsuitable) or interest rate (3% or 5%) RF financially outperformed CCF in both locations, Ruotsinkylä and Asmonkorpi when starting from a standing timber, i.e. ongoing rotation (Table 4). The superiority was distinctive: the maximum net present value associated with CCF was between 65% and 97% compared to the maximum net

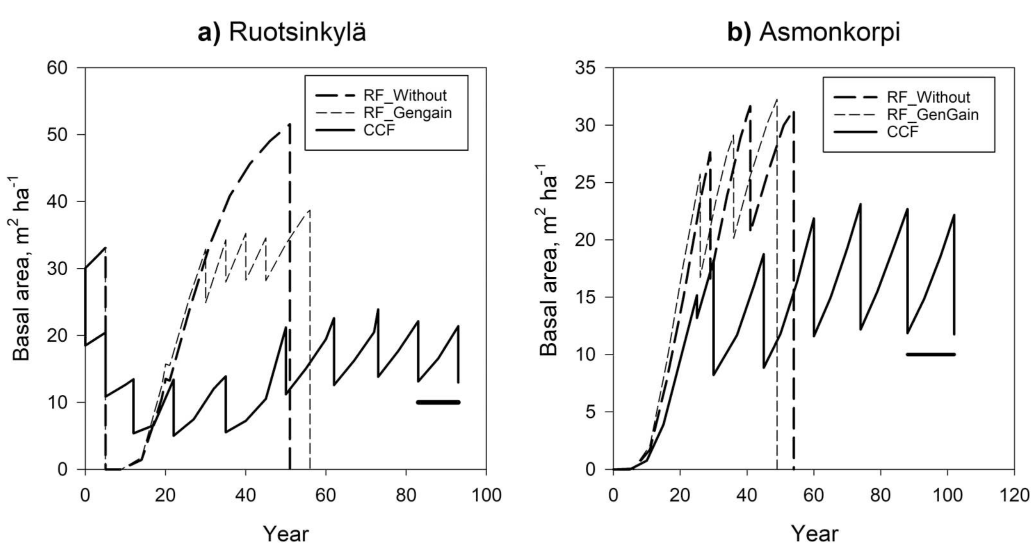

Figure 3. Stand development according to optimal management associated with RF and CCF in Ruotsinkylä with standing timber (i.e. ongoing rotation) representing unsuitable stand structure for CCF when interest rate 3% (a), and Asmonkorpi when starting from bare land with 5% interest rate (b). RF presented with genetic gain ("RF_Gengain") and without genetic gain ("RF_Without"). Horizontal lines (——) demonstrate the start and length of a steady-state in CCF.

Table 3. Cutting removals (m^3 ha^{-1}), timings (years) and saw log proportions (%) associated with optimal CCF and RF management with 3% and 5% interest rate

Location	Stand	Interest rate	RF	**CCF**, ongoing rotation		**RF**, bare land		**CCF**, bare land	
			ongoing rotation	conversion phase	steady-state	without[a]	Gengain[b]	conversion phase	steady-state
Ruotsinkylä	suitable	3%	**25**: 666.5 (77%)[c]	**67**: 742.6 (73%)[d]	**12**: 130.5 (74%)	3%[e]:	3%:	3%[g]:	3%:
		5%	**21**: 601.2 (74%)	**73**: 780.3 (71%)	**10**: 98.7 (67%)	**51**: 581.0 (71%)*	**56**: 720.1 (69%)*	**98**:504.2 (30%)*	**18**: 170.4 (83%)*
	intermediate	3%	**0**: 499.4 (61%)	**83**: 938.2 (73%)	**10**: 83.2 (55%)				
		5%	**0**: 499.4 (61%)	**89**: 953.7 (75%)	**10**: 78.0 (63%)	5%:	5%:	5%:	5%:
	unsuitable	3%	**2**: 459.8 (78%)*	**83**: 794.9 (78%)*	**10**: 86.7 (75%)*	**45**: 597.3 (60%)	**46**: 636.9 (66%)	**86**: 428.5 (22%)	**12**: 103.9 (72%)
		5%	**1**: 400.8 (77%)	**70**: 683.0 (77%)	**10**: 54.2 (49%)				
Asmonkorpi	suitable	3%	**4**: 209.9 (69%)	**58**: 362.7 (63%)	**16**: 99.0 (70%)	3%[f]:	3%	3%[g]:	3%
		5%	**4**: 209.9 (69%)	**56**: 379.8 (57%)	**12**: 55.4 (50%)	**65**: 533.3 (69%)	**51**: 437.3 (68%)	**93**: 290.2 (21%)	**14**: 71.0 (60%)
	intermediate	3%	**1**: 296.4 (79%)	**65**: 457.7 (73%)	**10**: 61.3 (59%)				
		5%	**1**: 296.4 (79%)	**62**: 438.6 (57%)	**10**: 54.3 (51%)	5%:	5%:	5%:	5%:
	unsuitable	3%	**1**: 360.9 (76%)	**82**: 531.8 (74%)	**12**: 64.7 (51%)	**54**: 396.6 (55%)*	**49**: 385.9 (54%)*	**88**: 239.1 (19%)*	**15**: 67.6 (62%)*
		5%	**1**: 360.9 (76%)	**70**: 480.7 (72%)	**12**: 64.0 (50%)				

Note: Results demonstrate two cases: starting from a standing timber (i.e. ongoing rotation) and a bare land. [Asterisks (*) refer to Figure 3 where the cases are depicted as stand development]. Stands (ongoing rotation) categorized as suitable, intermediate and unsuitable for CCF.
[a]In rotation forestry, RF the next generations are established without improved forest reproductive material, FRM.
[b]Next generations in RF are established with improved FRM.
[c]Bold number, **25** indicates timing for clearcut of ongoing rotation in years, the number, 666.5 presents cutting removal (m^3 ha^{-1}) of which saw logs proportion in parenthesis (77%).
[d]Bold number, **67** indicates the duration of conversion phase, or the length of steady-state (**12**) in years then the number, 742.6 shows cutting removal (m^3 ha^{-1}) of which saw logs proportion in parenthesis (73%).
[e]Since all stands (111, 39 and 41) in Ruotsinkylä represented identical soil type and they were located at proximity of each other, only one bare land case for future generations was simulated for all three stands (see note [a] for interpretation of values), interest rate 3% or 5%.
[f]In Asmonkorpi the same applies as in Ruotsinkylä: only one bare land case for future generations was simulated, interest rate 3% or 5%.
[g]For CCF the same applies as for RF with regard to bare land simulations.

present value of RF, depending on the interest rate applied (percentages derived from Table 4). Closest to the maximum net present value of RF came the CCF intermediate case in Ruotsinkylä when the interest rate was 3% (Table 4). An interesting detail was that the maximum net present values associated with CCF did not follow the initial division of stand structures: suitable case was the worst performer among the cases (suitable, intermediate and unsuitable) in both locations, Ruotsinkylä and Asmonkorpi (Table 4). In this connection, it is worth mentioning that the initial division into stand structures favorable for CCF was based on existing diameter distributions at the onset rather than the future development of the trees, i.e. their financial potential to create revenues.

Table 4. Net Present Values associated with stand-level optimization according to RF (objective function [2]) and CCF (objective function [3]), € ha^{-1}.

Location	Stand structure[a]	Management	3%	5%
Ruotsinkylä	suitable	RF without	30 780	23 115
		RF gengain	**32 151**	**23 773**
		CCF	22 226	15 027
	intermediate	RF without	34 808	27 890
		RF gengain	**36 179**	**28 548**
		CCF	*33 679*[b]	26 430
	unsuitable	RF without	32 910	25 950
		RF gengain	**34 281**	**26 608**
		CCF	26 545	22 049
Asmonkorpi	suitable	RF without	13 722	9 775
		RF gengain	**14 084**	**10 086**
		CCF	12 387	9 120
	intermediate	RF without	21 017	17 453
		RF gengain	**21 378**	**17 764**
		CCF	16 414	9 300
	unsuitable	RF without	24 333	20 769
		RF gengain	**24 694**	**21 080**
		CCF	17 983	15 897

Note: Simulations started from existing stand, i.e. ongoing rotation (see Table 1 for stand characteristics). For each stand structure best performer in bold. Interest rate 3% and 5%.
[a]Stand structure (suitable, intermediate or unsuitable for CCF) determined merely according to the stand characteristics at the onset of the simulations.
[b]This is the best result for CCF in relation to RF.

The main results shown in Table 4 also included the future generations associated with RF (objective function [2]). For CCF objective function [3] was applied. When a 3% interest rate was applied in maximizing bare land value, RF outperformed CCF in both locations (Figure 4). For example, in Ruotsinkylä the maximum bare land value of RF with genetic gains was 10 176 €ha^{-1} while with CCF the maximum bare land value was only 3 486 €ha^{-1} (Figure 4). However, with a 5% interest rate in Asmonkorpi, the maximum bare land value associated with CCF was higher than RF, regardless of whether improved FRM ("RF_gengain") was applied or not (Figure 4). Without genetic gains RF in Asmonkorpi turned negative when a 5% interest rate was applied in the optimization (Figure 4).

Discussion

With regard to boreal peatlands, only one recent paper (Juvonen et al. 2024) compares RF and CCF at stand level through optimization. Another paper on boreal peatlands compares RF and CCF by providing several optional management regimes without stand-level optimization (Juutinen et al. 2021) In this study the effect of genetic gain associated with RF was included into the analysis. To our knowledge, this is the first attempt to include the effect of genetic gain into

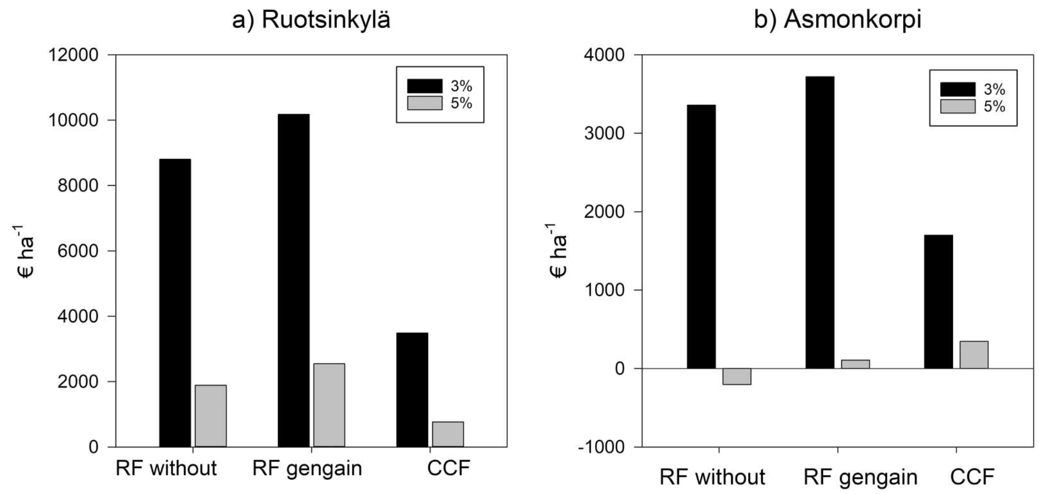

Figure 4. Maximum Bare land values associated with RF and CCF in Ruotsinkylä (a) and Asmonkorpi (b). Interest rate 3% and 5%.

the profitability comparison between RF and CCF on peatlands (cf. Juutinen et al. 2021; Juvonen et al. 2024).

When starting with standing timber (i.e. ongoing rotation) rotation forestry (RF) with improved FRM (genetic gain included) outperformed RF without genetic gain and distinctively outperformed CCF. The main reason for the superiority of RF with improved FRM was the enhanced growth rate due to genetic gain. It should be highlighted that the growth predictions with improved FRM were based on genetic-gain multipliers modifying the asymptote parameter of Chapman-Richards growth function (see Ahtikoski et al. 2012). This manipulation was in turn, based on genetic gain estimates derived from progeny trials (Haapanen 2020). There are, however, no long-term results on realized genetic gains on Norway spruce in Finland. Rather, the genetic-gain multipliers were modeled according to realized genetic gains representing field measurements between 22 and 30-year-old plots (Haapanen 2020). On the other hand, when comparing the growth and yield results underlying the optimization solutions of RF without genetic gain and CCF, the mean annual increments (MAIs) fall quite nicely within the range presented in earlier studies on peatlands (Ahtikoski and Hökkä 2019; Juutinen et al. 2021). For instance, in Juutinen et al. (2021) MAI associated with CCF was between 6.8 and 7.6 m^3 ha^{-1} $year^{-1}$ when basal area exceeded 10 m^2 ha^{-1}. In this study the corresponding MAI in CCF was app. 9.3-9.9 m^3 ha^{-1} $year^{-1}$ (depending on the interest rate applied in optimization) when starting from a bare land in southern Finland (Ruotsinkylä). In this study, the site type was slightly more nutrient-rich compared to Juutinen et al. (2021) which explains the difference (herb-rich vs. *Vaccinium myrtillus* type I). For RF the MAI in this study was between 11.3 and 12.9 m^3 ha^{-1} $year^{-1}$ when starting from a bare land in southern Finland. These results are comparable with Ahtikoski and Hökkä (2019) where the MAIs fluctuated between 11.0 and 12.7 m^3 ha^{-1} $year^{-1}$ in the optimum solution. RF with genetic gain resulted here in 13.9 m^3 ha^{-1} $year^{-1}$ when starting from a bare land – that value exceeds the corresponding value of RF without genetic gain by app. 8%, which seems reasonable. Then, our tentative division into suitable, intermediate and unsuitable stand structures for CCF showed that initial uneven-aged structure was not the most suitable for CCF management, at least if financial performance is taken into account (see Table 4). This was an unexpected result and suggests that beforehand categorizing stands to suitable or not suitable for CCF management based on initial stand structure may be a challenging task. Further studies on the subject are called for.

Although the financial results associated with ongoing rotation were clearly favoring RF with improved FRM, the outcome became intriguing when the simulations started from a bare land. Namely, in northern Finland (Asmonkorpi) with 5% interest rate the best performer among the options (RF without genetic gains, RF with genetic gains and CCF) was CCF (Figure 4). There is an explanation for that: with increasing interest rate, the rotation forestry becomes relatively more expensive since most of the costs are occurring at stand establishment whereas the cutting incomes (reflecting also the growth of trees) are discounted from a future when the time value of money (see, e.g. Mahajan 2020) is dominant and depress the discounted cutting revenues lower compared to the costs. This cannot be avoided even with genetic gains. With lower interest rates the time value of money is not so dominant, and the discounted cutting revenues compensate for the costs. In southern Finland, the discounted cutting revenues still can compensate the cost even with 5% interest rate since the growth of trees is considerably better in southern compared to northern Finland.

When comparing the results between southern (Ruotsinkylä) and northern Finland (Asmonkorpi) one should bear in mind that the site types were different. In southern Finland, herb-rich site type provides better growth potential than *Vaccinium myrtillus* type I in northern Finland. Further, the lower fertility of the land combined with harsher climatic conditions led to lower profitability (expressed in € ha^{-1}) in northern Finland compared to southern Finland – this was demonstrated in Figure 4. In general, better growth potential of trees correlates positively with profitability (see Cubbage et al. 2009).

In this study, 3% and 5% interest rates were applied in assessing the net present values. These interest rates fall into the range commonly applied in similar analyses (see, e.g. Tahvonen and Rämö 2016; Parkatti 2021). Interest rates around 2%-6% can be considered to be relevant in long-time horizon projects (Weitzman 2010), and for a large fraction of forest owners in the boreal zone (Hyytiäinen and Tahvonen 2001). Further, Price (2018) suggested interest rates in the UK, Norway and France fluctuated between 2% and 4% when the time horizon of the analyses falls between 30 and 200 years.

To avoid misinterpretations a few aspects underlying the results need to be raised in this connection. First, the Motti stand simulator was applied in this study to produce stand projections. The stand projections produced by the Motti stand simulator are based on individual-based statistical-empirical models while in majority of existing literature related to financial comparison between CCF and RF, has applied size-structured matrix models (e.g. Rämö and Tahvonen 2017; Parkatti et al. 2019; Parkatti et al. 2023). Using different types of growth simulators naturally results in slightly different outcomes, too. Then, stumpage prices were applied in this study. In existing literature roadside prices and harvesting costs are usually included into the analyses (see, e.g. Tahvonen and Rämö 2016;, Parkatti et al. 2019). This difference is relevant, and no doubt affects the outcomes. When harvesting costs are included (i.e. they are endogenous) into the analyses, the optimization chooses only thinnings where cutting revenues (valued as roadside prices) exceed harvesting costs. Since stumpage prices were used in the analyses, a special procedure was applied to avoid frequently repeated thinnings. In other words, repetitive minuscule cutting removals were prevented exogenously by setting a minimum cutting removal of 30 m^3 ha^{-1}. The main reason why harvesting costs were not included into the analyses in this study relates to a recent paper (Bianchi et al. 2023) indicating that harvesting costs models either underestimate or overestimate actual costs depending on the development stage of CCF: conversion or steady-state (Bianchi et al. 2023). Further, by applying stumpage prices corresponding to RF thinnings might lead to financial underestimations in CCF the closer to the steady-state the stand is. On the other hand, at early phases of conversion in CCF applying stumpage prices of RF thinnings (not first thinning stumpage prices – see Table 2) could lead to overestimations for CCF. We consider these two opposites (under- and overestimations) to cancel each other.

Another aspect affecting the results was that in this study regime switch, i.e. from CCF to RF or *vice versa* was not applied (cf. Parkatti et al. 2023; Tahvonen et al. 2024). This meant that either CCF or RF was chosen from the start (a bare land or an existing stand) to infinity. This approach narrows the solution space in evolving time, and one might argue that the results are sub-optimal in that sense. However, in this study, the effect of genetic gain was included into the optimization, and the technical framework of optimization could not be relaxed to allow a regime switch. Further, in CCF no silvicultural measures (e.g. site preparation and pre-commercial thinning) were allowed. This constraint admittedly affected negatively to tree growth. On the other hand, the costs of the silvicultural costs were absent in CCF. Thus, the net effect on allowing, e.g. site preparation and pre-commercial thinning into CCF remains unclear and definitely requires further studies. Undoubtedly, from the economic point of view, the net effect is conditional to the interest rate applied (see, e.g. Tahvonen and Rämö 2016 on interest rates and costs of artificial regeneration). Finally, in executing the optimizations a genetic algorithm PIKAIA was used (Metcalfe and Charbonneau 2003; Juutinen et al. 2018, Supplementary data). In existing literature, the approach has been slightly different: optimization task has usually been solved as a multi-level optimization problem by applying genetic, hill-climbing and gradient-based algorithms in different levels (e.g. Tahvonen and Rämö 2016; Parkatti et al. 2019). In most recent papers (Tahvonen et al. 2022; Tahvonen et al. 2024) reinforcement learning, RL has been applied in solving the optimization problem. However, there are only a few studies tackling with the comparison of optimization algorithms used in stand-level optimization (e.g. Pukkala 2009; Arias-Rodil et al. 2015). This is due to overwhelming work effort related to such comparison since it would technically require incorporation of alternative optimization algorithms into an identical tree growth simulator, which would be immensely time-consuming.

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