Forestry: An International Journal of Forest Research, 2024, 1–9
https://doi.org/10.1093/forestry/cpae037
Original Article

Economic evaluation of reopening a dormant tree improvement programme: a case study with Scots pine in Scotland

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Abstract

The deployment of improved forest reproductive material (FRM) selected to yield greater timber volume and quality than unimproved material could help to maintain productive, sustainable, and resilient forests and increase resistance to abiotic and biotic threats under extreme climate change events. In Scotland, Scots pine (*Pinus sylvestris* L.) is a productive species that aligns with these objectives. However, confidence in Scots pine has been low in recent years due to damage caused by the needle blight *Dothistroma septosporum*. Recent provenance/progeny trials using native Scots pine material from the Caledonian pine woods indicate a favourable genetic correlation between growth and resistance to *D. septosporum*, suggesting that simultaneous improvements are possible. The Scots pine breeding programme in Scotland was closed in 2002. Here, we present an economic case for reopening the breeding programme to further improve Scots pine FRM. Specifically, we evaluate the costs and potential benefits of supporting a new programme. We conduct an analysis using three improvement scenarios using a Faustmann formula (amended with thinnings) to maximize the land expectation value. Our results indicate that further improvement of Scots pine FRM would be cost-effective, outperforming the current Scots pine timber production and financial outcomes. The analysis shows that the Central scenario's land expectation value rises by £883 ha^{-1} compared to the baseline of £79 ha^{-1}, assuming a 3.5% interest rate. We employed both annuity calculations and a break-even analysis to show improved FRM could maintain a breeding programme investment of £3.5 million per year over a 30-year period with a break-even cost threshold increase of ~52% for purchasing improved planting materials from £0.33 to £0.50 per seedling. In conclusion, the study provides economic evidence of the commercial benefits for reopening the Scots pine breeding programme to increase timber production and financial returns.

Keywords: investment; optimal rotation; net present value; climate change; genetic gain; Scots pine; Pinus sylvestris L

Introduction

Deployment of improved forest reproductive material (FRM) is an important consideration for maintaining productivity, sustainability, and resilience of planted forests under climate change (Archambeau et al. 2022, Ray et al. 2022). In Scotland, commercial forestry is dominated by conifers, which comprise 73% of the forest cover. Sitka spruce [*Picea sitchensis* (Bong.) Carr.] is the most important species, accounting for 61% of land under forest (Forest Research 2022a) and is typically managed under a clear-fell silvicultural system, with nearly all plants deployed at restocking from an ongoing long-term genetic improvement programme. Scots pine (*P. sylvestris* L.) is the second-most important commercial conifer in terms of forest area (18%) and is particularly suited to sites in the North-East and East of Scotland, where the drier site conditions are less well suited to Sitka spruce, which is native to the moist oceanic region of the Pacific North-West of North America.

In Britain, Scots pine benefitted from a major tree improvement programme in the second half of the 20th century, involving progeny testing of over 1000 candidates in more than 100 half-sibling trials. After this round of progeny testing, breeding values for growth (height at year 10) and stem straightness (year 10) were estimated, to reselect a breeding population (Lee 2002). The breeding population was archived in clone banks, but no further breeding activity has taken place since that time. Improved FRM derived from the breeding programme is available from seed orchards, and accounts for ~55% of 9–10 million seedlings sold annually in Scotland (Forest Research 2022b) were set up in the 1970s and 1980s, which was before a complete set of breeding values were available and did not contain the best combinations of parents. Lee (1999) used index selection to show that predicted genetic gains from a seed orchard could be in the order of 14%–20% for height and 5%–19% for straightness, and so large increases in genetic gains are already available simply by establishing new orchards to replace or complement those established in the 1970s and 1980s. Nonetheless, additional improvement through further selection and testing may be justifiable if objectives have changed (e.g. new forestry objectives or emerging risks), if new information

Handling editor: Dr. Wei-Yew Chang
Received 30 June 2023. **Revised** 21 May 2024. **Accepted** 19 June 2024

has become available that can be used by breeders, and most importantly, if a significant expansion of the resource is anticipated. Burton et al. (2022) argued that these conditions have been met in the case of Scots pine in Scotland.

Burton et al. (2022) explored risks and opportunities for Scots pine improved FRM, in a stakeholder survey that identified disease, principally Dothistroma Needle Blight (DNB—*Dothistroma septosporum*), as the reason stakeholders had low confidence in planting Scots pine, considering this as a priority trait, in addition to the traditional volume and quality traits for improvement. New information was analysed from recently established provenance-progeny trials using unselected maternal half-sibling progenies grouped by population from the native 'Caledonian' pine woods (Beaton et al. 2022). These recent trials were evaluated for a range of ecologically important traits and show genetic variation in response to DNB, which is favourably correlated with higher productivity. Material from these trials could act as a source of disease-tolerant infusion material or otherwise provide useful information to guide renewed breeding efforts (Burton et al. 2022). There are opportunities to expand the Scots pine resource, particularly in areas previously stocked with exotic species of pine (Corsican pine—*Pinus nigra* var. laricio; lodgepole pine—*Pinus contorta*) that have been decimated by DNB damage. Given the dominance of Sitka spruce in Scotland, there is concern about production over-reliance, particularly in the climatically drier areas on sandy and loamy textured soils of North-East and East Scotland. The UK Climate Projections 2018 (Murphy et al. 2019) indicate problems of increasing drought severity by the 2050s and beyond. While Scots pine is unlikely to yield as much as Sitka spruce in terms of biomass, there is evidence to show that, under drier climatic conditions, Scots pine may be more tolerant and resilient to drought and therefore suffer fewer drought-induced stem defects (Davies et al. 2020, Ovenden et al. 2022) compared to spruce, and so could be a more reliable option for sawlog production (Haapanen et al. 2016, Laverdière et al. 2022).

To date, Scots pine improvement programmes in Scandinavia have resulted in genetic gains of ∼8%–25% in volume growth versus unimproved stock for Scots pine (for a concise summary, see Jansson et al. 2017, Table 1, pp. 275–276). Values of 14.5% and 33.5% improvement for first- and 1.5-generation seed orchards, respectively, have been reported for Finland (Haapanen et al. 2016). We consider that the growth conditions in Fennoscandia and in Scotland are similar with respect to factors, such as accumulated temperature and precipitation. Earlier review papers (Mullin et al. 2011, Ruotsalainen 2014) also indicate that for Scots pine a 10% improvement in the whole rotation volume production in northern Europe is reported for the current generation of seed orchards. For Norway spruce (*Picea abies*) and silver birch (*Betula pendula*), the corresponding genetic gains range from 5% to 29% (Jansson et al. 2017). In France, realized gains at young ages (first-generation Scots pine seed orchards) are expected to be ∼7% (Bastien et al. 2017). Further, in France, the precipitation rates differ from those in Fennoscandia and Scotland. Drought is a limiting factor for pine growth in France, while in Scotland and Fennoscandia other factors are more relevant, thus implying that achievable genetic gains might diverge between France and Fennoscandia and Scotland.

In Britain, we have predicted breeding values based on progeny tests for height and straightness but have not performed realized gain trials to understand how these values interact and impact on rotation volume at stand scale (Lee 1999). In general, for Scots pine, up to 20% higher early volume growth (compared to unimproved FRM) has been shown for phenotypic seed orchard material in several countries in northern and central Europe (Ruotsalainen, 2014). With respect to monetary impact, Scots pine breeding programmes have resulted in substantial economic gains. For instance, in Finland, the bare land value, BLV (expressed in € ha^{-1}), corresponding to improved Scots pine FRM was ∼350% compared to BLV of unimproved FRM (Ahtikoski et al. 2020b). BLV is also known as land expectation value (LEV), which is the present value of an infinite number of net present values (NPV) from one rotation (Amacher et al. 2009). In addition, internal rates of return as high as 8.9% have been reported for improved Scots pine FRM (Simonsen et al. 2010). Overall, economic gains from improved Scots pine FRM tend to be lucrative for the landowner (Serrano-León et al. 2021), sawmills (Ahtikoski et al. 2018), and society through access to healthy productive forests (Ahtikoski and Pulkkinen 2003).

The main objective of this study was to examine the economic case for reopening the Scots pine improvement programme based on the latest studies and knowledge of improved FRM.

We address the objective using scenarios related to potential genetic gains in quantity, quality, and security (in the sense of a more stable timber supply due to increased resilience) of improved Scots pine. We apply the Faustmann optimal rotation length approach (Faustmann 1968, Amacher et al. 2009) amended with thinnings to maximize the LEV over an infinite time horizon. Two methods are presented to investigate what the financial gains imply for the producers of improved Scots pine FRM (synonymous to the improved seedling providers or nursery producers), namely, an annuity approach and an equivalent planting material cost increase approach.

Methods

Data

The financial analysis applied existing yield models developed by Forest Research (Matthews and Duckworth 2005). In particular, the model 'M1' for Scots pine yield class (YC) 10, planted at 2 m spacing (i.e. a stocking density of 2500 trees ha^{-1}) was chosen since it is representative of the average value of productive Scots pine. In Britain, Scots pine YC ranges from YC4 to YC14 with a mean of YC10 (McLean 2019). Yield class is an index used in Britain to show the potential productivity of even-aged stands of trees. It is based on the maximum mean annual increment of cumulative timber volume achieved by a given tree species growing on a given site and managed according to a standard management prescription. It is measured in units of m^3ha^{-1} $year^{-1}$ (Edwards and Christie 1981). Hence, Scots pine YC10 implies a mean volume increment of 10 m^3ha^{-1} $year^{-1}$ over the rotation.

A survey of forest managers completed in 2007 (Macdonald et al. 2008) suggested that ∼80% of stands are thinned. Therefore, our study focuses on stands managed with thinning interventions. The typical thinning schedule for Scots pine YC10 (Table 1) is derived from the standard management table schedule for Scots pine in Britain (Forestry Commission 2015) and from discussions with forest managers of Scots pine stands in Scotland. The first thinning typically occurs at a stand age of 29 years with 49 m^3ha^{-1} removed. Subsequent thinnings occur at 7-year intervals, slowly decreasing in volume after the fifth thinning at the stand age of 57.

The total area planted with Scots pine in Scotland is 150 000 ha (Forest Research 2022a). The discount rate set out in the HM Treasury Green Book (HM Treasury 2022) was applied and assumes a 3.5% discount rate for projects of up to 30 years, declining in steps

Table 1. Thinning volumes for Scots pine YC10.

Age (Y)	29	36	43	50	57	64	71	78	85	92	99	106
Volume removed (m^3/ha)	49	49	49	49	49	46.6	40.2	33.8	28.3	21.7	16.9	12.3

thereafter. However, for this study and for simplicity, we assume a constant 3.5% discount rate.

Costs

The following attributes and costs are assumed for the economic analysis and are based upon standard costs for productive conifers (according to rotation forestry with thinning and clearcut management):

(1) Planting stocking densities: 2500 (trees ha^{-1})
(2) Planting material costs: £0.33 per seedling, £825 ha^{-1}
(3) Forest establishment operations: site preparation and actual tree planting cost. Estimated at £850 ha^{-1}
(4) Establishment, maintenance, and management costs: fencing, replacing failed plants, spraying/weeding; general maintenance (including Forest Agent/Craftsperson, covering Years 1–5). Estimated at £670 ha^{-1} in terms of present value (assuming 3.5% discount rate).

The average (re-)planting cost, taking account of all the operations, is £2345 ha^{-1}, for which the planting material comprises ∼35% of the total cost. These data on costs are compiled from various sources based on the standard costs for woodland and forestry grants (Forestry Commission England 2011, Scottish Forestry 2019, Forestry Commission 2021, Welsh Government 2021).

The same cost was used for unimproved and improved planting stocks for two reasons. First, the focus of this study was to assess the extra cost of improved planting material to break even with the benefits of using the improved stock. Thus, the results show how much more can be paid for improved seedling material compared to unimproved seedling material to assess if the extra cost would remain financially viable. This analysis closely resembles the analysis found in (Chang, Gaston et al. 2019a). Second, anecdotal evidence suggests that the price differential of planting improved versus unimproved material is currently small or even absent.

Benefits

For the study, we focus only on timber production, i.e. (discounted) timber revenues. These are calculated as a product of timber volume per ha and price per m3. Public benefits derived from other forest ecosystem services are not considered. It is important to keep in mind that timber value constitutes only ∼12% of the total annual value of woodland ecosystem services that besides timber also include carbon sequestration, air pollution removal, and recreation (ONS 2021). For forest owners, however, timber production and net revenues from it still play a crucial role (Juutinen et al. 2021).

Timber prices

Data on timber prices are taken from 'Timber Price Indices' (Forest Research 2022c), Table 2: Coniferous Standing Sales Price. Focusing on the last eight bi-annual observations (30 September 2018 to 31 March 2022) leads to an average price of £33.50 m^{-3} overbark (in 2021 prices). This is the timber price adopted for the calculations here. A standing sales price approach is adopted, indicating that harvesting costs (cutting and haulage) are left out of the financial analysis. In other words, timber is valued as a standing sale (or at stumpage).

Table 2. Scenarios for gains from use of improved Scots pine.

Scenarios	Quantity	Quality	Security
Low	5%	5%	5%
Central	10%	10%	10%
High	15%	15%	15%

Scenarios for improved Scots pine

Scenarios were developed with expert input from the tree breeding specialists (Table 2).

A renewed Scots pine improvement programme would seek to make simultaneous gains in quantity and quality of wood produced per unit area, as well as the likelihood of harvesting and marketing it, this is largely influenced by the susceptibility to biotic and abiotic damage. In our simulations, we consider that improvements in each of these trait categories ultimately condense into higher productivity. Mechanical properties (e.g. wood density and stiffness), which are often strongly adversely correlated with growth, are not important limiting factors in Scots pine, and so improving quality is likely to involve selecting on variation in branching characteristics and stem sinuosity, the latter of which is only marginally adversely correlated with height in British Scots pine (Lee 2002). Reduced susceptibility to *D. septosporum* is associated with (or results in) improved growth (Burton et al. 2022). While we are aware of the growth-differentiation balance hypothesis (GDBH), which suggests that there would be a tradeoff between different traits, for instance, decay resistance and volumetric growth (Herms and Mattson 1992, Koricheva et al. 1998), and the results of several studies seem to support the GDBH hypothesis (Swedjemark and Karlsson 2004, Oliva et al. 2010, Steffenrem et al. 2016). It is assumed that the overall gains from quite modest improvements of 5%–15% could be considered additive, with trade-offs being marginal or non-existent. For this case study, each of the improvements is assumed to have an equivalent impact on the total gain in production from improved SP, hence focusing entirely on equivalent impacts in terms of volume. The following multipliers are applied to the baseline volumes for the unimproved SP Scots pine: 1.15, 1.3, and 1.45 (described as low, central, and high improvement scenarios, respectively).

Assumptions and approach

Our economic analysis is based on a set of low, central and high scenarios (Table 2), whereby the low scenario represents a 5% improvement in quantity, quality, and security over unimproved material, the central scenario represents a 10% improvement, and the high scenario represents a 15% improvement. **Quantity** represents gains in timber volume. **Quality** represents gains in timber quality with a larger proportion of the felled timber assortment qualifying as 'green' saw logs, e.g. due to improved stem straightness or reduced frequency and size of knots (Macdonald et al. 2009). Analysis of average prices disaggregated by timber product categories for the last 12 years for Scots pine showed that the difference in price between high (saw logs) and low (firewood or woodfuel) values timber products is significant. High-value products could be up to 3.65 times more valuable than low value products, with a mean difference in value of 2 times. Hence, there is a larger price premium for higher-quality timber products. Similar differences in value between high- and low-quality timber products exist for Sitka spruce. Therefore, gains in quality can be quite important in an economic sense. For the standing sale, this gain could be accounted for by assuming a greater volume and improving the standing sale price. **Security** refers to the maintenance of timber supply from a more resilient forest reflecting the change to improved Scots pine becoming less susceptible to some abiotic and biotic threats. Given that abiotic and biotic damage generally reduces tree growth, we assume that these gains can also be added to the volume production. While unfavourable genetic correlations typically constrain simultaneous improvement of multiple traits [e.g. growth and mechanical properties (Zobel and van Buijtenen 1989)], greater breeding effort can help to identify correlation-breakers and overcome this limitation (Klápště et al. 2022). Thus, the three scenarios considered (low, central, and high) reflect possible levels of effort placed in obtaining the benefits through research and development.

Gains in the order of 5% are commonly available from first-generation seed orchards following phenotypic mass selection without testing (Serrano-León et al. 2021). While testing has already taken place in Scots pine, we expect that at least 5% additional gains could be realized simply by using up-to-date information to define new seed orchards, or thin existing ones where appropriate. Such a programme would cost <∼£0.5 million over 10 years to establish 10 ha of seed orchards. The central scenario (10% additional gains) is an estimate of what may be achievable with additional progeny testing, including evaluation of new phenotypes prior to, or in parallel with the establishment of new orchards (assuming a cost in the order of ∼£5–10 million over 10 years). The high scenario (15% additional gains) represents a situation where improvement activities are carried out at a scale or level of precision sufficient to take forward individuals that overcome potential unfavourable genetic correlations, e.g. by deploying tested families or turning the current breeding generation over (assuming a cost in the order of ∼£10–20 million over 10 years). The central scenario is considered as the most probable outcome, while the spread between low and high scenarios indicates uncertainty in outcomes. These scenarios are compared to a typical current Scots pine stand—the baseline (unimproved Scots pine). Economic analysis results are reported in terms of the value per hectare (£ ha^{-1}).

Finally, we assume that improved FRM will be available in the required quantities, which may not always be the case. In reality, sometime may be needed to grow the required amount of improved FRM. However, the focus of the study is not the transition effects of planting more improved FRM but the economic analysis of the benefits of genetic gain at the scale of the Scots pine resource in Scotland and the case for reopening the domestic breeding programme.

In this study, we focus on the LEV, the objective being to maximize the LEV through stand-level optimization. The Faustmann approach is a widely accepted way to analyse the economics of productive forest rotations and is adopted in this study (Ahtikoski et al. 2012, Saraev et al. 2017). The classical Faustmann formula (Faustmann 1849, 1968), also known as the LEV formula, 'gives the present value of net revenues growing an infinite series of identical timber stands' (Chang 2020). The optimum rotation length is estimated by maximising the associated value over an infinite series of identical rotations. A typical rotation would include planting the forest, waiting for it to grow, and then felling it for timber, but might also include other interventions such as regular thinnings throughout the rotation.

For an exogeneous thinning schedule, the model can be adjusted to take thinning into account as follows (Coordes 2014), (1) is for LEV according to the Faustmann model with thinnings:

$$\mathrm{LEV}(T) = \frac{p\,f(T)e^{-rT} - c + \sum_{i=1}^{K(T)} p^{*}\,g\,(t_i)\;e^{-r\,t_i}}{1 - e^{-rt}} \tag{1}$$

where T is an optimal rotation length (the variable to be changed to maximize the LEV); p is the timber value (here valued at stumpage), $p*$ is the value of thinnings, $f(T)$ is a growth function for the timber volume at time T, r is a discount rate, and c is costs (e.g. due to planting and tending of a young stand). The last term in the numerator is the sum of thinning revenues occurring at times t_i and volumes $g(t_i)$ given by the management tables; $p*$ is typically lower than p to reflect the lower average tree size of thinnings and the costs. The total number of thinnings $K(T)$ depends on the optimal rotation length, and potentially some other management rules, e.g. the rule of no thinning for a number of years after the establishment of the stand. Equation (1) is maximized to find the global optimum solution using a genetic algorithm (GA) implemented in R (Scrucca 2013, 2017), using the GA R package version 3.2.3 (R Core Team 2022). The use of a global optimisation is required because the LEV profile (see Fig. 2 below) is a non-convex sawtooth-type function with multiple local maxima. The following settings for the GA were used:

(1) Type: real-valued
(2) Population size: 100
(3) Number of generations: 500
(4) Elitism: 5
(5) Crossover probability: 0.8
(6) Mutation probability: 0.1
(7) Search domain: x1, lower = 20, upper = 100
(8) Iterations: 500

The estimated LEV can be converted to an equivalent annuity payment (A) over a specified number of years if required for the purposes of economic analysis. This allows investment projects of different lengths to be compared. When the interest or discount rate (r) is constant, (2) below yields an annuity payment (A) over N years:

$$\mathrm{A} = \frac{\mathrm{LEV}}{\frac{1-(1+r)^{-N}}{r}}. \tag{2}$$

Note that when N becomes infinite one is talking about perpetuity payments, and in this case, A = r ∗ LEV. Finally, we assume that the gains from improved Scots pine (as estimated by the higher LEV relative to the baseline) are divided equally between the forest owners (who take decisions on planting, management, and harvesting) and the producers of the improved planting stock. Without a detailed study of the market structure, which is currently not available, one cannot confirm whether the forest owners or the nursery producers have the greater bargaining power, and therefore, we consider a 50/50 split a fair assumption. In principle, one may also consider an extreme case where the forest owner is not economically disadvantaged and all the gains are appropriated by breeders and producers of the planting stock. This would strengthen the economic case for breeding and production of improved FRM.

Table 3. Optimal rotation lengths, LEV and volumes for baseline and scenarios.

Scenario	Improvement multiplier	Optimal rotation length (years)	LEV (£/ha)	Stand volume (m^3/ha)	Thinnings volume (m^3/ha)
Base	1.00	48.7	78.7	266.1	98.0
Low	1.15	48.7	520.4	306.0	112.7
Central	1.30	48.7	962.2	345.8	127.4
High	1.45	48.7	1403.9	385.6	142.1

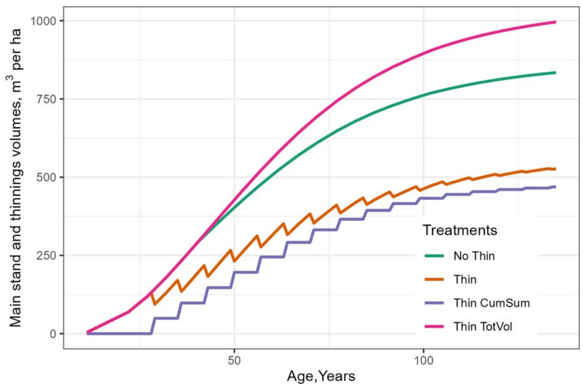

Figure 1. Growth curves for Scots pine yield class 10 and stand volume per ha: lower smooth line (No Thin)—stand volume with no thinning, top smooth line (Thin TotVol)—total thinned stand volume, which is the sum of the standing volume (sawtooth line, Thin), and cumulative volume of thinnings (lowest step like line)

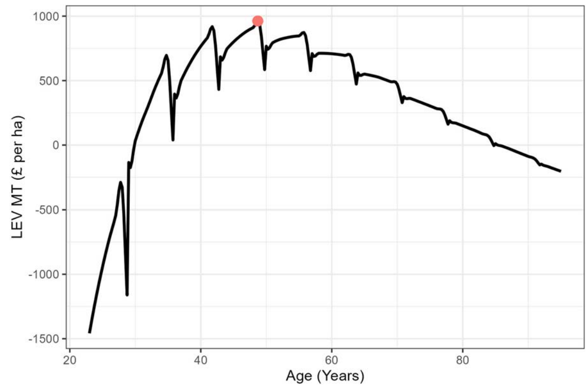

Figure 2. Typical LEV profile and the optimal rotation length (round dot mark), discount rate 3.5%

Table 4. LEV gains from baseline versus scenarios for improved FRM.

Scenario	Difference in LEV (£/ha)
Low	442
Central	883
High	1325

Results

The growth curves for Scots pine YC10 for an unthinned stand ('No Thin', dark green line) and a stand thinned according to the management tables ('Thin', dark orange line) (Fig. 1) show how the timber volume of a main stand develops over time. For a thinned Scots pine stand volume (dark orange line), we also plotted the cumulative volume of thinnings ('Thin CumSum', dark blue line) and the total volume ('Thin TotVol', dark red line), which is the sum of thinned stand and volume removed by a thinning operation. At age 41, the total cumulative live volume of a thinned stand starts (dark red line) to exceed the volume of a non-thinning stand (dark green line).

Table 3 below presents the modelled optimal rotation length, LEV, and volume for the baseline Scots pine YC10 and three growth improvement scenarios.

As expected, the improved Scots pine models predict higher yielding volumes and LEVs. For the Central scenario, the LEV is 12 times higher than the baseline LEV. As an example of the LEV profile and optimal solution (red dot) for the Central scenario, see Fig. 2.

Differences versus the baseline for the estimated optimal rotation length (stand age in years) were not significant ranging from −0.01 to −0.02 for low and high gain scenarios. This is due to two factors: first, the multiplier approach used for simulating the gains of improved FRM directly from the growth curve of unimproved FRM, and second, the fact that the gains are generally quite small. Together, these do not significantly change the shape of the growth curve to bring larger changes to the estimated optimal rotation length. Differences, i.e. gains, versus the baseline for the estimated LEVs are presented in Table 4.

Results for the Central scenario model show that the LEV per ha is £883 higher for the improved Scots pine than for the baseline unimproved LEV.

Analysis of feasible investments into the improved FRM breeding programme

As noted above, we assume the potential gains from improved FRM are split 50/50 between the forest owners and the producers of the planting material. We explore two approaches to investigating what the gains for the producers of improved FRM imply. The first approach converts the gains in the LEV assumed to accrue to the producers (i.e. a half of the total gain from Table 4) into equivalent annuity payments over 30 years that could be used to undertake the investments necessary to produce the improved planting material and aid the reinstatement of the breeding programme. The second approach converts the gains in the LEV assumed to accrue to the producers into equivalent cost increases that the producers could charge to cover the expenses of the improved Scots pine material.

Approach 1: annuity payments

The equivalent annuity value to the producers of improved FRM according to half the LEV gain over a period of 30 years (Table 5) indicates that for the central scenario, an annuity of ~£24 per ha

Table 5. Annuity values over 30 years for different scenarios.

Scenario	Annuity_30 (£/ha/yr)
Low	11.77
Central	23.55
High	35.32

Table 6. Potential aggregate gains in LEVs and 30-year annuity values for producers of improved FRM in Scotland from the use of improved Scots pine.

Scenario	Gain in LEV (£)	Annuity_30 (£/yr)
Low	66 255 244	1 765 905
Central	132 513 175	3 531 882
High	198 772 988	5 297 909

per year could be paid to the producers for 30 years to finance the investments required to run an improvement programme.

The financial implications may be clearer by comparing the aggregate results for Scotland, assuming that either all the present Scots pine area will be used for the improved SP or that the total area of new planting using improved Scots pine instead of Sitka spruce will amount to a similar size (Table 6).

The central scenario (Table 6), indicates the total gain in the LEV is ~£132.5 million, and if half of this gain is converted to a 30-year annuity, its value would be ~£3.5 million per year. This could be the amount potentially available to the improved FRM producers in Scotland to fund the extra investment needed in an improvement programme for Scots pine over 30 years. If the programme of investments could be shorter, this will lead to a higher level of annual investments. For example, if it is agreed that 10 years of additional investments will be sufficient to kick-start the improved FRM breeding programme, the annual finance available will increase to ~£7.7 million.

Approach 2: costs increases by producers of the improved FRM

The alternative approach to exploring what could be done with the LEV gains due to improved Scots pine involves computing the potential planting material cost increase that could be fully financed by the gains. In this case, we assume the increased cost per seedling covers the cost of all genetic improvement (i.e. the nursery is also the breeder and seed producer). To be precise, the producer takes half (maintaining a 50/50 split assumption between the forest owners and the producers of the improved planting material) of the LEV gain from Table 4 to calculate an associated feasible total planting cost increase in LEV, making this gain zero. These cost increases could be paid to the producers of the planting material (seedling producers) for the improved planting stock, allowing them to increase their price per seedling accordingly. The results are presented in Table 7.

The first column of Table 7 shows the new maximum level of total planting costs that would be feasible for the improved seedling producers to cover the increased LEVs (assuming that half the gains accrue to the seedling producers). The second column (Table 7) shows the feasible total cost increases compared to the baseline of £2345 ha^{-1}. Assuming that these increases could be directed to the producers of the improved plant material, the percentage increase over the baseline planting material cost (£825) is given in the column three (Table 7). Finally, column four (Table 7) shows the new feasible price per seedling grown from improved FRM (assuming 2500 trees per ha), which could be compared with the baseline price of £0.33 per seedling. For the central scenario, e.g. over 51% increase in price per seedling could be afforded to break-even (costs equalling benefits of improved FRM for Scots pine).

Discussion

The examples of how investment in a Scots pine breeding programme might be funded and how these two methods generate incentives for actors (producers and forest owners) to participate are clearly demonstrated in our analysis. The first approach, with annual investments into the sector and the improved FRM breeding programme, would require administration by a central agency or co-operative. The agency could be tasked with collecting an additional tax on profits from timber harvests (equivalent to half of the gains) to redistribute gains to those involved in improving FRM. The second approach, where the improved FRM producers could charge higher prices, would avoid administration costs. Both approaches rely on the sector understanding and accepting the economic analysis of the benefits of improved FRM.

Our analyses show that ~£3.5 million per annum could be allocated to a Scots pine improvement programme that would be financially viable, given the assumptions made in our scenarios (deployment area, genetic gains, etc.). Our rough estimates of the likely costs of realising the low, medium, and high (£0.05–£2 million per year for 10 years) gain scenarios fall comfortably within this range. An initial investment would need to be front-loaded and have a long return horizon.

It would be interesting and helpful to have data on the actual cost of a Scots pine breeding programme. Unfortunately, there is a lack of published evidence presenting such numbers, since the budgets of breeding programmes are rarely fully exposed in scientific papers. For instance, a recent review on economic evaluation of tree breeding (Chang et al. 2019b) does not reveal any budget related to national breeding programmes, but a more recent paper (Fugeray-Scarbel et al. 2023) provides some figures from which one can trace estimates on national breeding programme costs. In France, the investment in breeding for maritime pine is on average 693 000 euros annually. This value falls within the range of our rough estimate on the annual costs of reopening the Scots pine breeding programme in Scotland: from £0.05 to £2 million, depending on the scenario applied (low, central, or high). Further, our analysis showed that ~£3.5 million per annum could be allocated to a Scots pine breeding programme and it would still be financially viable, given the assumptions of the study (genetic gains, deployment area, etc.).

The economic analysis explores what would be feasible under the assumption of a 50/50 split in the gains from improved Scots pine between the producers of the improved plants and the forest owners, and the analysis is based on the average case. There will always be variability among forest owners with respect to objectives and silvicultural activity and a range in site productivity (as expressed by the YC), which influence the extent to which genetic gain can be realized. Other factors that must be considered are timber prices and discount or interest rates. Nevertheless, our analysis may serve as a useful starting point for discussions on possible solutions to enable more improved Scots pine to be produced and planted in Scotland.

Table 7. Alternative cost approach results estimating how much more could be charged per improved seedling (in percentage and absolute terms).

Scenario	New total costs, £/ha	Cost increase compared to the baseline, £/ha	Percentage increase in costs compared to baseline for planting material	Feasible new cost per seedling (£0.33 baseline), £
Low	2590	245	29.7%	0.43
Central	2771	426	51.6%	0.50
High	2952	607	73.5%	0.57

However, the economic feasibility does not address another crucial question: how willing would forest owners be to pay for the improved planting stock? This question still lacks a definitive answer. A recent paper on the subject stated: '...forest owners value improved FRM (improved forest reproductive material) only moderately because of long lags between plantation and harvest...' (Fugeray-Scarbel et al. 2023). In other words, forest owners may not be so willing to pay extra for improved FRM. On the other hand, a survey by (Tikkinen et al. 2021) indicated that forest owners—at least in Finland—are willing to pay more for the improved traits in FRM. Since the focus of this study was to evaluate and present positive economic evidence to restart the breeding programme in Scotland, the willingness to pay aspect was not addressed and may be the subject of future research.

Plantations of genetically improved forest trees are critical to sustainable forest management (Jansson et al. 2017), and seed orchards are the most widely used delivery system to transfer gains from tree breeding programmes to practical forestry (White et al. 2007). Ruotsalainen (2014) has concluded that forest tree breeding will become an integral part of successful bioeconomies because genetically improved trees can increase the supply of high-quality wood materials and the long-term profitability for forestry. For instance, in Sweden, Rosvall (2011) estimated that the economic gain from using genetically improved seedlings in Sweden would correspond to ~14% of the value of the entire Swedish harvest in 2006. Similar encouraging results for Scots pine breeding have been reported in Finland (Ahtikoski and Pulkkinen 2003, Ahtikoski et al. 2020a), and in France and other countries (Serrano-León et al. 2021). However, justification of any breeding programme in economic terms is complex—since one needs to assess the financial incentives accruing to each relevant participant involved in deployment. In our study focusing on Scotland, the relevant participants are the forest owners, who are expected to accrue the benefits at rotation following additional investment up-front, and those involved in the development and deployment of improved material (i.e. breeders, seed, and seedling producers). To be able to re-launch an improvement programme for Scots pine, parties throughout the supply chain need to find financial incentives to participate in the programme, and our study provides these data.

In view of the current lack of realized gain trials over a full rotation, we rely on predicted breeding values for parents (Lee 2002), analysis of genetic variability in disease response in younger trials (Beaton et al. 2022), and expert knowledge. It is assumed for this economic analysis that all the quantity, quality, and security gains are additive and equivalent in each case to a corresponding increase in growth in terms of their impacts on the total timber harvest volume [cf. (Oliva et al. 2010, Steffenrem et al. 2016) for non-additivity, i.e. the growth-differentiation balance hypothesis (GDBH)]. The assumption of additivity implies that the overall effect of genetic gain might result in an overestimation in economic terms. On the other hand, we applied a scenario analysis corresponding to a range of alternative assumptions on quantity, quality, and security—within that range, the additivity issue also plays a different role. Considering multiplicative effects for the scenarios leads to the following gains: 1.16, 1.33, and 1.52, which are not significantly different from the additive case used in this study.

The models used in this case study were parameterized using the land area occupied by Scots pine in Scotland. Extension to the rest of Great Britain is valid due to the common national breeding zone for improved Scots pine and expected increase in demand for Scots pine planting stock in England, where exotic pine plantations have suffered damage from Dothistroma needle blight (*D. septosporum*). Extending the use of improved Scots pine FRM from Scotland to the whole of Great Britain would further strengthen the economic case for re-starting the breeding programme.

Finally, since stand-level optimization was applied in this study to maximize the LEV, a word of caution is warranted. In real-world forestry, forest owners seldomly (if ever) optimize the management—rather they follow existing silvicultural guidelines, which are a compromise of financial performance, social and ecological sustainability, and climate aspects, an example of such guidelines for Finland is (Tapio and Ministry of Agriculture and Forestry of Finland 2023). Thus, one can argue that the calculated LEVs in this study correspond to more theoretical than practical financial values of Scots pine breeding in Scotland.

Conclusion

The economic sensitivity analysis demonstrated how further use of improved Scots pine forest reproductive material (FRM) could positively influence volume and net present values (LEVs) compared to unimproved or status-quo material. The annuity approach shows that improved FRM producers could be paid ~£24 ha^{-1} $year^{-1}$ for 30 years to finance producing the improved planting material. The equivalent planting cost increase approach estimates that an increase of ~£426 ha^{-1} in total planting costs could be afforded, equating to a 52% increase in planting improved material costs from the baseline of £0.33–£0.50 per seedling.

Two potential funding approaches show how annual investments could be recovered, by a central agency or co-operative, or by planting material producers charging higher prices. The study provides evidence that there are no economic barriers for re-starting the breeding programme for improved Scots pine. Furthermore, the economic case would be strengthened by extending the use of improved Scots pine FRM to the whole of Britain.

Acknowledgements

We are grateful to Elspeth Macdonald for comments on an earlier draft and for suggestions from reviewers of the article.

Author contributions

Vadim Saraev (Conceptualization, Formal analysis, Methodology, Project administration, Visualization, Writing—original draft, Writing—review & editing), Anssi Ahtikoski (Methodology, Writing—review & editing), Richard Whittet (Methodology, Writing—review & editing), and Duncan Ray (Methodology, Writing—review & editing)

Conflict of interest

None declared.

Funding

This study was funded by the European Project H2020 'Adaptive breeding for productive, sustainable and resilient forests under climate change' (B4EST; grant agreement No. 773383) and the Forest Research Science and Innovation Strategy Core Program.

Data availability

The data underlying this article were derived from sources in the public domain references in the article. No new data were generated.

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