FORWARD PROJECTIONS

SCOTLAND

SUPERB
Upscaling Forest Restoration

Author(s)

Sara Filipek[1], Silke Jacobs[1], Gert-Jan Nabuurs[1], Tom Locatelli[2], Bruce Nicoll[2], Daniele Ferraretto[2]

Affiliations

[1]Wageningen Environmental Research, Droevendaalsesteeg 3a, 6708 PB Wageningen, The Netherlands

[2]Forest Research, Bush Estate, Roslin EH25 9SY, United Kingdom

Recommended citations

Filipek S., Jacobs S., Nabuurs GJ., Locatelli T., Nicoll B., Ferraretto D., 2025. Deliverable D6.5: The Scottish forest development under varying restoration scenarios projected until 2055. Horizon 2020 project SUPERB, project no. 101036849, Wageningen Environmental Research.

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EXECUTIVE SUMMARY

Forest restoration initiatives are becoming widespread in many European countries. Within these initiatives, attempts are being made to restore various forest habitat types and a wide range of areas with different socioeconomic and ecological backgrounds. Forest restoration goals in Europe may not always align with those of historical reference forests, as climate change increasingly makes such restoration unfeasible. As a result, objectives are often redirected toward managed forest states that support the continued provision of desired goods and ecosystem services. Therefore, the most likely trajectories of future forest development are needed to assess and evaluate restoration outcomes, as well as to advise on successful measures that could support upscaling of the restoration initiatives.

This Scottish projection report is part of the deliverable D6.5 on projected ecosystem data. The forest development under varying restoration scenarios is projected for the upcoming 30 years, until 2055, using the EFISCEN-Space model.

The model projections showed that (1) deintensification of forest management in high-risk wind areas and the conversion of even-structured forest to coniferous CCF increased structural complexity yielding higher growing stock in upcoming 30 years, (2) reforestation through planting future-suitable species allows for quick recovery of forest growth but also positively affects soil organic carbon (SOC) stocks, (3) to support further development of forest resources and structural diversity, forest management needs to consider both suitable harvesting and thinning intensities and (re)planting measures, (4) the 463 536 hectare of forest restoration area may cost around 2.78 billion Euro (at average hectare costs of 6 000 Euro; see Scottish workplan v2.0).

DEMO INFORMATION

Queen Elizabeth Forest Park (QEFP) is part of the Scottish national public forest estate, owned by the Scottish Government and managed by Forestry and Land Scotland (FLS). It is located in the central region of Scotland and comprises 16 Management Blocks which collectively cover an area of approximately 20,000 ha, of which about 54% is forested. It is embedded within the Loch Lomond & the Trossachs National Park where a variety of land uses are present: large areas are covered by lochs, by conifer and by broadleaf forests, as well as agricultural land and pastures, and some small but locally important towns and villages. Tourism is a considerable source of revenue for local communities across QEFP and LL&TNP.

Since the beginning of the 20th century the conifer forests in QEFP have included a large proportion of Sitka spruce *(Picea sitchensis)* monoculture stands to provide timber products and to generate income, a legacy of the post-war forestry policy of the last century (Figure 1). However, following changes in UK forest policies (such as the UK Forestry Standard), FLS has carried out targeted management activities that have significantly reduced the extent of Sitka spruce stands. These efforts aim to diversify the forest and increase species and structural complexity, thereby supporting biodiversity and the delivery of a range of other ecosystem services (e.g., flood risk mitigation). Throughout QEFP, forest diversification is ongoing, with action to increase both species and structural diversity. Riparian zones are being cleared of conifers and replaced with native species – both broadleaves and conifers, selected on the basis of their suitability to different woodland types. Restoration activities for the SUPERB project take place in three sites: one in the Allt Glas site (restoration of riparian woodland and implementation of Natural Flood Management practices), one near the Honeymoon bridge in Glen Crow (high-elevation planting), and one in Achray Forest (transition from pure Sitka spruce to Continuous Cover Forestry (CCF)).

Figure 1. The initial state of the forest in the Scottish demo area, monocultures of Sitka spruce.

MODEL DESCRIPTION

EFISCEN-Space model

EFISCEN-Space is an empirical European forest model that simulates development of forest resources under varying scenarios of forest management and climate change. It keeps track of the development of the diameter distribution of 20 tree species (groups) for individual plot locations (Schelhaas et al., 2022). The diameter distribution changes over time due to the growth of trees (simulated by the growth of trees to a larger diameter class), the removal of trees due to natural (background) mortality or harvest, and the occurrence of new trees (ingrowth) in lowest diameter classes. The EFISCEN-Space model is initialised on tree-wise observations from forest inventories, usually National Forest Inventories (NFIs), and driven by environmental datasets with pan-European coverage (Nabuurs et al., 2007, Schelhaas et al., 2022, Filipek et al., In prep). These data are used to initialize forest structure and are the basis for the model's detailed and dynamic (i.e. sensitive to forest structure) simulation of growth (Schelhaas et al., 2018). Growth is related to the current forest structure (plus the abiotic predictors), and is incorporated here under a RCP 4.5. scenario for all baseline (BAU) and restoration scenarios. As the growth functions are fitted on repeated NFIs with a wide range of sites and weather data this results in a climate sensitive growth function. EFISCEN-Space is not a process-based model, but it incorporates climate sensitivity by linking its growth functions to annually downscaled weather data from the MPI-ESM1-2-LR global climate model under RCP 4.5. This means forest growth responds to the projected climate changes.

Planting, thinning and final felling can be carried out in EFISCEN-Space according to specified regimes. Natural mortality and harvesting can both be based on fixed regimes (based on repeated forest inventories), and on dynamic modules for natural mortality and ingrowth and simulating harvest using harvest rule patterns. Dynamic modules for mortality and ingrowth are both fitted on large sets of repeated NFI plot and tree wise data (Schelhaas et al in prep; König et al., 2025).

Model outputs provide information about forest resources (growing stock volume, increment, harvested volumes, biomass), carbon pools (biomass, litterfall and soil), biodiversity (number of large size trees, species composition, Gini index, deadwood).

SCENARIO DESCRIPTION

EFISCEN-Space scenarios

For the baseline and two restoration scenarios we used the Scottish NFI (2010 – 2019). In total we simulated 15 523 plots which represented 1 411 958 ha of forest area (100% of the Scottish forest area; Figure 2). As the model was initialized on the latest processed NFI data, it was first simulated to the year 2025 with currently observed management rules to account for forest development until 2025. Then the state of the forest in 2025 was used to re-initialize and simulate forest development trajectories from this common point in time until 2055 for each scenario.

As forest restoration measures need to be adaptive to climate change, both baseline and restoration scenarios were simulated under climate change scenario RCP4.5 (MPI-ESM1-2-HR). To represent forest dynamics; dynamic ingrowth and mortality were applied to all scenarios.
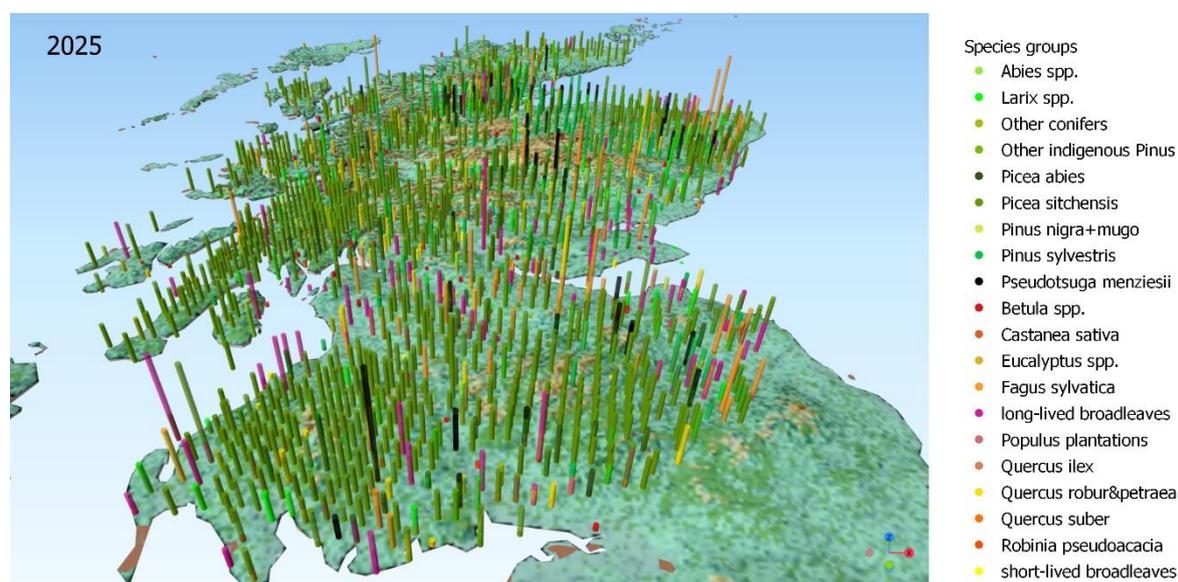

Figure 2. Map of initialized NFI plots in Scotland, in total 15 523 plots. Colour of the bar represents the initial dominant species or species group per plot, and height of the bar shows the initial growing stock volume (the higher the bar, the larger the growing stock volume).

1.   Baseline (BAU)

The Baseline (BAU) scenario simulates the development of forest resources under recent forest management practices and prior to *Phytophthora ramorum* infestation in *Larix* forest occurred in Scotland. This forest management is based on observed harvest rule patterns from Ireland, which we adapted to Scottish conditions to reflect the management of conifer forests for timber production where the primary constraint is wind damage risk, and a target harvest dbh (diameter at breast height) value of 30 cm as the preferred size for the sawmill industry. The rules patterns were defined by a set of rules which included information about tree species, tree diameter class, stand basal area, number of trees per hectare, country and biogeographical region where the stand was located (Filipek et al., in prep; Feliciano et al., 2025). Each rule pattern included information about the probability of cutting (both thinning and harvesting) , its intensity (e.g. amount of basal area removed from the forest stand) and its shape (e.g. thinning from below or from above, to indicate cuttings of different cohorts of the forest stand diameter distribution). In addition, we applied volume functions for the United Kingdom as a whole due to the lack of Scottish-specific volume functions.

2.   Restoration scenario #1 – Region-specific *Larix* removal

The region-specific *Larix* removal scenario implements current Scottish Government regulations on sanitation felling in *Larix* dominated forests infested with *Phytophthora ramorum*. For any identified infested *Larix* forest, Scottish Forestry, an agency of the Scottish Government and the forestry regulatory body in Scotland, issues Statutory Plant Health Notices (SPHNs) to require the felling of the infested forests and other susceptible *Larix* trees within a 250-meter buffer zone.

To simulate this scenario, in all forests in the western part of Scotland where *Larix* is the predominant species, we applied early harvest to comply with Scottish Forestry SPHNs and to reflect the high threat of *Phytophthora ramorum* infestation in the suitable characteristics of the climatic and soil conditions of these regions. Early harvest was also applied to *Larix*-dominated forests in the southeastern part of Scotland, to reflect the likelihood of the spread of the pathogen in these areas due to their proximity to the heavily affected central region of Scotland. The Larix removal was simulated on a total of 879 plots which represent 65 007 hectares of forest area (5% of total Scottish forest area). The intensely harvested, *Larix*-dominated forests in both the western and southeastern regions of Scotland were then replanted with a mixture of three alternative species. The alternative species were selected based on their suitability to support forest restoration, promote species diversification and increase biodiversity in these areas. The three future-suitable species were identified for each forest using the Ecological Site Classification (ESC) decision support tool that forms an integral part of forest management in private and public forests across the British Isles,

providing forest managers with information on the suitability of over 60 different conifer and broadleaf species. The three site-specific alternative species identified with the ESC tool were ranked based on their suitability in affected *Larix* forests and planted in numbers that reflect their rankings. For the most suitable species the density was 1200 seedlings per hectare. For the second most suitable species, the density was 800 seedlings per ha and 400 seedlings per ha for the third ranked species. According to the ESC tool, the most frequently suitable species for those areas were *Betula, Picea sitchensis*, species grouped as short-lived broadleaves (e.g. *Sorbus*), and other conifer species. As for the *Larix*-dominated forests in northeastern region (total of 302 plots that represent 23 781 hectares of forest area; 2% of total Scottish forests), the forest management followed currently observed harvesting patterns as infestation of *Phytophthora ramorum* is not present in those areas due to the large distance from the infested areas in the central region and climatic conditions (cold and relatively dry) that are unsuitable for the biology of the pathogen.

3. Restoration scenario #2 – Diversification of forest structure

The diversification of forest structure scenario represents management strategies to deviate, when possible, from productive forest approaches. It specifically simulates silvicultural interventions in productive conifer stands, aimed at transforming these forest types along a trajectory from even-structured forests to more complex stand structures. The primary constraint to the management of productive forest stands in Scotland is the risk of wind damage, which can be very high in large parts of the country and as such, it often dictates the choice of silvicultural interventions including thinning. Silvicultural systems such as Continuous Cover Forestry (CCF) are believed to provide some protection against wind damage, and one of the three restoration actions in the Scottish demo in Queen Elizabeth Forest Park (QEFP) involves the conversion of stands that had been planted and managed as even-aged, monospecific conifers, to a target state sometimes referred to as "coniferous CCF". To support this conversion, a combination of thinnings from below and above (as proxy of selective crown thinnings) were employed in selected high-wind risk Sitka spruce forests, covering a total of 28% of total forest area. These interventions aimed to promote the development of trees with larger dbh, opening the stands to encourage natural regeneration, and focusing on retaining seed trees well beyond the end of what would be a typical commercial rotation to further promote regeneration while developing a more diverse stand structure. Because of the marked predominance of Sitka spruce (*Picea sitchensis*) in commercial forestry across Scotland, targeted conversion of even-age and even-structured Sitka spruce stands to coniferous CCF conditions was essential in this scenario to model the increase in the future resilience of Scottish forests. To reflect the approach taken by forest managers in the public forest sector in Scotland, a combination of thinning and harvesting operations were employed to simulate the silvicultural interventions applied in the

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conversion to coniferous CCF. The diversification of forest structure was only applied to the forests where a windiness threshold was not exceeded. The DAMS scores (Detailed Aspect Method of Scoring), a topex-based measure of windiness developed by Forest Research in the late 1990s, are one of the tools most used in the UK forestry sector to help forest management decisions with regards to wind risk constraints. The current approach in the public forest sector is not to thin a stand when the DAMS score is greater than 14. To simulate this scenario, we used this consideration, thus only *Picea sitchensis* dominated forests in locations with DAMS scores below or equal 14 were managed to promote a conversion to coniferous CCF. In total we applied the CCF approach on 4 201 plots, which cover 398 529 hectares of Scottish forest area.

PROJECTION RESULTS

EFISCEN-Space

Growing stock

All 3 scenarios showed a decreasing trend of the growing stock (m³/ha) in the next 30 years (Figure 3). Under baseline (BAU) the growing stock volume loss was the highest after 30 years of simulation (in 2055), in comparison to the region-specific *Larix* removal (Scenario 1) and the diversification of forest structure (Scenario 2) scenarios with differences of 12 m³/ha (Scenario 1) and 11 m³/ha (Scenario 2) respectively. The observed decreasing trend in the growing stock under the baseline scenario was a consequence of many trees reaching harvestable diameter size, which resulted in their harvest and removal from the forest. While, the difference between the two restoration scenarios was mainly due to reforestation measures in forest previously dominated by *Larix* carried out in Scenario 1. As for Scenario 2, selective thinnings that aimed at CCF conversion in high wind risk *Picea sitchensis* forests stimulated growth of trees and occurrence of natural regeneration, resulting in higher volume stocks. Additionally, lowering the intensity of thinnings of larger diameter trees in other *Picea* dominated forests facilitated higher growing stock volume.
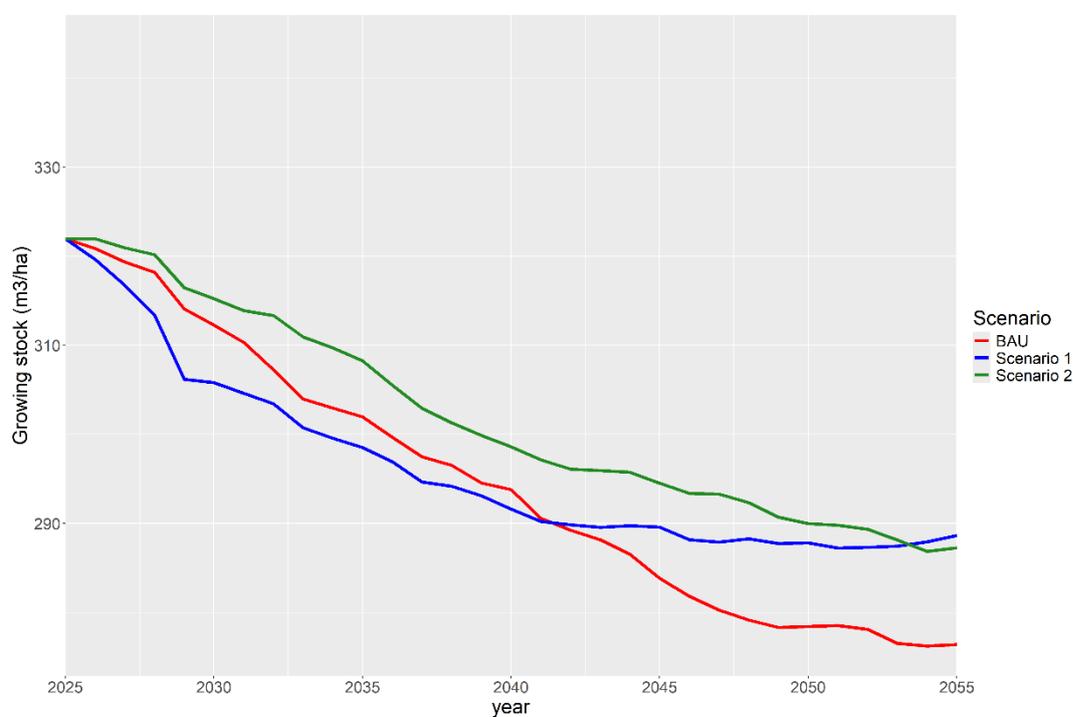

Figure 3. Growing stock (m³/ha) development from 2025 till 2055 for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

Considering that forest grows continuously, for all three scenarios more trees and thus volume was found in the medium size diameter classes with dominant diameter class of 30–40 cm (Figure 4). In addition to the natural ingrowth which was dominated by *Picea sitchensis* in smaller diameter classes (0-20 cm), the reforestation measures with planting future-suitable species e.g. *Betula*, short-live broadleaves, other conifers and Picea *sitchensis*, in forests previously dominated by *Larix* (Scenario 1) resulted in slightly higher volumes in the diameter classes 10-20, 20-30 and 30-40 cm (increased by 2.2 m³/ha, 3.0 m³/ha and 2.6 m³/ha, respectively). After 30 years, volume decrease of *Larix* in Scenarios 1 was observed across all diameter classes (overall decrease of 2.73 m³/ha in 2030 in comparison to the baseline), with the highest change of 0.77 m³/ha and 0.67 m³/ha in 40-50 cm and 50-60 cm diameter classes, respectively. As for Scenario 2 where the change of forest management was applied to *Picea sitchensis* forests, the increased volume of the species was observed across all diameter classes, with the highest volume change in the diameter classes 20-30, 30-40 and 40-50 cm (increased by 2.7 m³/ha, 2.3 m³/ha and 1.7 m³/ha, respectively). This positively reflects the development of more complex forest structure of Picea sitchensis dominated forests.
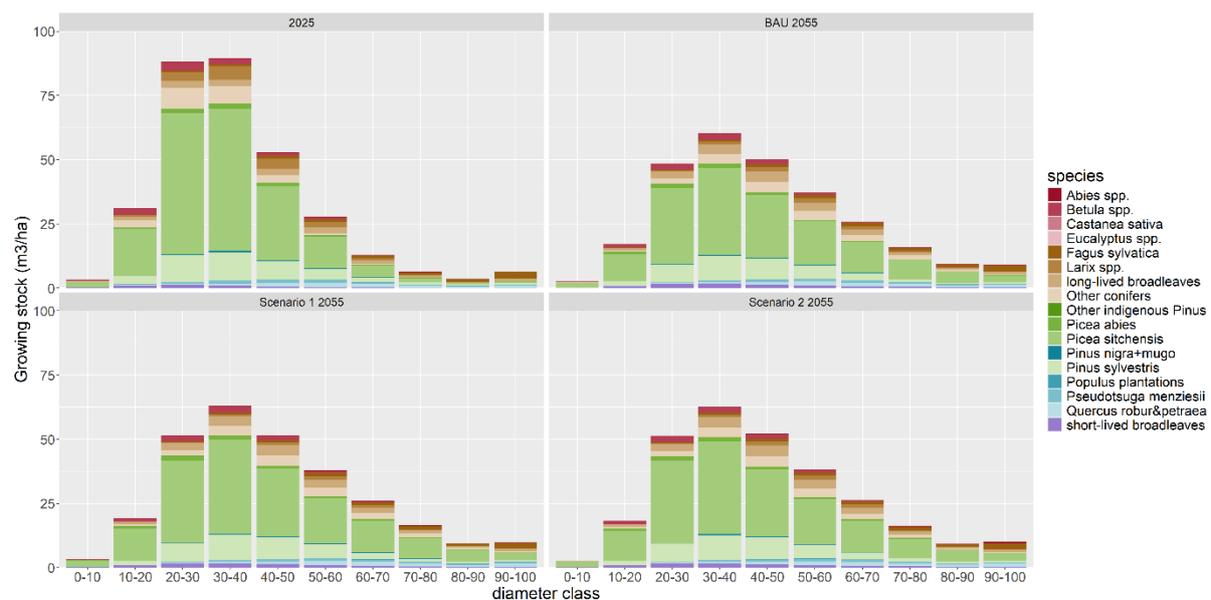

Figure 4. Growing stock (m³/ha) development per species over diameter classes (cm) from 2025 till 2055 for the three different scenarios.

Increment

Under all 3 scenarios the gross increment (m³/ha/year) showed a decreasing trend in the first 15 years as was consequence of harvest activities (thinning and final fellings), which were carried out under baseline scenario, but also in the total removal of *Larix* in certain regions (Scenario 1) and change of forest management in selected *Picea sitchensis*-dominated forest to continuous cover forest (Scenario 2). However, after 15 years (in 2040) forest growth started recovering as a consequence of natural regeneration and replanting measures applied in Scenario 1, while for Scenario 2 this is ascribable to improved growth of larger

diameter size trees and promotion of natural regeneration through the diversification of forest structure. The reforestation measures in Scenario 1 proved to be very effective, with the gross increment after 30 years recovering to a value close to that initially estimated for 2025 (initial gross increment: 8.68 m³/ha/year; after 30 years: 8.13 m³/ha/year).
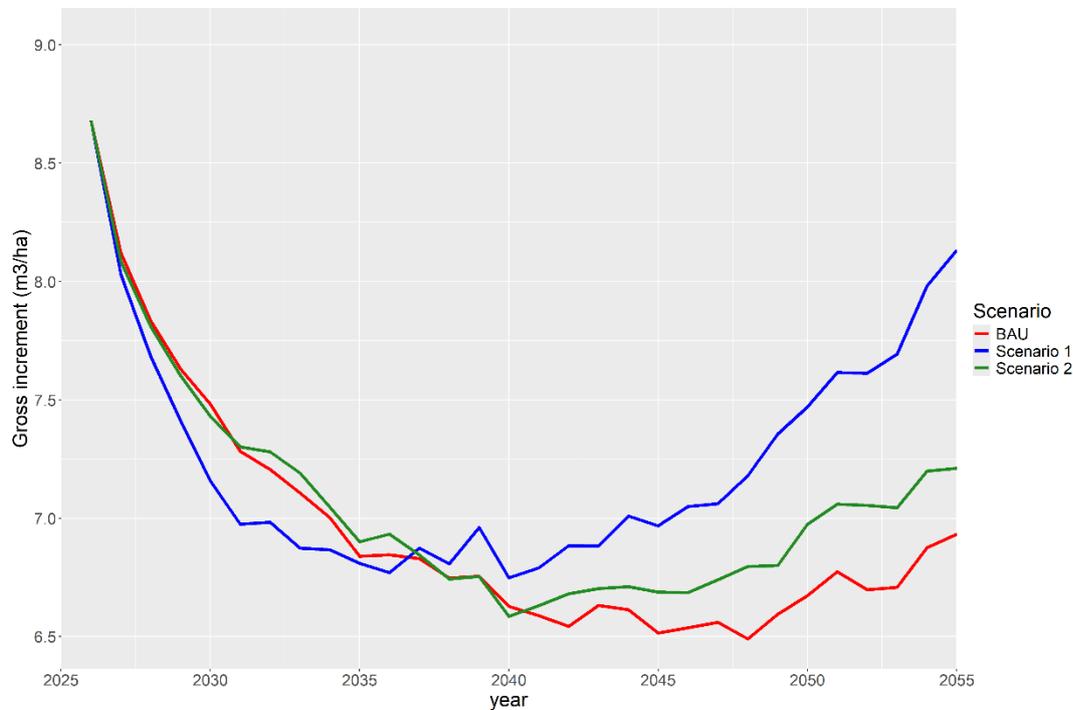

Figure 5. Gross increment (m³/ha) development from 2025 till 2055 for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

Harvest

As trees grew into the harvestable thresholds applied in the scenarios, the wood harvest fluctuated with more harvest observed in certain years e.g. peaks approximately every 4-5 years (Figure 6). In comparison to Scenario 2, the mean annual harvested volume was higher by 0.16 m³/ha/year in Scenario 1.The increase of harvest in Scenario 1 was observed as a results of rapid removal of *Larix* dominated forests infested by *Phytophthora ramorum* and in close proximity to affected stands (difference of 1.77 m³/ha between other scenarios in period 2025 – 2030). As for Scenario 2, the harvested volumes were the lowest due to selective thinnings in *Picea sitchensis* forests (in high-risk wind areas) and lighter cuttings intensity to facilitate their slow conversion from even-structure forests to more resilient continuous cover forest. The applied changes of forest management only slightly affected the amount of harvested wood in comparison to BAU, which still yielded higher volumes from the year 2030 to 2055.
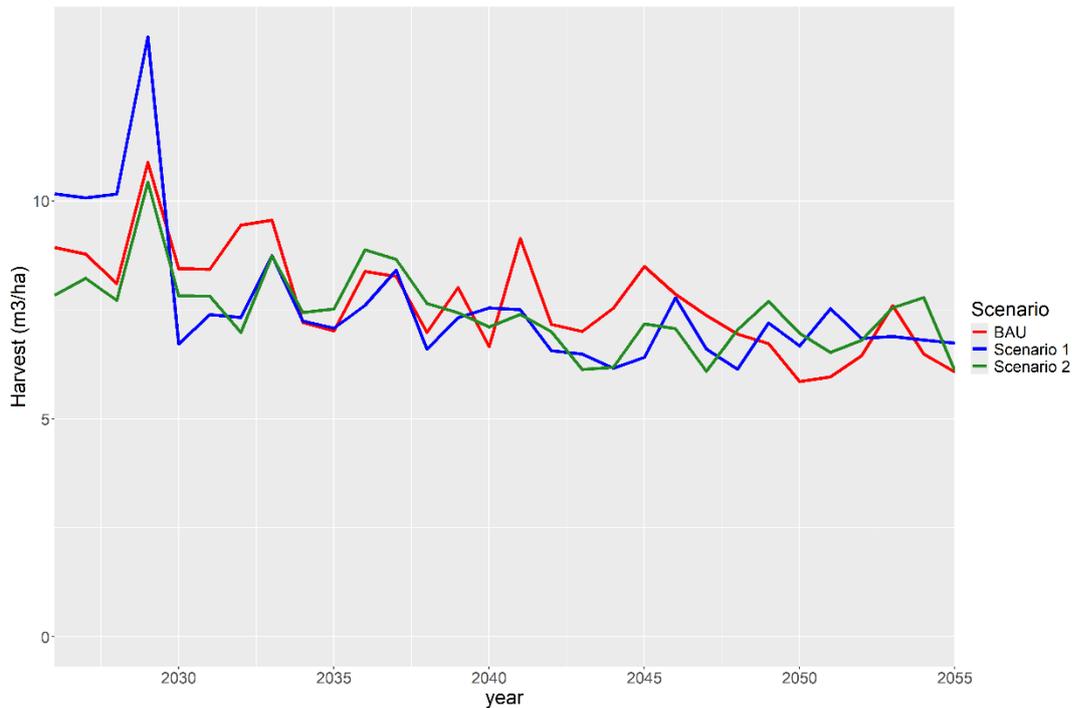
Figure 6. Harvested volume (m³/ha) development from 2025 till 2055 for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

Mortality

Mean mortality showed similar patterns across all three scenarios, with the highest mortality in diameter classes 20-30 and 30-40 cm (1.9 m³/ha and 1.8 m³/ha, respectively) and its gradual decrease with larger tree sizes (Figure 7). Reforestation measures applied in former *Larix*-dominated forest (Scenario 1) resulted in only a very slight increase of tree mortality in the first diameter class (0-10 cm) in comparison to BAU. These slight increase in mortality was caused by self-thinning and competition for space between smaller sized, planted trees of *Betula*, *Picea sitchensis*, species group as short-live broadleaves (e.g. *Sorbus*), other conifer species and some natural regeneration that occurred spontaneously.
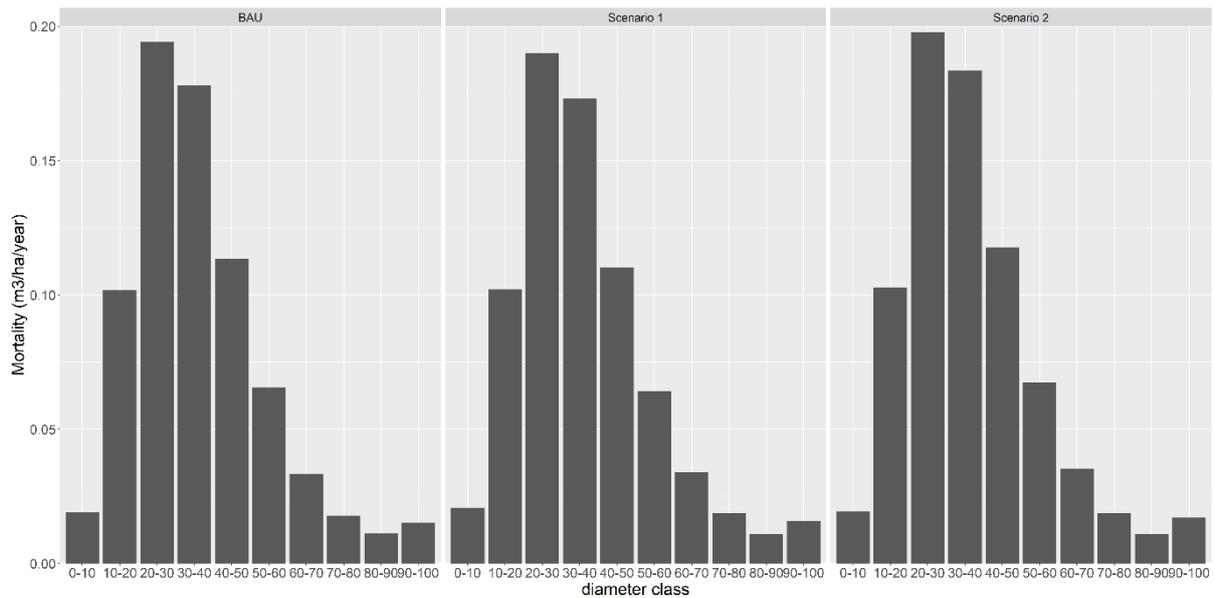
Figure 7. Mean mortality (m³/ha/year) development over diameter classes (cm) for the three different scenarios. Here mortality is estimated as an average of 30-year simulation (from 2025 till 2055).

Gini index

For all three scenarios structural heterogeneity (Gini index) was initially below 0.50 which indicated more homogenous (less complex) forest structure (Figure 8). However, the forest structural diversity increased from the initial 0.42 to 0.54 (for BAU) and 0.53 (for Scenario 1 and 2) within the next 30-years. As in both restoration scenarios the forest structure was affected by changes in forest management (either removal of selected *Larix* forests in first years or slower conversion with a lighter cutting intensity in *Picea sitchensis* forests), the structural diversity was slightly lower (difference of 0.01) in comparison to BAU development trajectory which implied current (more intense harvest). Considering the initial structure of forest in 2025 (Figure 4), larger proportion of trees was present in medium size diameter classes (20 – 40 cm), which resulted in initially higher structural diversity (Gini index) in comparison to both restoration scenarios. However, as the harvested volumes under BAU were higher in period from 2030 to 2055, the development of the structural diversity was hampered and resulted in similar patterns as for restoration scenarios. Under all scenarios structural diversity started slightly stabilising by the end of 2055.
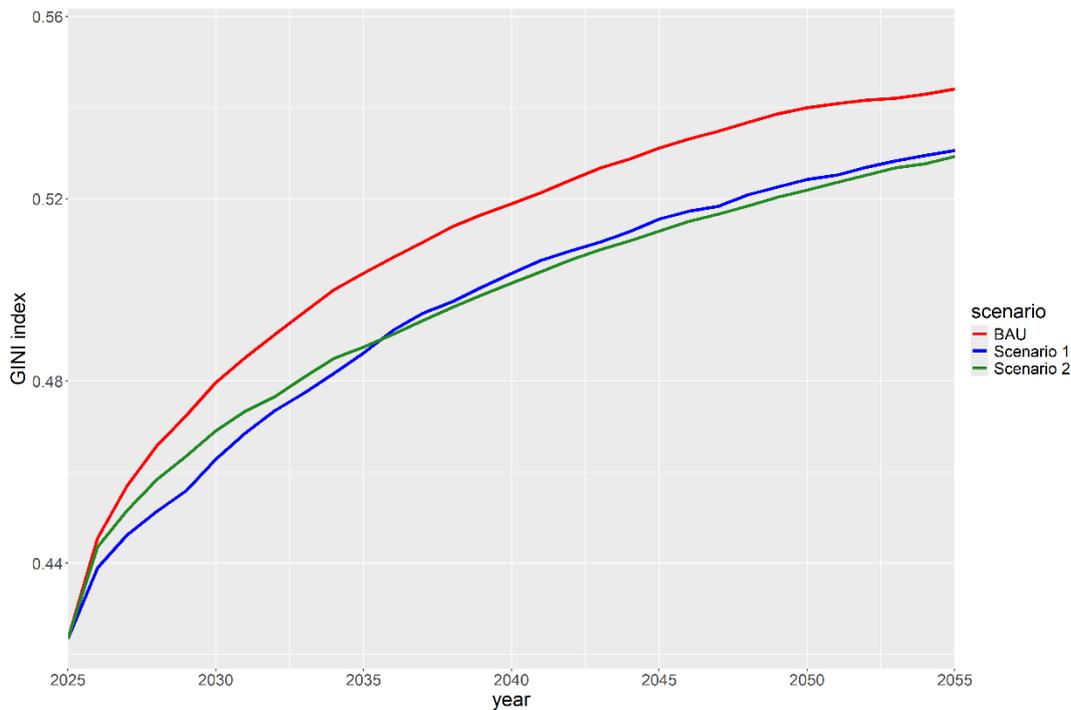
Figure 8. Gini index (inequality index) development for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

Soil organic carbon

As soil organic carbon (SOC) was affected by the forest response to varying restoration scenarios, which were used for spin-up in Yasso15 (soil carbon model), the starting conditions differed for all three scenarios (Figure 9), with the highest initial SOC of 218 ton C/ha under Scenario 1 and the lowest of 208 ton C/ha in BAU. The differences in SOC were mainly driven by varying amount of the litterfall on the forest floor and decomposition, enriching soil carbon pools. More litterfall was accumulated in Scenario 1 due to removal of infested (and under high risk to be infested) *Larix* dominated forests and reforestation measures applied afterwards; this resulted in increase of SOC within first 4 years (SOC increased by 8 ton C/ha). Whereas under BAU, the forest management followed current patterns of harvesting and excluded any additional planting measures. As for Scenario 2, where restoration focused on diversification of forest structure, the results suggested that cuttings stimulated litterfall input to the soil. In general, SOC was sensitive to changes in aboveground biomass showing decreasing patterns until 2050.
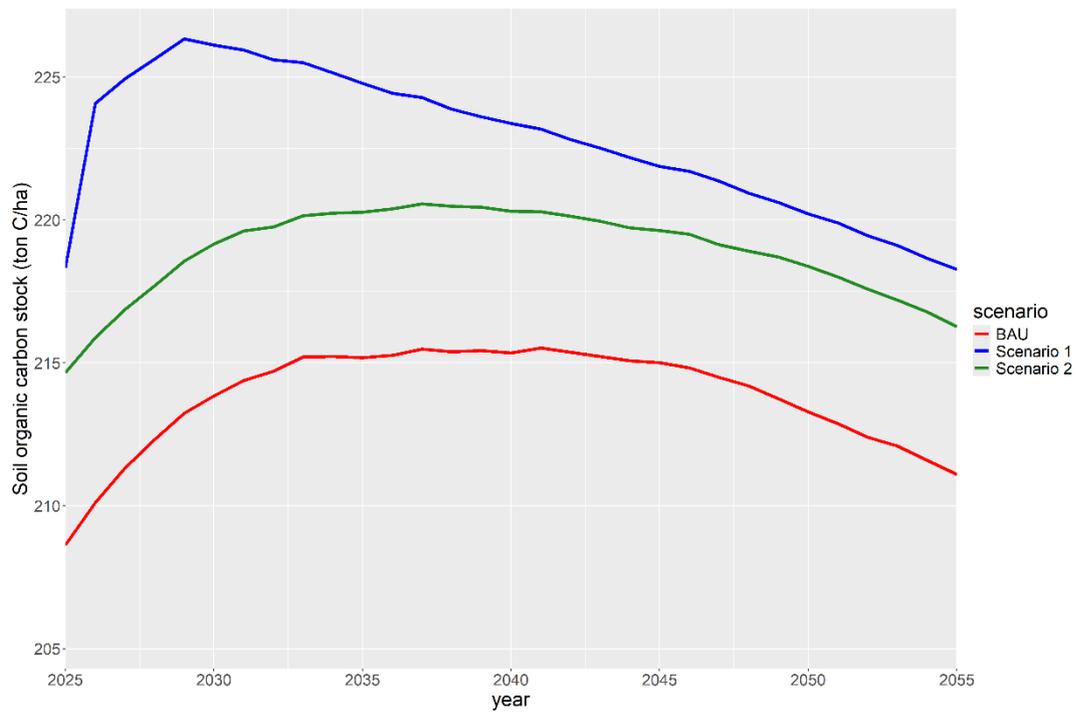
Figure 9. Soil organic carbon (SOC; ton C/ha) development for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2. The SOC was simulated using Yasso15 model (Järvenpää et al., 2018) coupled with EFISCEN-Space.

KEY FINDINGS

In Scotland ,with 1 411 958 ha of forest (represented by 15 523 NFI plots), the removal of infested *Larix* forests and other *Larix* forests in close proximity to affected areas was applied on 879 plots (65 007 ha; 5% of total forest area). Meanwhile, the structural diversification of *Picea sitchensis*-dominated forests was carried out on 4 201 plots (398 529 ha; 28% of total forest area). Therefore, the restoration measures in both restoration scenarios were applied only to selected forests that were either highly affected by spread of *Phytophthora ramorum* or targeted for conversion to coniferous CCF.

Key finding #1

Removal of *Larix*-dominated forests infested with *Phytophthora ramorum* and other *Larix* forests in close proximity to affected areas (Scenario 1) resulted in an increase in harvested volumes during the first 4 years. However, due to the applied reforestation measures (such as planting of more future suitable species), the gross increment volume recovered from 7.16 m^3/ha/year in 2030 to 8.13 m^3/ha/year by 2055).

Key finding #2

Although there is a general decreasing trend in growing stock and harvested volumes, the structural diversification of Picea sitchensis-dominated forests (Scenario 2) resulted in higher growing stock volumes. This was because more trees were present in medium to large diameter classes (20–50 cm) and the structural diversity index increased to 0.53, which could lead to improved resilience of the forests in the next 30 years.

Key finding #3

Reforestation measures in formerly *Larix*-dominated forests had a positive effect on the development of soil organic carbon (SOC) stocks, which were the highest across all scenarios (218 ton C/ha in 2055). Similarly to the diversification of *Picea sitchensis* forests (Scenario 2), the removal of infested *Larix* and subsequent reforestation measures resulted in increased structural diversity of forests over the upcoming three decades.

RECOMMENDATIONS

Takeaway #1

Reforestation measures that support improved forest resilience, such as planting future-suitable species, enhance the development of forest resources (e.g., growing stock volume) and forest structural complexity. These planting measures also allow for faster recovery of forest growth and help sustain stable harvest levels in the long-term.
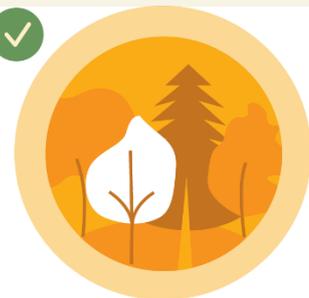
Takeaway #2

Conversion of even-structured forests to coniferous continuous cover forestry (CCF) in the high-risk wind areas, positively affects the development of a more complex forest structure, resulting in higher growing stock volumes in upcoming 30 years.

Takeaway #3

To maintain the development of forest resources and structural diversity, forest management need sto consider both suitable cuttings intensities and (re)planting measures that facilitate forest recovery after harvest. At average restoration costs of 6 000 Euro/hectare (see Scottish workplan v2.0), the total costs of the 463 536 hectare would amount to 2.78 billion Euro in total over the coming decades.

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Takeaway #4

Graduate and subtle restoration activities are difficult to monitor and prove their effectiveness, especially when implemented on only a small part of the forest to maintain sustainability.

Takeaway #5

Forest development is a very long process, taking at least 100 years. Therefore, assessing the effectiveness of management changes and restoration activities requires a long-term perspective.

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