



FORWARD PROJECTIONS

SPAIN



SUPERB
Upscaling Forest Restoration



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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 Forest restoration goals in Europe may not always align with those of historical reference forests, as climate change increasingly makes such restoration unfeasible.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 advise on successful measures that could support the upscaling of restoration initiatives.

This Spanish projection report is part of the deliverable D6.5 on projected ecosystem data. The forest development under varying restoration scenarios was projected for the upcoming 30-years, till 2055, using the EFISCEN-Space and FastTrack models.

The models' projections showed that (1) planting density strongly affects the CO₂ capture in the restored forests, (2) specific tree species contribute differently to the total carbon capture of a forest. To optimise CO₂ capture, in addition to species selection, it is also important to consider trait differences (e.g. wood density), growth patterns, and the environmental conditions of the site, (3) underplanting measures support the improvement of forest resources and structural complexity in the upcoming 30-years, (4) improving forest resilience to fire by intensifying forest management might not benefit development of forest resources, however it will make forests less prone to disturbance, (5) the 483 802 hectare of forest restoration area may cost around 1.45 billion Euro (at average hectare costs of 3 000 Euro; see Spanish workplan v2.0).



DEMO INFORMATION

Castilla y León is the largest autonomous community in Spain. Nevertheless, it is sparsely populated and suffers from severe rural abandonment. On the other hand, after decades of decline, brown bear populations are recovering and expanding. In many cases, the spreading of brown bears is restricted by a lack of corridors among suitable areas or by clashes with rural populations and their activities. Rural population aging and abandonment of traditional activities have led to increased forest cover, which in turn affects the strength and complexity of forest fires.

The region's topography has significantly influenced human settlement and land utilization patterns. Mountainous areas are characterized by a blend of forestry, extensive livestock farming, and historical mining activities, shaping the landscape's rugged charm. On the other hand, the valleys thrive with agricultural land, with El Bierzo emerging as a viticultural haven, celebrated for its native grape varieties. Furthermore, the region's chestnut production, deeply ingrained in the forest landscape, adds to its agricultural diversity and economic significance.

The dynamic interplay between rural abandonment and evolving land use practices has presented both opportunities and challenges for landscape restoration. Efforts to combat landscape homogenization and mitigate forest fire risks are underway through targeted reforestation initiatives. These initiatives aim to restore forest cover, enhance ecological connectivity, and create habitats suitable for vulnerable species like the Cantabrian brown bear (*Ursus arctos*). Achieving these goals requires a multifaceted approach, encompassing changes in forest management practices, habitat enhancement strategies, and community engagement efforts.





Figure 1. Landscape and internal appearance of *Quercus pyrenaica* dominated forests

The current restoration focuses on interventions in the oak forests (*Quercus pyrenaica*) where a lack of management (caused by rural abandonment) is the most common practice due to the great extension and its scarce profitability (Figure 1). Restoration activities are implemented through forest management in areas where brown bears are present or where the habitat is suitable for them (such as fruit-bearing plantations), around villages (chestnut plantations), and in high fire-risk areas (e.g., thinning operations and the creation of fuel breaks)). As a result of these practices, the downturn of the forest fuel load help with the contraction of the forest fire intensity, the fruit-bearing plantations provide suitable corridors for bears, and chestnut plantations become a supplementary economic pillar for rural populations.

MODEL DESCRIPTION

EFISCEN-Space model

EFISCEN-Space is an empirical European forest model that simulates the 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 as 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 trees, species composition, Gini index, deadwood).

FastTrack model

The FastTrack model was developed by Land Life to provide locally accurate CO₂ accumulation forecasts of mixed species planted reforestation projects across the globe. The model is an extension of the IPCC Tier 2 approach Eggleston et al (2006) with crown competition and tree density dynamics allowing forecasting of carbon capture of planting

configurations including planting, direct seeding and combinations thereof. A full description of the FastTrack model is presented in Kramer et al. (2024).

The Tier 2 methodology used in FastTrack to calculate CO₂ capture involves a step-by-step multiplication approach. First, stem volume increment is multiplied by wood density to obtain stem biomass increment. This is then multiplied by shoot-to-stem ratio to obtain above-ground woody tree biomass increment, followed by its multiplication by root-to-shoot ratio to obtain below-ground woody tree biomass increment. The resulting total biomass is transformed with the wood carbon fraction to obtain tree carbon increment. Then, the tree carbon increment is translated into CO₂ capture by using the CO₂-to-carbon ratio. Finally, tree density was divided by 1000 kg/ton and summed over the tree species to obtain total CO₂ capture in tons per hectare. The different tree components are calculated in FastTrack to compare them with observations in the calibration process.

As crown competition was added to the IPCC Tier 2 approach, the assumptions in FastTrack are that (1) the maximum individual tree stem volume growth is attained when a species reaches its full canopy size, (2) maximum stand growth is reached when full canopy closure is attained.

To obtain high local accuracy, site-dependent, species-specific parameter values are estimated through calibration to representative local data. For that, the National Forest Inventories (NFIs) data is used and filtered according to the environmental conditions of the study site. The aim of the calibration is to determine parameter values such that unbiased forest growth is projected by FastTrack. See Kramer et al (2024) for the technical details of the calibration. These site-dependent, species-specific parameters are: maximum stem volume increment, maximum crown radius increment and maximum crown radius. Site-independent, species-specific parameters such as carbon fraction, wood density are obtained from the scientific literature and scientific databases including TRY (Kattge et al 2020), the Global Wood Density database (Zanne et al, 2009).

The FastTrack model is embedded in a graphical user interface that allows for the selection of representative NFI sites, and subsequent calibration and projection. The selection process is based on both geographic and environmental distance between the NFI site and the planting site, taking into account mean annual temperature (MAT), mean annual precipitation (MAP) and optionally soil classification, slope and aspect.

SCENARIO DESCRIPTION

EFISCEN-Space scenarios

For the baseline and two restoration scenarios we used the subset of Spanish NFI-3 (1997 – 2007) measured in four provinces León, Burgos, Palencia and Zamora (Figure 2).

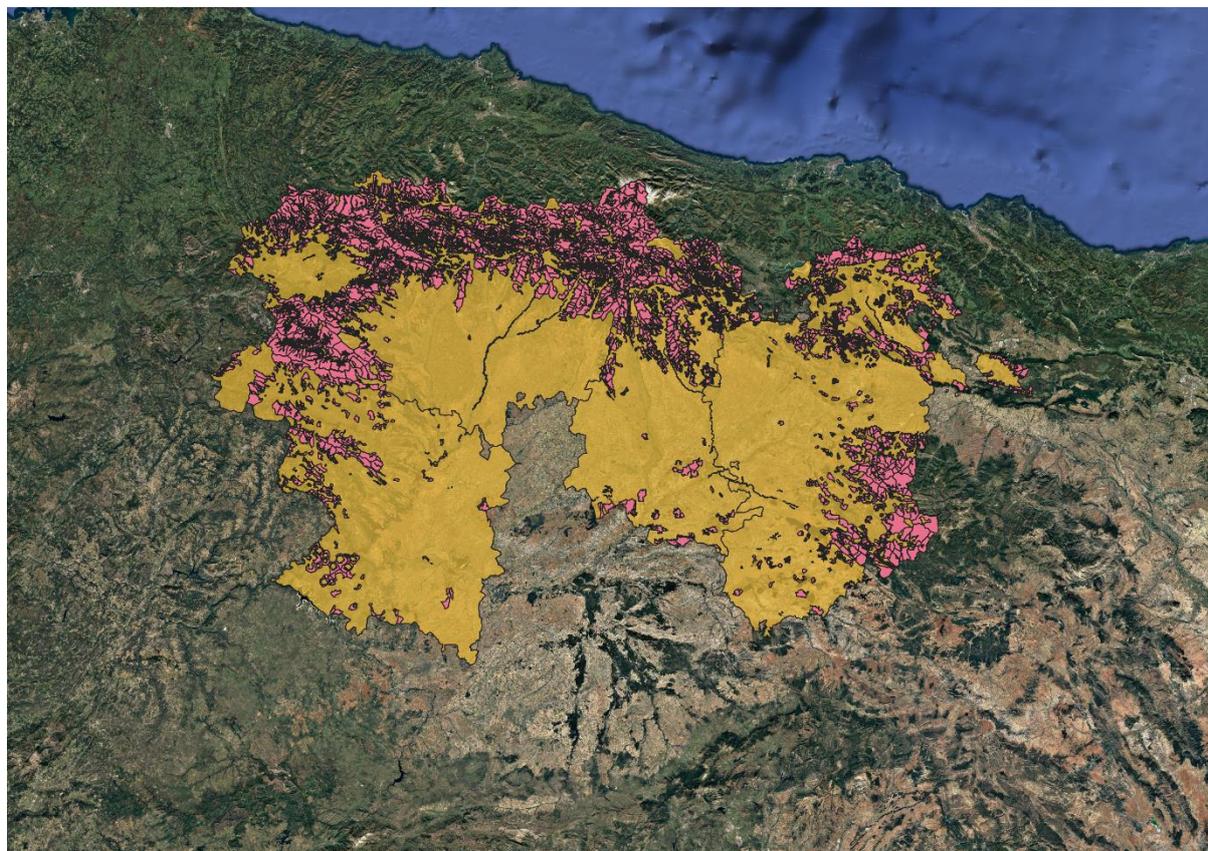


Figure 2. Map of Spanish demo includes large demo area (yellow) and MUP-public use forests where restoration measures can be upscaled (pink).

In total, we simulated 6 099 plots which represented 1 354 268 ha of forest area (8% of total Spanish forest area). As the model was initialized on the latest processed NFI data, the model was first simulated to year 2025 with current observed harvest rule patterns to account for the forest development until 2025 (Figure 3). Then the state of the forest in 2025 was used to re-initialize and simulate demo 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-

LR). To represent forest dynamics, dynamic ingrowth and mortality were applied to all scenarios.

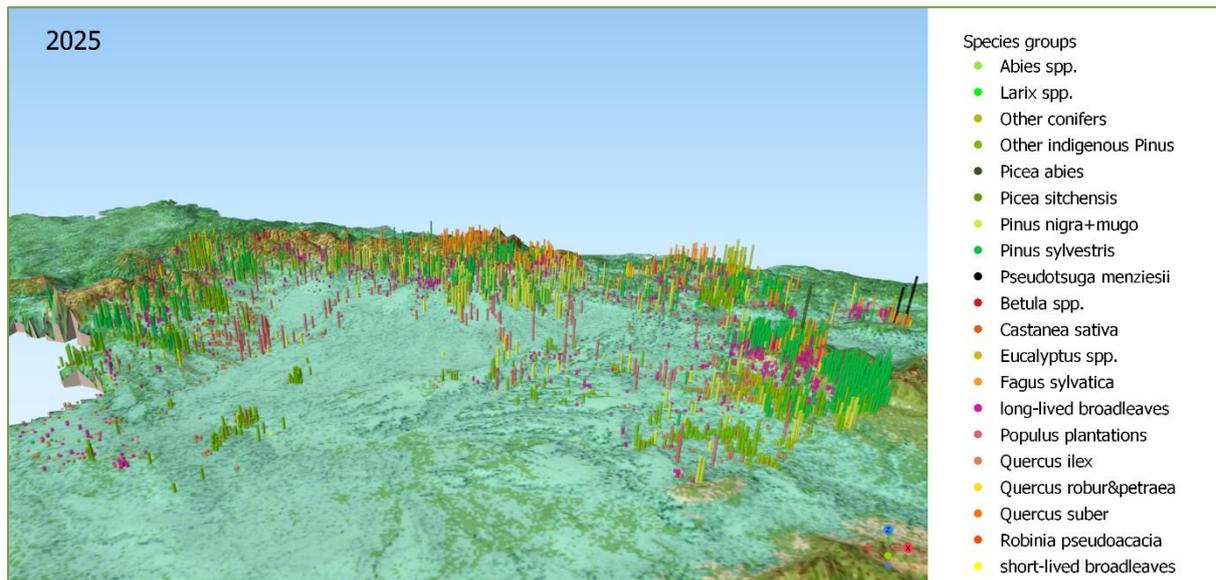


Figure 3. Map of initialized NFI plots in Spanish demo, in total 6 099 plots. Colour of the bar represents the initial dominant species or species group per plot, and height of the bar shows the initial growing stock volume (the higher the bar, the larger the growing stock volume).

1. Baseline (BAU)

Baseline (BAU) scenario simulates the development of forest resources under current forest management. The current forest management was defined based on observed Spanish harvest rule patterns from two NFI cycles (NFI-3 and NFI-4). The harvest rule patterns were described by two types of cutting: thinning and final felling. 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 forest stand was located (Filipek et al., in prep; Feliciano et al., 2025). Each rule pattern included information about the probability of cutting, its intensity (e.g. amount of basal area removed from the forest stand) and its shape (e.g. thinning from below or from above, which emphasises cuttings of different cohorts of the forest stand diameter distribution).

2. Restoration scenario #1 – Accompanying species

The accompanying species scenario implements forest management for brown bear conservation. Restoration measures such as planting fruit bearing trees improve the habitat quality and makes it more suitable for brown bears habitat. The selection of suitable tree species is based on native species that are present in the area. However, in many areas, the promotion of these accompanying species is challenging due to the oak forest dynamic related to high capabilities of root resprouting and reoccurring forest fires. In addition,

species such *Sorbus aria*, *Sorbus aucuparia*, *Prunus avium* do not create groups and they occur as an admixture between the dominant forest species. Therefore, this scenario was designed as a result of those parameters, restricted to current and potential brown bear habitats, involving low densities planting with accompanying species within the forest dominated by *Quercus pyrenaica*.

To simulate this scenario, we identified the possible brown bear corridors within the MUP-public use forests where the density of forest dominated by *Quercus pyrenaica* was lower than 500 trees/ha (a total of 469 plots that represent 105 304 ha of forest). In these selected low density forests we underplanted mixture of *Sorbus sp.*, *Prunus sp.*, and *Malus sp.* with density of 800 trees/ha to increase food availability for brown bears and reduce the interactions between bears and human. As a result, we expected that the habitat was ameliorated for holding brown bears, increasing the food availability, and promoting a more diverse forest ecosystem where many other species could benefit from the presence of these accompanying species.

3. Restoration scenario #2 – Improving forest resilience and forest structure

Decreasing forest fire risk

Most common challenge in oak forests (*Quercus pyrenaica*) in Castilla y León are reoccurring fires. The extensive roots resprouting capabilities of *Quercus pyrenaica* creates a dense undergrowth layer which was formerly controlled by cattle grazing (Figure 4). Nowadays, this causes a challenge for forest firefighters due to increased difficulty to access and work on fire extinction. Moreover, it also increases fuel load and creates a perfect ladder to increase the flame height and magnitude of wildfires. Therefore, reducing forest fuel load by using strategic forest management can support the fire extinction tasks, which is easier to execute than modifying the surface fire model.



Figure 4. Sheep grazing on *Quercus pyrenaica* root sprouts (Calvo, 2016)

To simulate this scenario, we identified the areas with high forest fire risk (risk index 4 and 5) within the MUP-public use forests with forest dominated by *Quercus pyrenaica* and *Pinus sylvestris* (total of 570 plots that represents 123 810 ha of forest). The high forest fire risk areas were identified based on Territorial Fire Risk Index (TFRI) map that indicated forest vulnerable to fires and droughts in the region of Castilla y León (Gallego et al., 2024). For the selected forests we increased thinning from below to removal of 50 % of trees in stands dominated by *Pinus sylvestris* and 25 % in stands dominated by *Quercus pyrenaica* every 10 years, assuming that other types of cuttings were conducted in the same way following currently observed harvest patterns. As a result we expected that the modified forest surface and structure decreased the forest fire risk and fire power (flame height).

Improve the valorization of forest products

One of the reasons for the rural abandonment is the absence of opportunities for people to establish and profit in those areas. Vast territories with low (poor) forest management and lack of profitable forest products are of concern for improving local economy. As *Quercus pyrenaica* forest resprouts after fire and are resistant to cattle grazing, it is challenging to establish good quality timber that can be of similar value to *Pinus sylvestris* forests. Therefore, converting these coppice forest into high forest applying [ProSilva criteria](#) aims to improve the valorisation of timber allowing new income sources in the rural areas and facilitating the arrival of population (Figure 5).



Figure 5. *Quercus pyrenaica* stand with high forest structure

To simulate this scenario, we identified the areas within the MUP-public use forests with forest dominated by *Quercus pyrenaica* and *Pinus sylvestris* which are not in high forest risk area (total of 1 182 plots that represent 254 688 ha of forest). For the selected forests, we applied ProSilva management, defined as 10% reduction of canopy cover (reduction of the mean quadratic diameter) in *Quercus pyrenaica*, and 25% in *Pinus sylvestris* stands, with both interventions being applied every 15 years. As ProSilva management criteria put strong

emphasis on applying continuous-cover forestry (CCF) measures, we assumed only thinnings without any final felling. The currently observed patterns of thinning intensities were increased by 10% and 25% respectively.

As a result, we expected that the ProSilva management strategies would support increased timber valorisation of *Quercus pyrenaica* and *Pinus sylvestris*.

FastTrack scenarios

Since FastTrack is designed to simulate the growth of planted forests, the restoration actions modelled for the Spanish demo consist of tree planting. The tree-level simulations are designed with a minimal planting unit of 1 hectare, where for each scenario, the different tree species in the designs are mixed randomly across the area (see Table 1). Besides, the model runs are initialised from a seedling size for the trees.

The model output consists of the CO₂ accumulation over 40 years in tCO₂/ha captured in the alive biomass, and the effective species diversity change (Hill number, $q = 1$). Note that live biomass refers to the biomass of the living trees, meaning that no other carbon pools are modelled (e.g. deadwood, litter nor soil organic carbon).

Table 1. Planting design of the Spanish demo's restoration actions simulated with FastTrack

| Restoration action | Total action area (ha) | Planting density (tree/ha) | Tree species | Composition (%) |
|---------------------------|------------------------|----------------------------|-------------------------|-----------------|
| Sweet chestnut plantation | 5.03 | 156 | <i>Castanea sativa</i> | 100 |
| Enrichment planting | 26.94 | 200, 400, 600 and 800 | <i>Castanea sativa</i> | 10 |
| | | | <i>Prunus avium</i> | 20 |
| | | | <i>Frangula alnus</i> | 10 |
| | | | <i>Sorbus aria</i> | 5 |
| | | | <i>Sorbus aucuparia</i> | 5 |
| | | | <i>Malus spp.</i> | 10 |
| | | | <i>Arbutus unedo</i> | 5 |
| | | | <i>Betula alba</i> | 35 |
| | | | Total | 100 |
| Cover planting | 2.42 | 1600 | <i>Castanea sativa</i> | 5 |
| | | | <i>Pinus sylvestris</i> | 65 |
| | | | <i>Prunus avium</i> | 5 |
| | | | <i>Frangula alnus</i> | 5 |
| | | | <i>Sorbus aucuparia</i> | 5 |
| | | | <i>Malus spp.</i> | 5 |
| | | | <i>Betula alba</i> | 10 |
| | | | Total | 100 |

1. Restoration scenario - Sweet chestnut plantation

About 5 ha are planted with sweet chestnut (*Castanea sativa*). The planting density is of 156 trees/ha and the stands are only composed of sweet chestnut.

2. Restoration scenario - Enrichment planting

For this restoration action, the demo implements 4 different planting densities of broadleaves and fruit-bearing tree species across about 27 ha: 800, 600, 400 and 200 tr/ha. The enrichment planting takes place at different forest stands across the Demo area, some are dominated by conifer species such as *Pinus nigra* and *Pinus sylvestris*, and others are dominated by broadleaved *Quercus pyrenaica* individuals. In any case, the species composition of the planting mix is consistent across different stands and planting densities (see Table 1).

3. Restoration scenario - Cover planting

The cover planting is implemented at a higher planting density of 1600 tr/ha across more than 2 ha. The species mix is mainly composed of *Pinus sylvestris* and broadleaved species (see Table 1).



PROJECTION RESULTS

EFISCEN-Space

Growing stock

Under baseline (BAU) and accompanying species (Scenario 1) scenarios, the growing stock (m^3/ha) increased gradually over time, from the initial $107 \text{ m}^3/\text{ha}$ to $119 \text{ m}^3/\text{ha}$ (BAU) and $124 \text{ m}^3/\text{ha}$ (Scenario 1) respectively (Figure 6). In contrast, in the improving forest resilience and forest structure scenario (Scenario 2) the growing stock increased only slightly in comparison to its initial state (increased to $111 \text{ m}^3/\text{ha}$). These differences are mainly driven by underplanting measures carried out in Scenario 1, which resulted in a higher density of trees, and over time this reflected an increase in growing stock volumes. As Scenario 2 focused on using adaptive forest management strategies to increase the forest resilience and its valorization, the restoration measures required intensification of cuttings in high fire risk areas and exclusion of clear-cutting in other area under ProSilva management; therefore, the steady development of growing stock was strongly affected by applied cutting regimes.

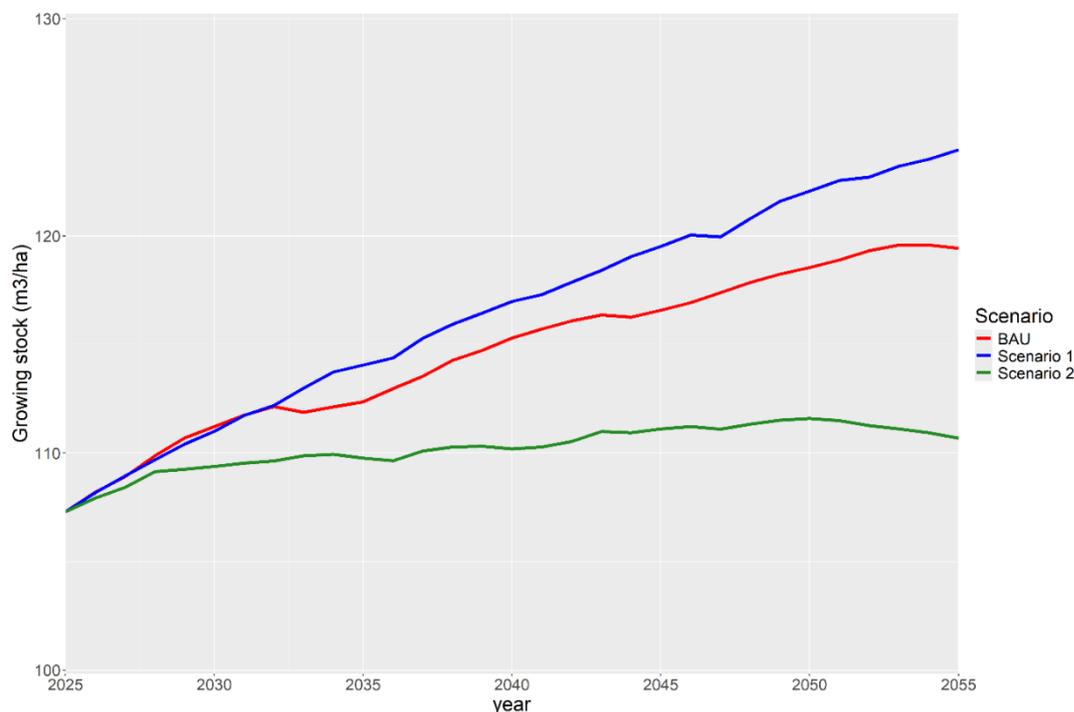


Figure 6. Growing stock (m^3/ha) development from 2025 till 2055 for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

Considering that forest grows continuously, for all three scenarios more trees and thus volume was found in the larger diameter classes with dominant diameter class of 40–50 cm (Figure 7). In addition to the natural ingrowth which was dominated by *Quercus ilex* in smaller

diameter classes (0-20 cm), the underplanting trees like *Sorbus sp.*, *Prunus sp.*, *Malus sp.* (grouped as short-lived broadleaves) in Scenario 1 resulted in a slightly higher volume in the diameter classes 0-10 and 10-20 cm (increased by 0.1 and 0.3 m³/ha, respectively). In Scenario 2, where changes in forest management were applied to selected *Quercus pyrenaica* (grouped as long-lived broadleaves) and *Pinus sylvestris* forests, this resulted in lower volumes of these species in diameter classes from 10 up to 50 cm in comparison to the baseline (BAU) scenario. The differences for both species were relatively small due to only slight changes in forest management intensity and interval length, which were 10 and 15 years in this 30-years model simulation.

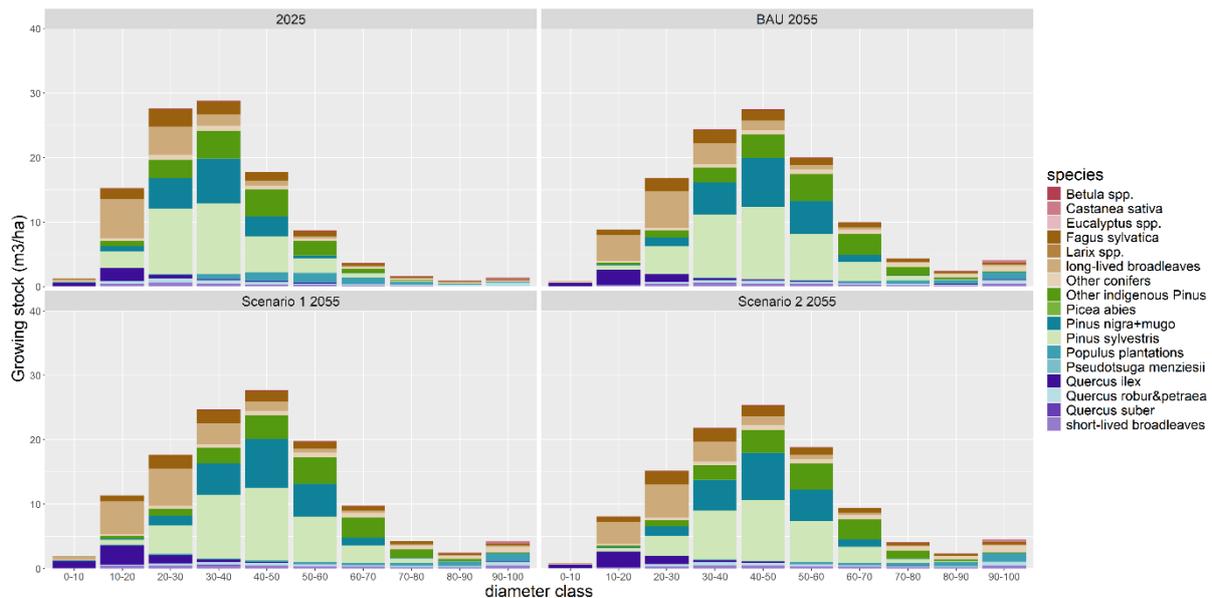


Figure 7. Growing stock (m³/ha) development per species over diameter classes (cm) from 2025 till 2055 for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

Increment

Under accompanying species (Scenario 1), the gross increment volume (m³/ha) was the highest in comparison to other scenarios due to underplanting of the accompanying species (Figure 8). However, the increment development showed slightly decreasing pattern within first 25-years (decreased by 0.10 m³/ha). Whereas for Scenario 2 the decrease of the gross increment was more rapid, similarly to the baseline scenario, from the initial 2.48 m³/ha to 1.91 m³/ha by 2055. As gross increment (tree growth) was affected by harvest and natural tree mortality, the steep decrease observed in 2050 reflected the applied cutting intervals.

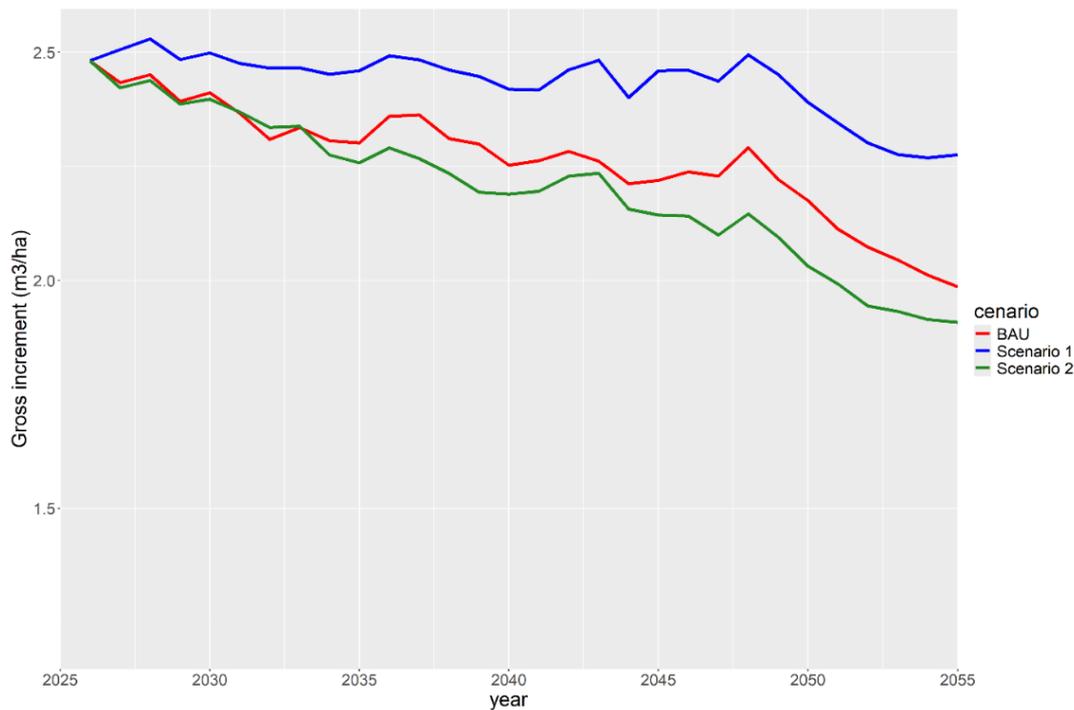


Figure 8. Gross increment (m^3/ha) development from 2025 till 2055 for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

Harvest

As trees grew to meet the harvestable thresholds applied in the scenarios, wood harvest fluctuated with more harvesting observed in certain years e.g. peaks approximately every 10 years in Scenario 1 (Figure 9). In comparison to Scenario 1 and baseline, the mean annual harvested volume was higher by $0.21 m^3/ha/year$ in Scenario 2. Since Scenario 2 applied intensification of forest management measures due to the high fire risk and change from traditional management to CCF, the most volume was harvested within first 15 years and stabilized later to approximately $1.88 m^3/ha/year$. As for Scenario 1, the harvested volumes were similar to those observed in the baseline, although due to higher tree density and volume build-up (when trees reached harvestable volume), harvest increased in certain years.

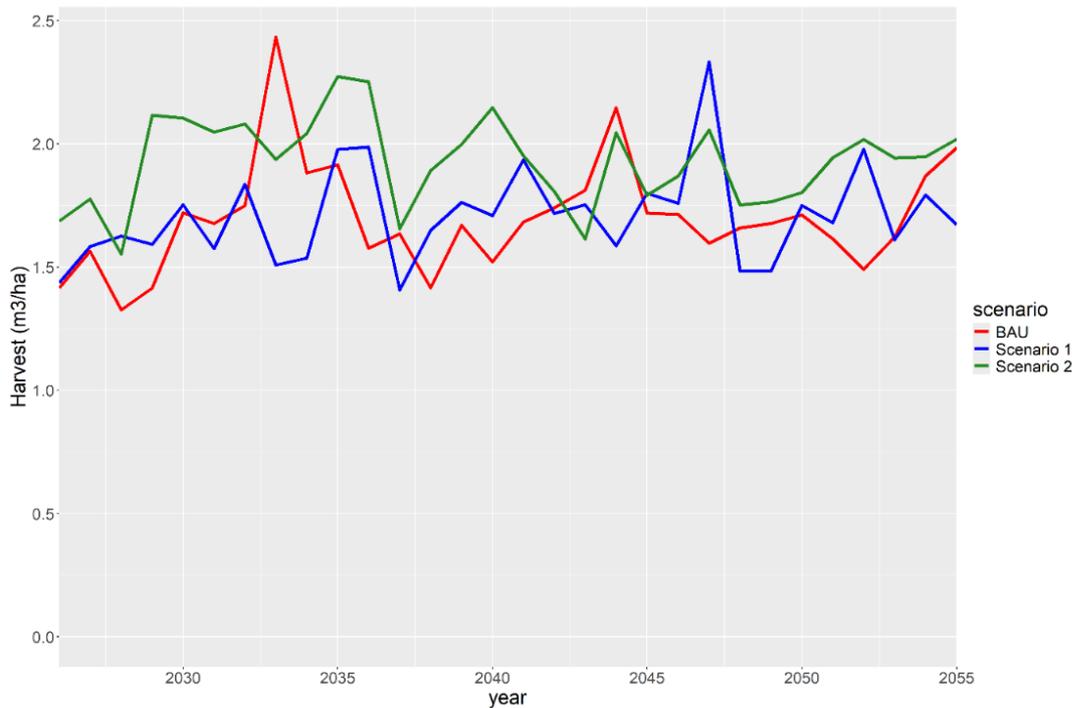


Figure 9. Harvested volume (m³/ha) development from 2025 till 2055 for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

Mortality

Mean mortality showed similar patterns across all three scenarios, with the highest mortality in diameter class 20-30 cm (0.037 m³/ha) and its gradual decrease with larger tree sizes (Figure 10). Although similar patterns were observed, after applying the underplanting measures like in Scenario 1 in which tree densities were higher in the first diameter classes (0-10 and 10-20 cm) the results suggested increase in mean mortality (increased by 0.003 m³/ha/year, in comparison to both BAU and Scenario 2). The increase in mortality was caused by self-thinning and competition for space between smaller size planted trees of *Sorbus sp.*, *Prunus sp.*, *Malus sp.* (grouped as short-live broadleaves).

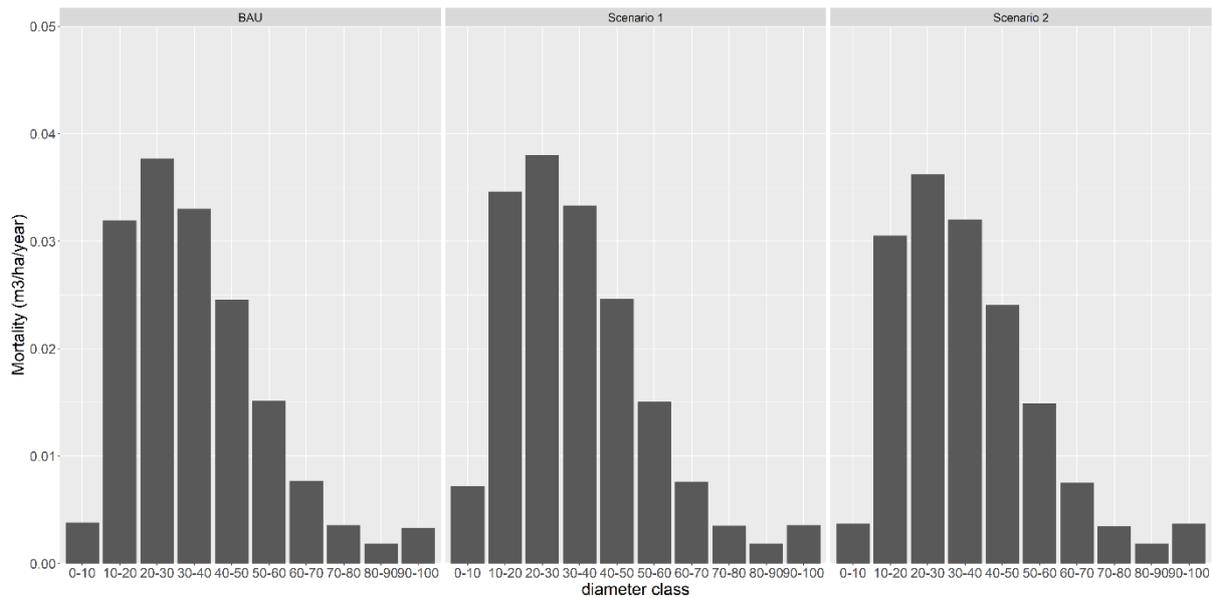


Figure 10. Mean mortality ($m^3/ha/year$) development over diameter classes (cm) for the three different scenarios. Here mortality is estimated as an average of 30-year simulation (from 2025 till 2055).

Gini index

For all three scenarios structural heterogeneity (Gini index) was below 0.50 which indicated more homogenous (less complex) forest structure (Figure 11). Under Scenario 1, where underplanting measures were applied, forest structural diversity increased from an initial 0.35 to 0.40 within 20-years. However, as smaller size trees were affected by other forest dynamics like growth and mortality the structural diversity began to stabilize slightly by the end of 2055.

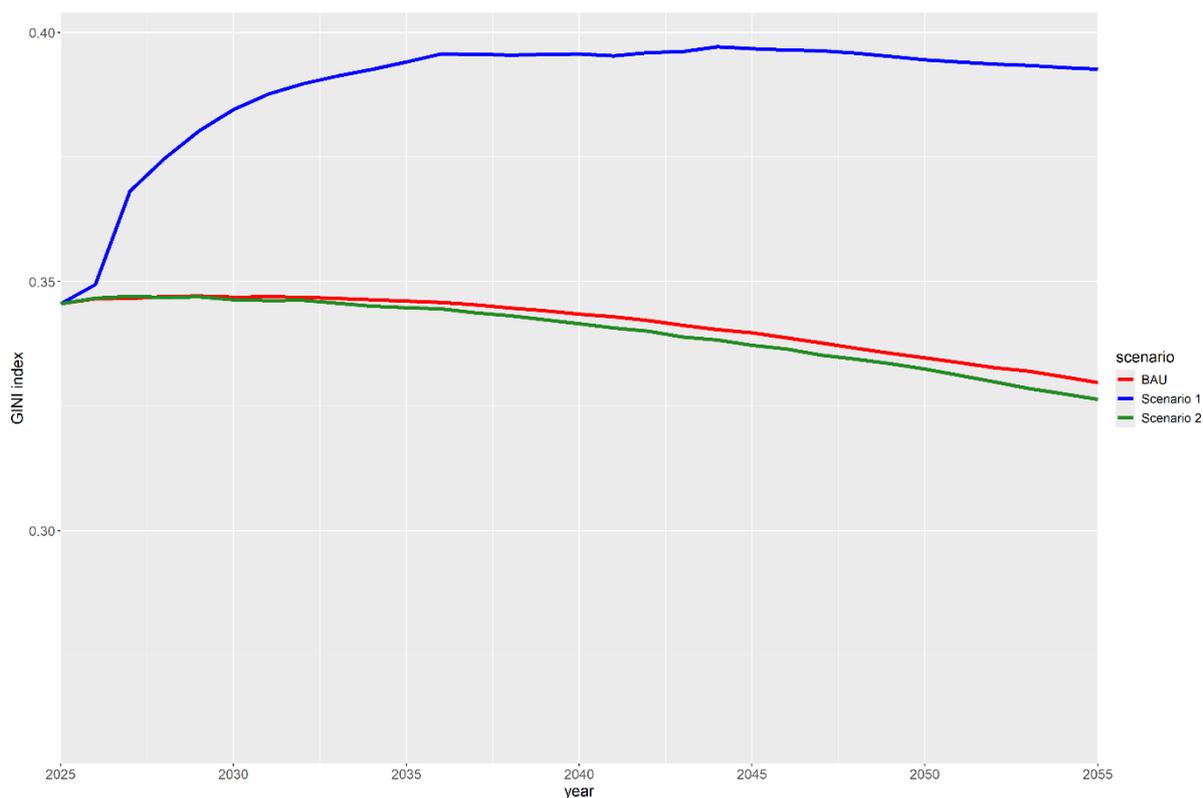


Figure 11. Gini index (inequality index) development for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

Soil organic carbon

As soil organic carbon (SOC) was affected by the forest's 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 12). Scenario 1 had the highest SOC of 150 ton C/ha, while scenario 2 had the lowest of 135 ton C/ha. The differences in SOC were mainly driven by the varying amount of the litterfall that fell on the forest floor and decomposed, enriching soil carbon pools. More litterfall was accumulated in Scenario 1 due to the higher density of trees which were planted to enrich *Quercus pyrenaica* forest stands. Whereas under Scenario 2, more trees were harvested and removed from the forest, resulting in lower amounts of litterfall. In general, SOC were sensitive to changes in aboveground biomass showed the decreasing patterns until 2050.



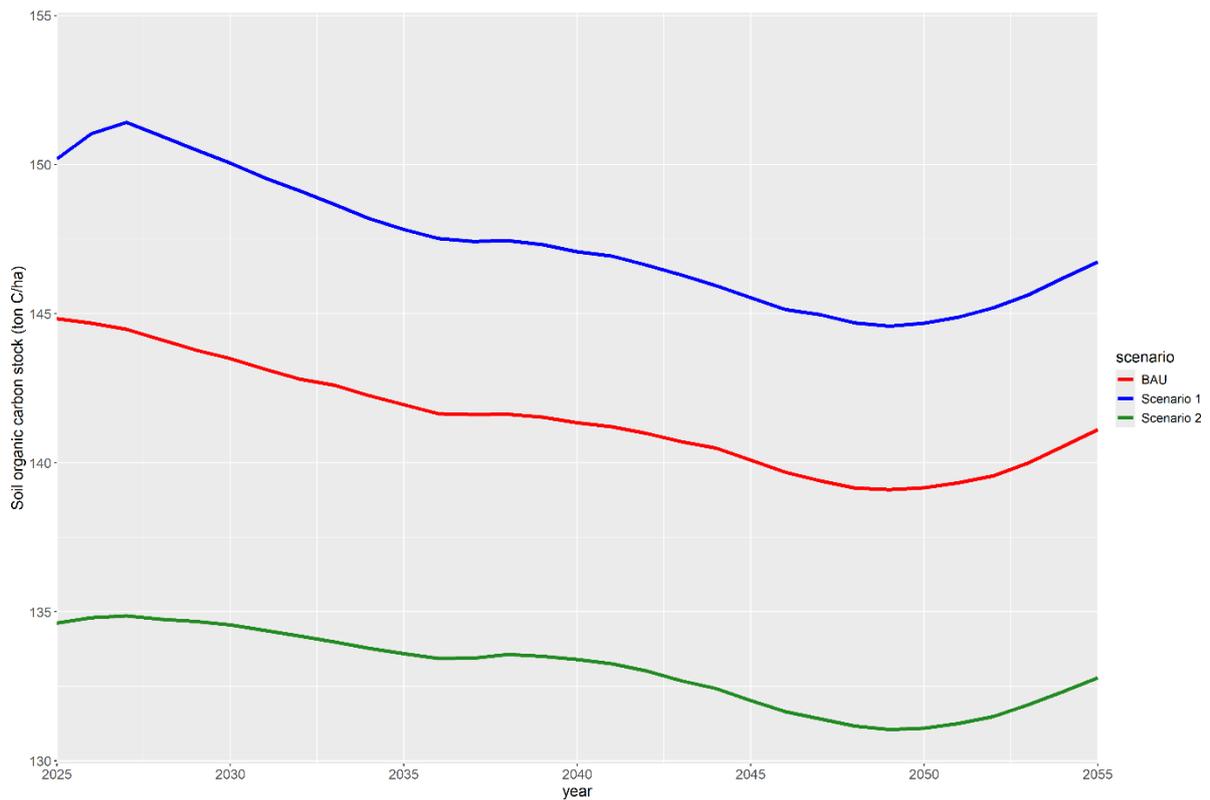
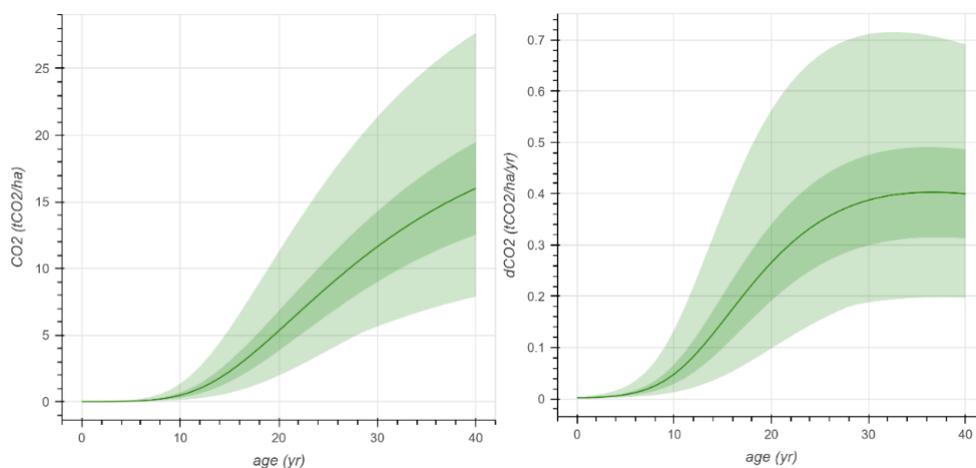


Figure 12. Soil organic carbon (SOC; ton C/ha) development for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2. The SOC was simulated using Yasso15 model (Järvenpää et al., 2018) coupled with EFISCEN-Space.

FastTrack

1. Sweet chestnut plantation

Carbon capture results



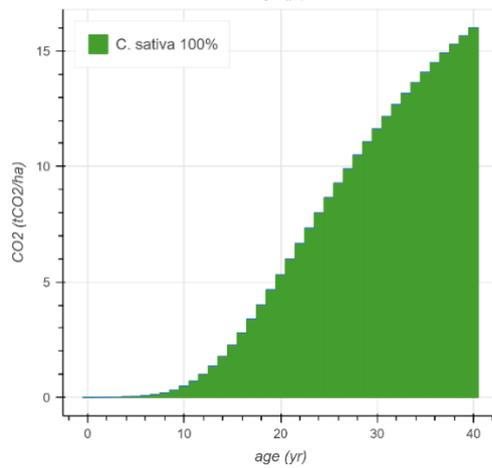


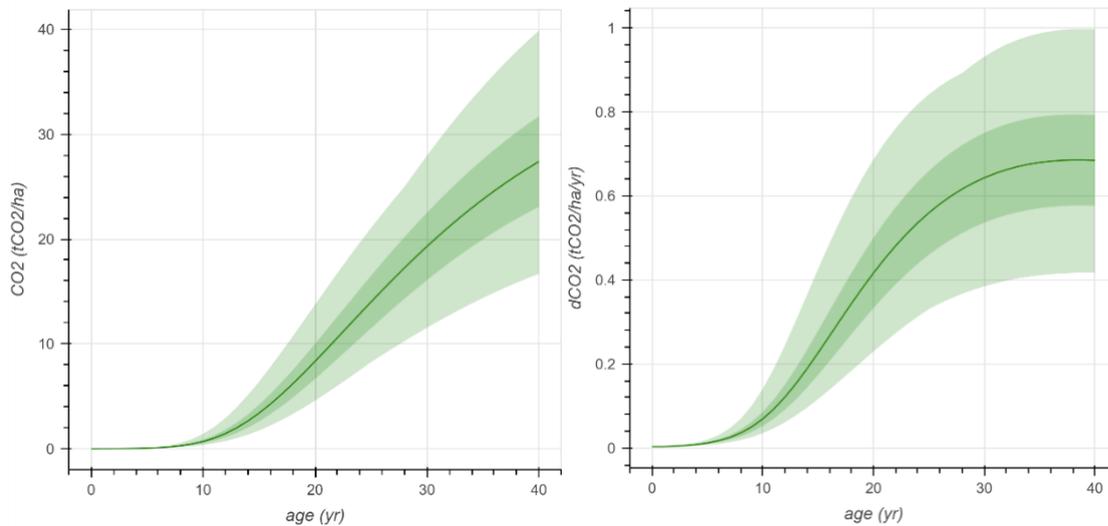
Figure 13. Carbon capture results for the sweet chestnut plantation scenario. On the left, the CO₂ accumulation over 40 years in tCO₂/ha. On the right, the annual CO₂ capture over 40 years in tCO₂/ha/yr. At the bottom graph, the *Castanea sativa*-specific carbon capture contribution of 100%.

The carbon capture of the forest stand composed of only sweet chestnut trees, which are planted at a density of 156 trees per hectare, is estimated to be **16 tons of CO₂ per hectare over 40 years**, or **0.4 tons of CO₂ per hectare on average every year over a 40-year period**.

2. Enrichment planting

Carbon capture results

1. Density = 200 tr/ha



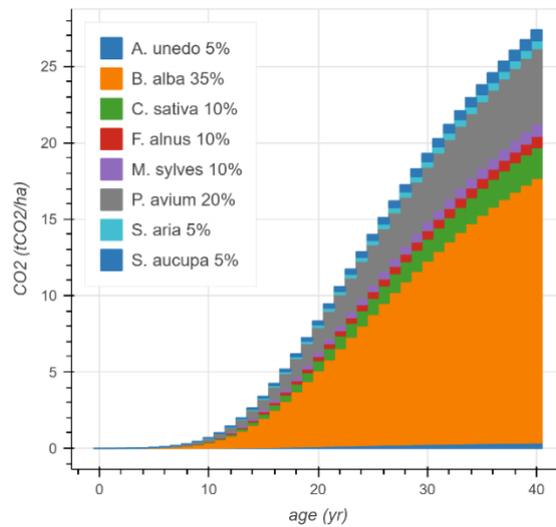
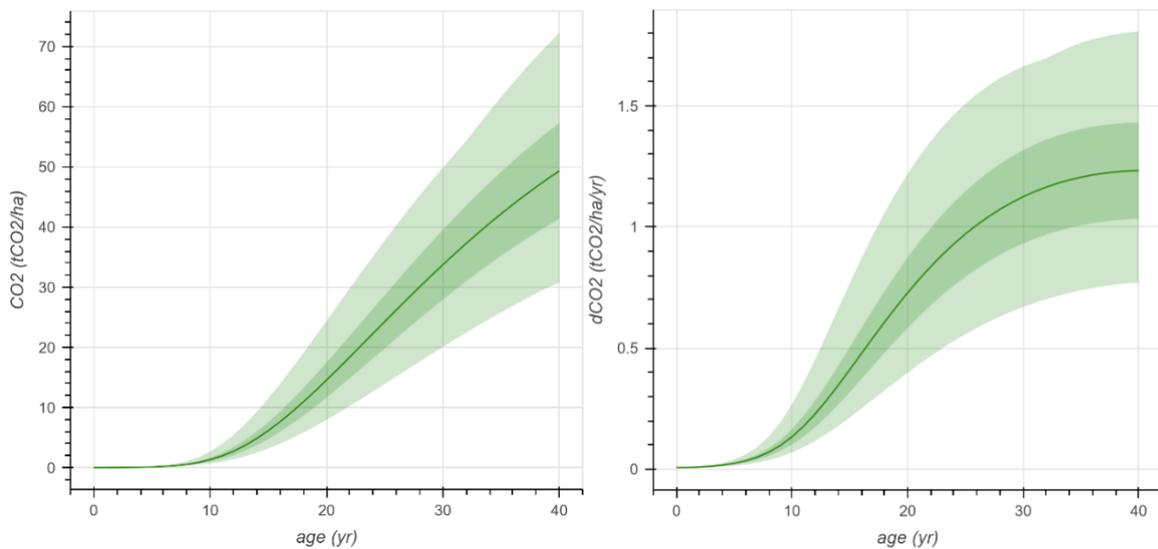


Figure 14. Carbon capture results for the enrichment planting at 200 tr/ha density scenario. On the left, the CO₂ accumulation over 40 years in tCO₂/ha. On the right, the annual CO₂ capture over 40 years in tCO₂/ha/yr. At the bottom graph, the species-specific carbon capture contribution in percentage.

The carbon capture for the enrichment planting of broadleaves at a density of 200 trees per hectare is estimated to be **27.39 tons of CO₂ per hectare over 40 years**, or **0.68 tons of CO₂ per hectare** on average every year over a 40-year period. As shown in the right Figure 14, the species contributing the most to the total carbon capture is *Betula alba* (not only for the high abundance but also for its growth characteristics), followed by *Prunus avium* and *Castanea sativa*.

2. Density = 400 tr/ha



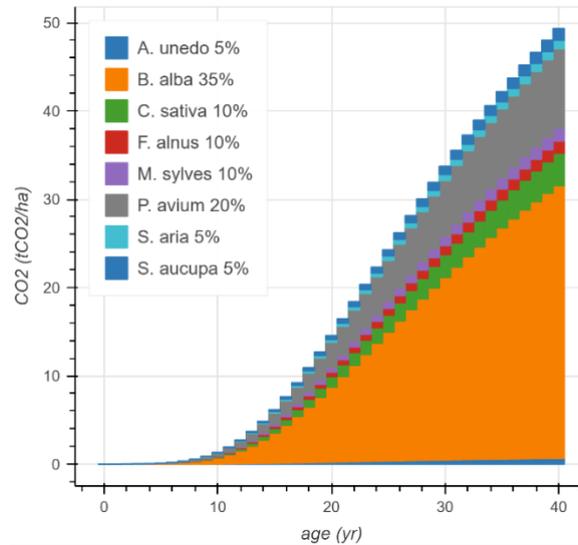
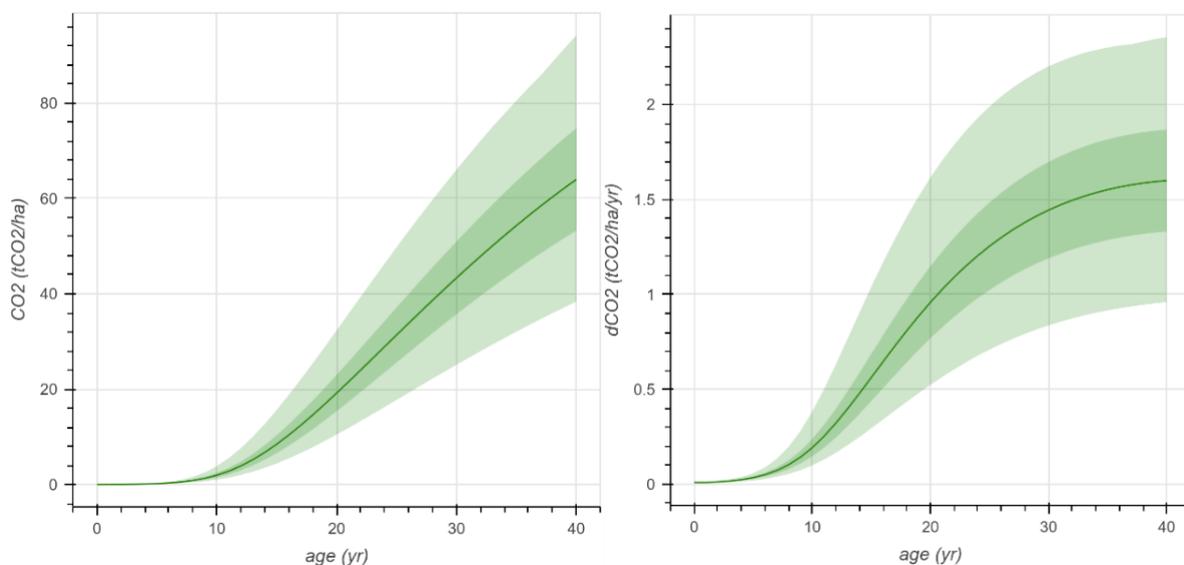


Figure 15. Carbon capture results for the enrichment planting at 400 tr/ha density scenario. On the left, the CO₂ accumulation over 40 years in tCO₂/ha. On the right, the annual CO₂ capture over 40 years in tCO₂/ha/yr. At the bottom graph, the species-specific carbon capture contribution in percentage.

The carbon capture for the enrichment planting of broadleaves at a density of 400 trees per hectare is estimated to be **49.32 tons of CO₂ per hectare over 40 years**, or **1.23 tons of CO₂ per hectare** on average every year over a 40-year period. As shown on the right of Figure 15, the species contributing the most to the total carbon capture is *Betula alba* (not only for the high abundance but also for the growth development), followed by *Prunus avium* and *Castanea sativa*. The relative species contribution is equivalent to the rest of the enrichment planting scenarios since the species mix is the same in terms of percentage of each species. For example, for *Betula alba*, the absolute carbon capture is higher in this scenario compared to the 200 tr/ha scenario because there are more trees, but the share of carbon capture that this species represents out of the total is the same in both scenarios.

3. Density = 600 tr/ha



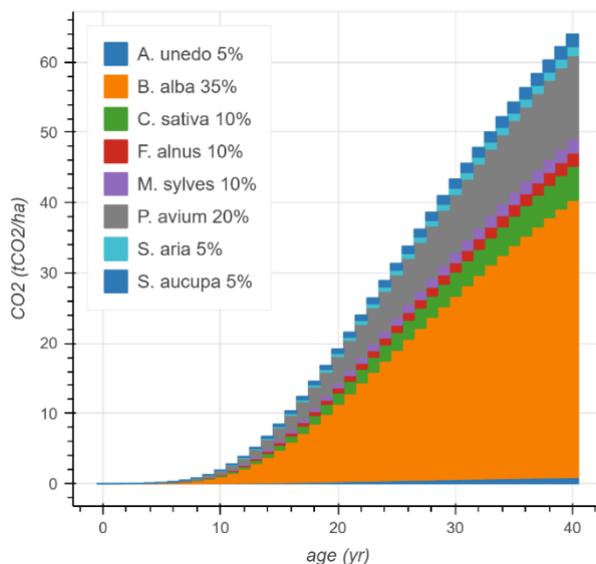
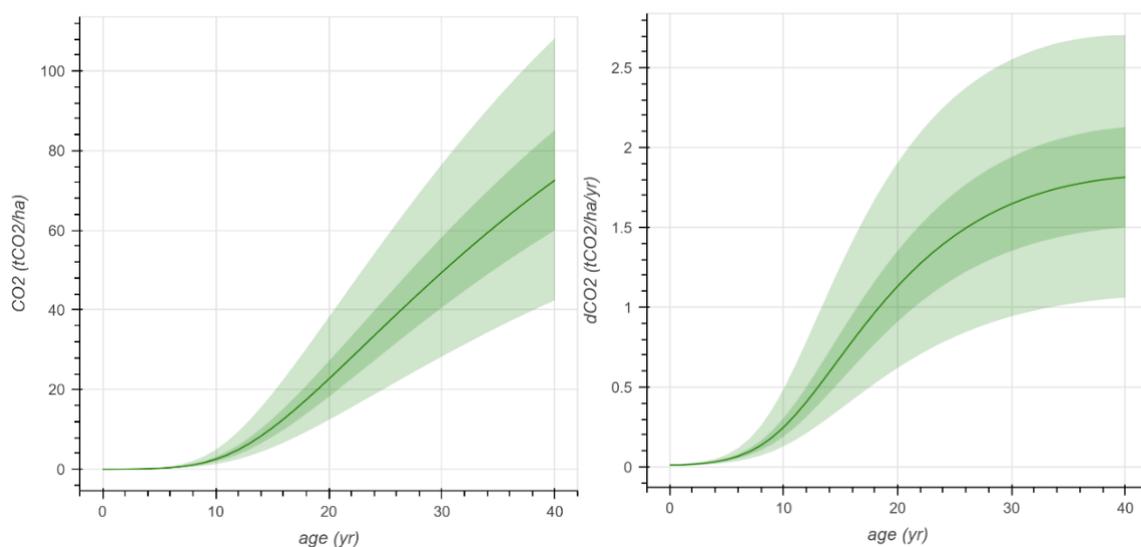


Figure 16. Carbon capture results for the enrichment planting at 600 tr/ha density scenario. On the left, the CO₂ accumulation over 40 years in tCO₂/ha. On the right, the annual CO₂ capture over 40 years in tCO₂/ha/yr. At the bottom graph, the species-specific carbon capture contribution in percentage.

The carbon capture for the enrichment planting of broadleaves at a density of 600 trees per hectare is estimated to be **64 tons of CO₂ per hectare over 40 years**, or **1.60 tons of CO₂ per hectare** on average every year over a 40-year period. As shown on the right of Figure 16, the species contributing the most to the total carbon capture is *Betula alba* (not only for the high abundance but also for the growth development), followed by *Prunus avium* and *Castanea sativa*. As explained in the previous scenario, the relative species contribution is equivalent to the rest of the enrichment planting scenarios since the species mix is the same in terms of percentage of each species.

4. Density = 800 tr/ha



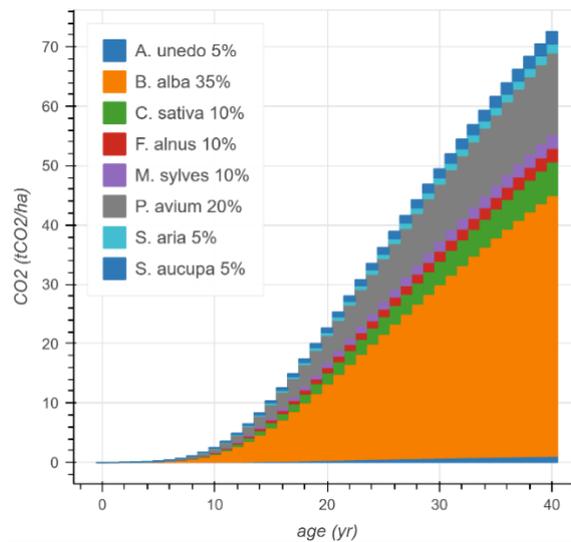


Figure 17. Carbon capture results for the enrichment planting at 800 tr/ha density scenario. On the left, the CO₂ accumulation over 40 years in tCO₂/ha. On the right, the annual CO₂ capture over 40 years in tCO₂/ha/yr. At the bottom graph, the species-specific carbon capture contribution in percentage.

The carbon capture for the enrichment planting of broadleaves at a density of 800 trees per hectare is estimated to be **72.58 tons of CO₂ per hectare over 40 years**, or **1.67 tons of CO₂ per hectare** on average every year over a 40-year period. As shown in the right Figure 17, the species contributing the most to the total carbon capture is *Betula alba* (not only for the high abundance but also for the growth development), followed by *Prunus avium* and *Castanea sativa*. As explained in the previous scenario, the relative species contribution is equivalent to the rest of the enrichment planting scenarios since the species mix is the same in terms of percentage of each species.

Interestingly, and common to all enrichment planting scenarios, *Castanea sativa*, showing the same abundance as *Frangula alnus* and *Malus sylvestris* in the planting mix (all are present as a 10% of the total trees in the mix), contributes more to the cumulative carbon capture at year 40 (green area at the right graphs of Figures 14-17). This is because *Castanea sativa* grows bigger than *Frangula alnus* and *Malus sylvestris* at this site over the projected period. Some of the important factors affecting the species' contribution difference: trait differences (e.g. wood density), growth patterns, or the environmental conditions of the site. Hence, when planning restoration projects where carbon capture is a relevant ecosystem service to assess/enhance, the consideration of the species growth at the study area is crucial for the optimization of the planting designs.

Species diversity results

Given that the four enrichment planting scenarios are composed of the same species mix (same number of species), the results show that the effective species richness increases with increasing planting density (Figure 18). Since the relative species abundance in the planting mix is uneven (ranging from 5 to 35 % depending on the species), the theoretical maximum species richness of 8 (even abundance of the 8 species in the mix) is not attained.

Figure 17 furthermore shows that the relationship between the asymptotic values of the Hill-diversity and the planting density is non-linear. Thus, although the effective species richness increases with density, this effect is less so at higher densities. In other words, although increasing density in an unevenly distributed species mix can compensate for a lower effective species richness compared to an evenly distributed species mix, the maximum value is not reached, based on the densities tested.

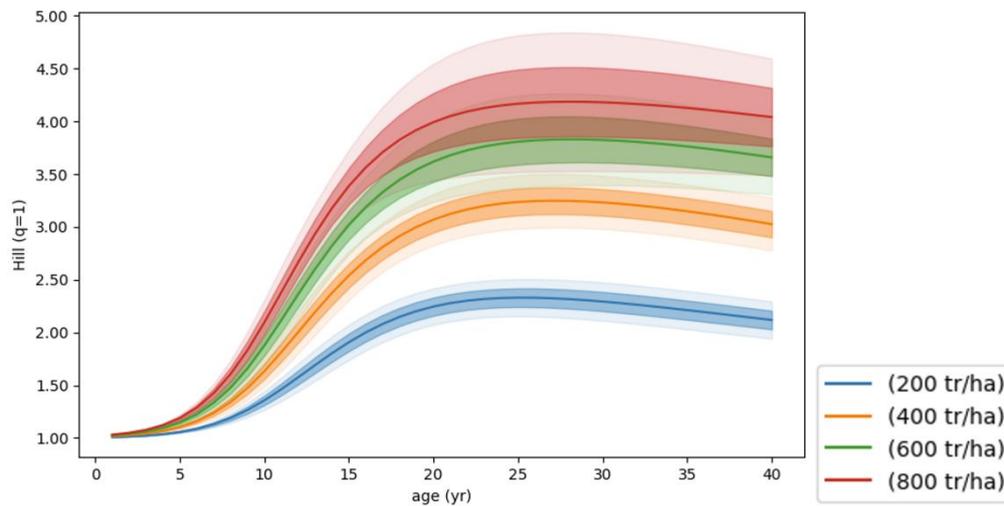
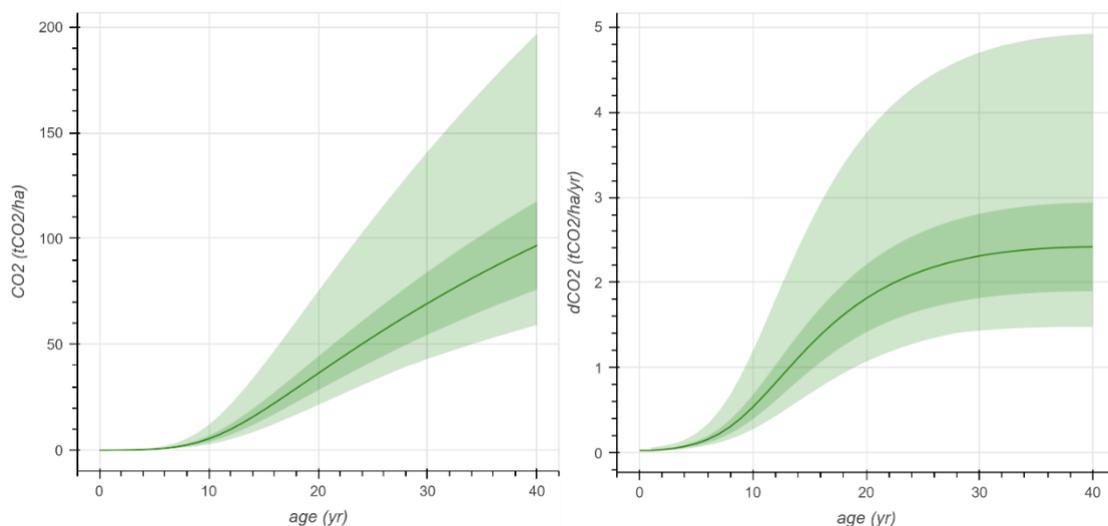


Figure 18. Time evolution of Hill-diversity ($q=1$) for enrichment planting. Representing four scenarios with the same species richness (8 spp.) but with different planting density.

3. Cover planting

Carbon capture results



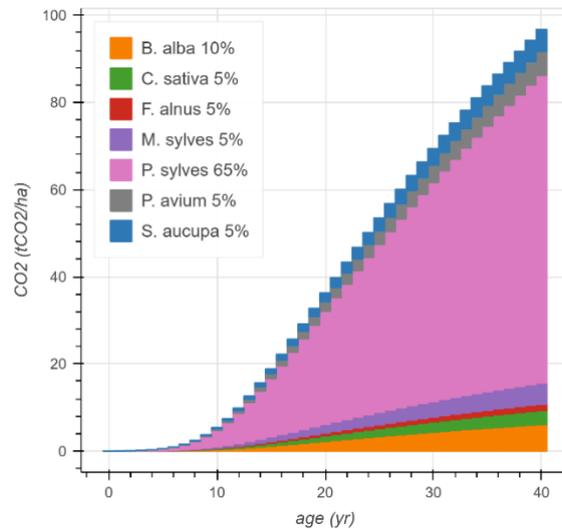


Figure 19. Carbon capture results for the cover planting at 1600 tr/ha density scenario. On the left, the CO₂ accumulation over 40 years in tCO₂/ha. On the right, the annual CO₂ capture over 40 years in tCO₂/ha/yr. At the bottom graph, the species-specific carbon capture contribution in percentage.

The carbon capture for the cover planting of broadleaves at a density of 1600 trees per hectare is estimated to be **96.74 tons of CO₂ per hectare over 40 years**, or **2.42 tons of CO₂ per hectare** on average every year over a 40-year period. As shown on the right in Figure 19, the species contributing the most to the total carbon capture is *Pinus sylvestris*, followed by *Betula alba*.

Species diversity results

In the case of the cover planting, the total number of species is 7, and the tree contribution is skewed toward a single species (65% *Pinus sylvestris*). The Hill number at year 40 shows a lower Hill-diversity as compared to half of the scenarios of the enrichment planting (cf. Figure 18 vs 19, Figure 20). The effective species diversity is ~40% of the theoretical maximum in case of perfect evenness (~3/7).

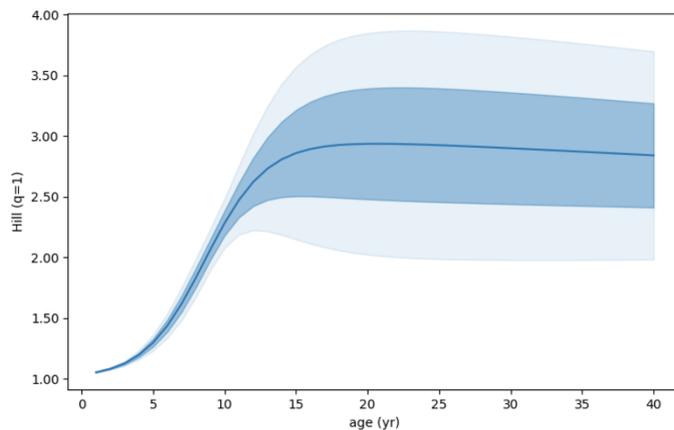


Figure 20. Time evolution of Hill diversity ($q=1$) for the cover planting scenario.

Summary of FastTrack results

The findings of the FastTrack's simulations are summarized in Table 2. A general trend observed across scenarios is that, with an increase in the planting density, there is an increase in the carbon capture per hectare (at the stand level), while the carbon capture per tree decreases. This means that the more the density, the thinner the trees grow, but still resulting in higher cumulative CO₂ capture per hectare.

The consequence of the different planting configurations on the Hill-diversity is that, across scenarios, this metric increases with increasing planting density (see enrichment planting scenarios) but declines with uneven planting tree composition (as in the cover planting scenario composed of mostly Scots pine).

Table 2. Carbon capture projections and Hill-diversity values for the different planting restoration scenarios. The percentage of Hill-diversity value of the theoretical maximum (perfect evenness over all species) is presented between brackets.*

| Restoration action | Planting density (tr/ha) | Cumulative carbon capture (tCO ₂ /ha/40yrs) | Mean annual carbon capture (tCO ₂ /ha/yr) | Cumulative carbon capture per tree (tCO ₂ /tree/40yrs) | Hill (q=1, at t=40) |
|---------------------------|--------------------------|--|--|---|---------------------|
| Sweet chestnut plantation | 156 | 16.00 | 0.40 | 0.10 | - |
| Enrichment planting | 200 | 27.39 | 0.68 | 0.14 | 1.6 (20%) |
| | 400 | 49.32 | 1.23 | 0.12 | 2.6 (33%) |
| | 600 | 63.99 | 1.60 | 0.11 | 3.4 (43%) |
| | 800 | 72.54 | 1.81 | 0.09 | 3.9 (48%) |
| Cover planting | 1600 | 96.74 | 2.42 | 0.06 | 2.8 (41%) |

* Carbon capture refers to alive biomass only, excluding deadwood, litter, and soil organic carbon.

KEY FINDINGS

In Castilla y León with 1 354 268 hectare of simulated forest area (represented by 6 099 NFI plots), the improvement of habitat quality for brown bears by planting fruit-bearing tree species was applied on 469 plots (105 304 hectare ; 8 % of total simulated forest area). Meanwhile, the reduction of forest fire risk and improvement of quality of forests was carried out on 570 plots (123 810 hectare ; 9 % of total simulated forest area) and 1 182 plots (254 688 hectare ; 19 % of total simulated forest area), respectively. Therefore, the restoration measures in both restoration scenarios were applied only to selected forests that were either meant to improve the habitat quality or forest highly vulnerable to fires and with low forest quality.

Key finding #1 – FastTrack

The mean annual CO₂ capture for the planting restoration scenarios carried out at the Spanish demo area ranges from 0.4 to 2.4 tCO₂/ha/yr. This result depends strongly on planting density.



Key finding #2 – FastTrack

Tree diversity based on Hill-diversity for the planting restoration scenarios of the Spanish demo area shows that this biodiversity metric increases with increasing planting density and declines with uneven tree composition.

Hill-diversity can be used to compare the effective diversity across different forest restoration actions.



Key finding #3 – EFISCEN-Space

Underplanting measures (Scenario 1) resulted in an increase of growing stock volumes, increment, structural diversity (Gini index) and soil organic carbon (SOC) stocks.



Key finding #4 – EFISCEN-Space



Improvement of forest structure and forest resilience through change in forest management (e.g., intensification of cutting) in Scenario 2, led to an increase in harvested volumes in the upcoming 30-years. Consequently, it resulted in a decrease in the increment, lower growing stock volumes, less structurally complex forest and lower soil organic carbon (SOC) stocks.



RECOMMENDATIONS

Takeaway #1

To attain both high CO₂ capture and high Hill-diversity in 40 years, relatively high tree planting densities with an even distribution of the composing tree species are recommended.



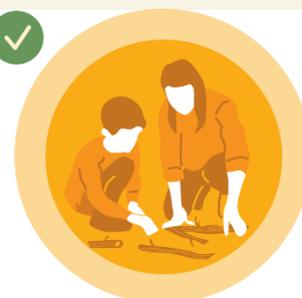
Takeaway #2

Different tree species contribute significantly differently to the total carbon capture of a forest. When aiming to optimise carbon capture alongside other restoration goals, consider some of the important factors affecting the species contribution difference: trait differences (e.g. wood density), growth patterns, or the environmental conditions of the site.



Takeaway #3

Underplanting measures support the improvement of forest resources and structural complexity. However, to maintain growing stock volume development and structural diversity of forest, forest management, including cuttings, has to be also considered. This could regulate and sustain the resources in the long-term.



Takeaway #4



Improvement of forest structure through forest management does not have immediate positive effects on the development of forest resources. Since forest fires greatly affect *Quercus pyrenaica* and *Pinus sylvestica* dominated forest, improving resilience in these forests is more important than focusing solely on resource availability. At average restoration costs of 3 000 Euro/hectare (see Spanish workplan v2.0), the total costs of the 483 802 hectare would amount to 1.45 billion Euro over the coming decades.



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