Small4Good

Sustainable Multifunctional Management by Small Forest Owners
in Support of Bioeconomy, Biodiversity, and Climate

Grant Number: 101135517

Deliverable D4.1

MULTIFUNCTIONAL MANAGEMENT FOR SMALL FOREST OWNERS

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Abbreviations

ALS	Airborne Laser Scanning
AOI	Area of Interest
bal	Basal area of larger trees
BAU	Business-as-usual
BM	Business Model
CCF	Continuous Cover Forestry
CER	Carbon-oriented extended rotation
CH	Switzerland
D	Deliverable
dbh	Diameter at breast height
DE	Germany
DEC	Dissemination, Exploitation, and Communication
DEM	Digital Elevation Model
dg	Stand quadratic mean diameter
EC	European Commission
ES	Spain
EU	European Union
FES	Forest Ecosystem Services
G	Stand basal area
GA	Grant Agreement
Ho	Stand dominant height
HWP	Harvested Wood Products
LGRB	Landesamt für Geologie, Rohstoffe und Bergbau

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LL	Living Labs
N	Stand density
NFI	National Forest Inventory
NOK	Norwegian krone
PES	Payment for Ecosystem Services
PNV	Potential Natural Vegetation
RCP	Representative Concentration Pathway
S4G	Small4Good
SI	Site index
V	Stand volume over bark
WP	Work Package

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Executive Summary

This deliverable addresses the challenge faced by small forest owners in Europe: the difficulty of implementing sustainable forest management adapted to their properties, joined to the absence of established markets for their ecosystem services and the lack of silvicultural guidelines aligned with their goals. The objective of the document is to define, simulate, and evaluate specific silvicultural prescriptions and viable business models for four Living Labs (LL) representing Europe's forest diversity, with the aim of guiding owners toward an inclusive and resilient bioeconomy.

To achieve this objective, a methodological approach based on collaboration was deployed through workshops, field visits, and individual interviews, integrating advanced simulation and modeling tools tailored to each regional context. The simulations cover time horizons of 70 to 100 years, including historical climate scenarios and RCP4.5/RCP8.5 projections, evaluating timber production, carbon sequestration, biodiversity, and ecosystem services.

- **Optimization in LL South (Spain):** Simulations in *Pinus pinaster* showed that moderate thinning maximizes mushroom production and mean diameter, while the transition toward *P. pinea* mixed stands in with *Quercus ilex* increases pine nut and cone production.
- **Vulnerability and resilience in LL Central (Switzerland/Germany):** Under severe climate change scenarios, potential increments and harvest volumes decline markedly across all properties, although the protection of habitat trees effectively preserves structural biodiversity indicators.
- **Economic and ecological trade-offs in LL East (Romania):** Pure-stand yield trajectories projected high accumulated volumes and spatial analysis at the Cobor site showed that the group-shelterwood regime (BAU) maximizes net present value compared to carbon-sink or strict conservation alternatives.
- **Efficiency of continuous cover forestry in LL North (Norway):** The application of continuous cover forestry (CCF) in spruce stands outperformed clear-cutting regimes in timber yield over 100 years and maintained a higher standing carbon stock, while applicability should be restricted to those high productivity areas.

Results demonstrate that there is no single universal solution; rather, combining specific silvicultural guidelines with business models makes it possible to reconcile short-term economic viability with biodiversity conservation and climate adaptation. These findings provide small owners with practical, science-based tools, laying the operational foundations for the project's subsequent milestones.

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1. Introduction

Small forest owners face severe problems to implement adequate management in their properties. Besides the lack of a suitable market for their ecosystem services they require adequate management guidelines oriented to their needs. This deliverable pretends to fulfil this need by defining silvicultural prescriptions for the four living labs where the project focuses its activities. Small4Good Living Labs covers the main forest types across Europe and represents a collection of forestry conditions relevant for small forest owners.

By implementing multifunctional management small-forest owners put themselves on the pathway towards sustainable and multifunctional management of their ownerships. These guidelines have been defined as management models through a multi-actor living lab approach across Europe. Small4Good's management guidelines approach involves understanding the motivations of small forest owners and are aligned with personal owners' motivations, are financially viable and are tailored with the local ecosystem and socioeconomic conditions.

In this deliverable, first we introduce the scenarios envisaged for each living lab, second we define the modelling framework and present the dataset applied in each living lab, and finally we describe the main results obtained and distill the conclusions.

Our final aim is that by applying these targeted management guidelines, small-forest owners contribute to safeguarding biodiversity and enhancing ecosystem services, acting as promoters for a fair and inclusive transition towards the bioeconomy.

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2. Simulation Scenarios

The simulation scenarios outline various possible forest management strategies in order to illustrate how forest conditions will evolve and to compare alternatives within the framework of a common management objective. These simulation scenarios were developed through a collaborative process with WP3, the "Living Labs" (LL) coordinators (WP1), and in direct contact with the forest owners of each LL via workshops, field visits, and individual interviews, providing additional information from each property. For each LL and each property, the actual management scenario was considered "business-as-usual" (BAU), that is, the continuation of the owner's current silvicultural practice. Building on the BAU, other scenarios were developed to illustrate alternative silvicultural systems and management objectives, formulated within the framework of the business models (BM) from WP3 and considering management guidelines for every specific case.
In the following sections, the scenarios from each LL (South, Central, East, and North) are described along with the modeling framework used to run those simulations, as well as the input (forest inventory) and output data (predicted forest evolution) from every simulation.

2.1 Scenarios description

LL South

The properties involved in this LL represent a *Pinus pinaster* and a *P. pinea* mature stands in Segovia (Spain), both of them in the Mediterranean region characterized for dry conditions and under active management.



Figure 1. LL South Pinus pinaster (left) and P. pinea (right) stands overview. The red lines mark the boundaries of the landowner's property, which is part of a larger forest stand.

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For the *P. pinaster* stand (100-year rotation), three silvicultural alternatives were evaluated against an unmanaged control that serves as a natural baseline: a business-as-usual (BAU) scenario consisting of a single heavy thinning from above (removing 45% of basal area) designed to maximize early economic return, reduce operational entries, and release remaining trees; a wildfire-prevention itinerary involving two systematic thinnings spaced 10 years apart (each extracting 10% of basal area) aimed strictly at fuel reduction rather than merchantable yields; and a moderate, continuous-cover approach applying two successive thinnings from below (extracting 15% and 10% of basal area from smaller size classes) to steadily improve stand quality and structure despite higher cumulative investment costs.

For the *P. pinea* stand (140-year rotation), three silvicultural alternatives were evaluated too, considering an unmanaged control baseline: the business-as-usual (BAU) strategy applies four light, systematic thinnings at 15-year intervals, removing 10% of stems while reserving the top 30% largest diameter classes untouched, to sustain long-term canopy growth without over-depleting the stand; the wildfire itinerary applies a single low-intensity intervention without supplementary understory clearings due to baseline low fire risk, retaining the extended timeframe strictly for comparative consistency against standard 110–120-year harvest ages (Piqué et al., 2015); and the pine cone production itinerary implements a single, conservative thinning from below at age 115 (extracting 20% of basal area), moderately reduced in intensity relative to regional standards to safeguard canopy area and prevent understocking (Piqué et al., 2015). Additionally, these scenarios were replicated to simulate the transition toward mixed stands through the underplanting of 300 *Quercus ilex* trees per hectare at stand age 80 (20 years into the simulation). Given that *Q. ilex* is a prevalent secondary species in the study area, this modification aimed to assess the effects on biodiversity, stand structural diversity, and potential trade-offs with pine nut production.

LL Central

Living Lab Central currently comprises five small-scale private forest properties, three located in Switzerland and two in Germany (Figure 2; Table 1). This cross-boundary LL is jointly coordinated by the two respective regional forest owner associations WaldBeiderBasel (CH) and Forstkammer Baden-Württemberg (DE).

The initial selection of forest properties is described in detail in Deliverable 1.1. Since then, the composition of the LL has been adjusted: two German properties originally included in the project (Property 5 - Beetle areas and old stands, Malsburg-Marzell and Property 6 - Near-natural old Stock, Gerspach) are no longer part of the project. To ensure continued representation of private forest ownership on the German side, the LL coordinators successfully engaged an additional private forest owner from the neighbouring region. This new site (Property 7) covers in total approx. 1.9 ha of forest and consists predominantly of formerly spruce-dominated forest areas affected by

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disturbances. The disturbed areas have subsequently been replanted with a diverse range of tree species, which formed the starting point for our simulations (see below).
For each property, a business-as-usual (BAU) management scenario was defined, representing the continuation of the forest owner's current silvicultural practices. These scenarios were developed collaboratively with the LL coordinators (WP1) and the forest owners through workshops, site visits and individual interviews (see Table 2).
Building on the BAU scenarios, further management scenarios were developed to explore alternative silvicultural approaches and management objectives. Their definition involved project partners from WP3, with the aim of linking alternative forest management strategies to the development of innovative business models (BM). All scenarios were simulated over a period of 70-years (2025–2095), accounting for the impacts of climate change. An overview of the scenarios developed for each property is given in Table 1.

The BAU scenarios reflect the current management practices and priorities of the respective forest owners and can be described as following:

- **Property 1 & 4**: Future crop tree management; both forest owners actively manage their forests with a focus on timber production. Current management activities include thinning in pole-stage stands to promote selected future crop trees. Property 4 is strongly affected by climate change-related disturbances, and the forest owner aims to restore affected areas through replanting and the adaptation of existing spruce-dominated stands.
- **Property 2 & 3**: Low-intensity plentering; both properties are managed at relatively low (to medium) intensity, with timber production playing a minor role. Management focuses primarily on multifunctional objectives, including recreational use, particularly in property 3 (Citizens' Community).
- **Property 7**: Planting and thinning; following disturbance events, the forest owner has already replanted the affected areas with a diverse range of sponsored tree species. Future management focuses on the establishment and development of these young stands through appropriate thinning interventions.

The alternative management scenarios were developed around the following overarching management objectives:

- **Climate change adaptation**: Enhance forest resistance and resilience to climate change and future disturbance events by reducing the proportion of spruce, promoting tree species diversification and actively supporting tree species conversion through planting.
- **Biodiversity enhancement**: Increase the biodiversity value of actively managed forests by fostering the retention and protection of habitat trees, particularly large living trees that provide valuable microhabitats for forest-dependent species.

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- **Protection of natural processes**: Leave forest areas unmanaged to foster natural processes and stand dynamics.

Table 1. Main characteristics of each property (P1-P7).

Property	ID	Country	Elevation (m)	Main tree species	Stand type
Rothenfluh 1	P1	CH	690	Picea abies, Abies alba	Unstable spruce/fire polewood; forest area at climate change risk
Rothenfluh 2	P2	CH	590	Fagus sylvatica, Abies alba	Beech timber wood; potential multifunctional forest
Aesch (Citizens' Community)	P3	CH	320 - 610	Fagus sylvatica, Abies alba, Quercus robur, Acer spp., Sorbus spp.,	Hardwood mixed forest, uneven-aged; multifunctional forest
Wehr	P4	DE	510	Picea abies, Abies alba	Unstable spruce/fir polewood; forest area at climate change risk; partly replanted disturbed area
Hägelberg (not included in D1.1)	P7	DE	390	Pseudotsuga menziesii, Quercus spp.	Replanted disturbed area

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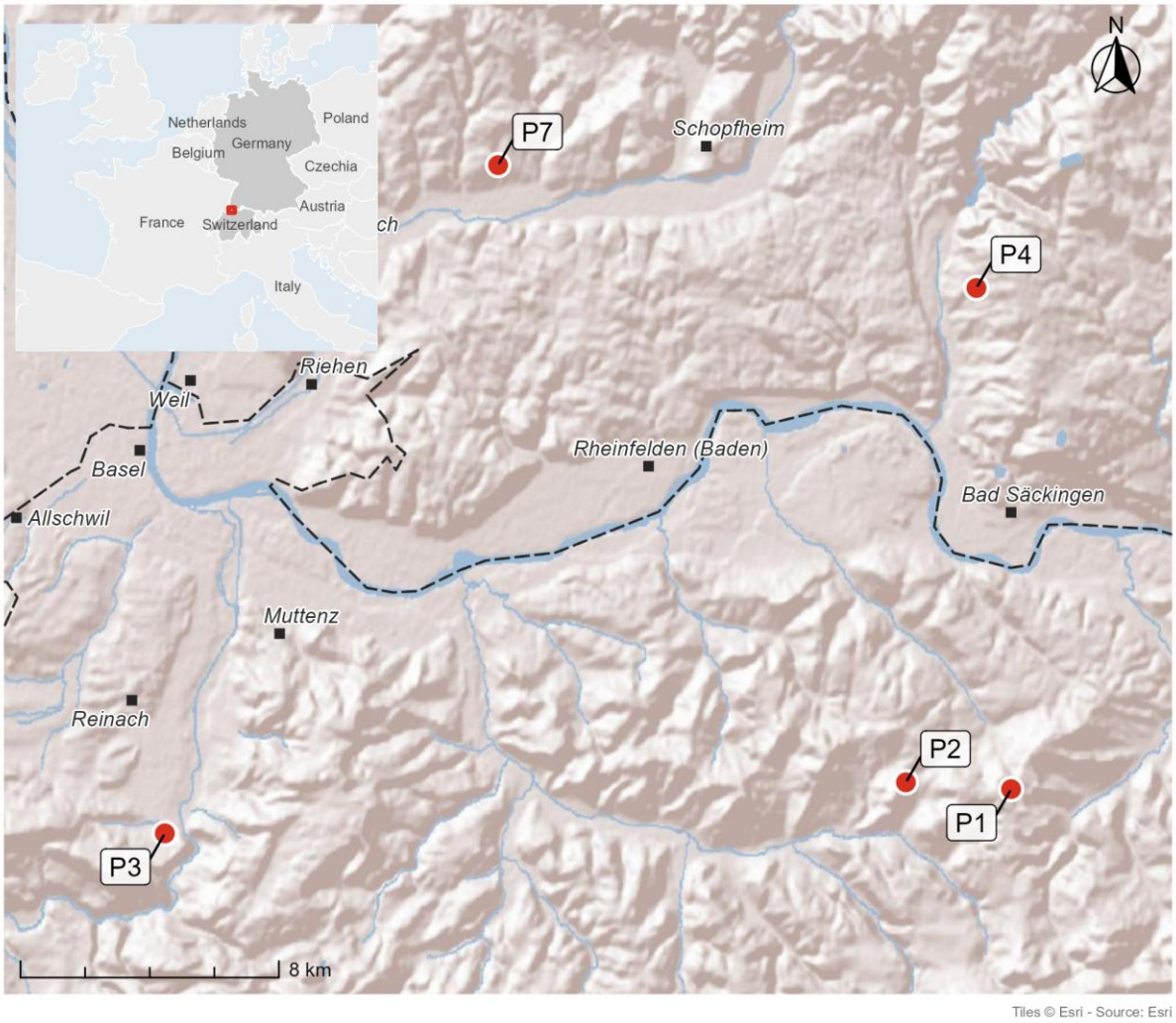


Figure 2. Location of the five properties in LL Central in the cross-border region near Basel, three in Switzerland (P1-P3) and two in Germany (P4, P7). The dashed line is the national border.

Table 2. Simulation scenarios for each property, designed to develop business models in WP3 (BAU = business-as-usual, BM = business model).

Property	ID	Silvicultural system	Key parameters	Difference to BAU
P1	BAU	Future crop tree	25 Z-trees/ha, thinning every 10 yrs removing 20 % of standing volume, dbh target 50 cm, final harvest 2090	-
	BM1	Target cut + planting	Target dbh: spruce 40, fir 45, beech 60, Douglas 65 cm; planting after each intervention	Species conversion, spruce reduced
	BM2	as BM1	+ 10 habitat trees/ha	BM1 plus habitat tree protection, sponsoring-financed

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	NO	No-management	-	Process protection
P2 + P3	BAU	Low-intensity plentering	Single-tree selection, residual basal area 40 m^2/ha, dbh target 60 cm, 10-yr cycle	-
	BM1	as BAU	+ 10 habitat trees/ha	BAU plus habitat tree protection, sponsoring-financed
	BM2	High-intensity plentering	Residual basal area 20 m^2/ha, dbh target 60 cm, 10-yr cycle; + 10 habitat trees/ha	Higher removal intensity, plus habitat tree protection
	NO	No-management	-	Process protection
P4	BAU	Future crop tree	25 Z-trees/ha, thinning every 10 yrs removing 20 % of standing volume, dbh target 50 cm; final harvests 2060, 2070, 2080	-
	BM1	Target cut + planting	Removal of spruce and fir ≥ 25 cm dbh and planting in 2030; planting scenario informed by PNV simulation; thinning from above every 10 yrs (2040–2090)	Rapid species conversion
	NO	No-management	-	Process protection
P7	BAU	Planting + thinning	Species as planted by the owner (2025, 450/ha), thinning from above every 10 yrs (2035–2085)	-
	BM1	Planting + thinning	Alternative planting scheme informed by PNV simulation, same planting year and similar density (475/ha), native species only, thinning from above every 10 yrs (2035–2085)	Alternative species choice, sponsoring-financed
	NO	No-management	-	Process protection

LL East

Living Lab East (Romania) used two complementary simulation approaches: (i) stand-level yield trajectories for representative pure stands, produced with SIMANFOR, and (ii) spatially explicit, individual-tree management alternatives evaluated in the ForestFuture Portal. These are separate demonstration datasets and should not be interpreted as simulations of the same forest area.

In SIMANFOR, high-production, quality-class I stands of beech (*Fagus sylvatica*), silver fir (*Abies alba*), Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) were projected

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from age 15 to their species-specific rotation ages. Romanian business-as-usual (BAU) thinning was applied. The input package includes CON, CVA and PRO pathway identifiers for several species, but their simulated intermediate treatments and live-tree growth coincide; therefore one representative BAU trajectory per species is reported. The distinctions among conservation (CON), continuous cover (CVA) and production (PRO) concern retention, species mixtures and regeneration methods that the pure-stand model cannot resolve. The package additionally contains a spruce CLR export, while pine is represented by one CON export; these files should not be taken as equivalent complete multi-scenario comparisons.

In ForestFuture, a measured mixed deciduous stand at Cobor was used to demonstrate BAU alongside biodiversity-oriented and carbon-sink alternatives. The BAU reference can be selected from 35 locally adapted Romanian pathways covering conservation, group shelterwood, irregular shelterwood and clearcut/strip treatments. The alternative scenarios change tree-removal priorities, retention, deadwood and regeneration assumptions while keeping the measured starting stand common.

Table 3. Management scenarios implemented for LL East (BAU = business-as-usual; CON = conservation; CVA = continuous cover; PRO = production).

Approach / scenario	Silvicultural system	Key management parameters	Difference from BAU
SIMANFOR: BAU, four pure stands	Even-aged thinning and maturation	Species-specific intervals and thinning intensity; no commercial thinning in the pre-regeneration quiet period	Reference trajectory
SIMANFOR: CON / CVA / PRO labels	Alternative management objectives	Same pre-regeneration thinning and growth schedule in the supplied stand-level runs	Retention, mixtures and regeneration differences not resolved in these outputs
ForestFuture: BAU	Romanian pathway (35 selectable)	Regulated thinning, non-intervention interval and pathway-specific regeneration sequence	Reference against which other alternatives are compared
ForestFuture: biodiversity	Retention-oriented treatment	Protects large/rare trees, increases habitat-tree and deadwood targets and favours structural diversity	Greater structural biodiversity priority
ForestFuture: carbon sink	Carbon-oriented treatment	Prioritises retention of large biomass and reduces removals of major carbon-bearing trees	Higher standing biomass/carbon priority

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Table 4. SIMANFOR BAU intervention schedules for the four species, as specified in the submitted Romanian simulation reports. Percentages refer to the indicated thinning criterion; no final-regeneration cuts are simulated in these species-specific series.

Species	Rotation (years)	Thinning age(s) and prescribed removals	Age of last thinning
Fagus sylvatica	110	20, 30: 15% density; 40: 18% G; 50, 60: 15% G; 70: 12% G; 80: 10% G	80
Abies alba	110	30: 15% density; 40, 50, 60: 15% G; 70: 12% G; 80: 10% G	80
Picea abies	100	20: 25% density; 30: 20% density; 40: 20% G; 50: 15% G; 60: 10% G	60
Pinus sylvestris	70	20: 18% G; 30, 40: 15% G; 50: 10% G	50

Transitioning from the stand-level and tree-level modeling approaches evaluated in LL East, the analysis turns to LL North to examine boreal forest dynamics under small-scale management regimes.

LL North

A small-scale private forest property in Fagerstrand, Nesodden, south-eastern Norway (Akershus), was selected for Living Lab North (Figure 3; Table 5). According to the owner's forest management plan, the property covers approximately 165 ha divided into 128 stands. However, the simulations presented here focus on a subset of 16 stands covered by a Unmanned Aerial Vehicle (UAV) LiDAR-based tree inventory, as an initial test of the modelling approach. Of these, ten are classified as productive forest, covering 12.84 ha, and six as unproductive forest.

The study area consists of boreal mixed forest comprising Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula* spp.). According to the management plan, five of the ten productive stands are pine-dominated and five are spruce-dominated. Site index (H40) ranges from 8 to 20 m, and stand age ranges from 4 to 135 years. Most of the productive forest area falls within development classes IV and V under the Norwegian forest classification system (Viken and Breidenbach 2025).

Table 5. Main characteristics of the LL North property.

Property	ID	Country	Area (ha)	Elevation (m a.s.l.)	Main tree species	Stand type
Fagerstrand	P1	NO	12.84 productive (10 stands) + 6 unproductive stands	133-162	Pinus sylvestris, Picea abies, Betula spp.	Even-aged boreal pine and spruce stands with birch admixture, mostly mature (development classes IV-V); one young spruce plantation

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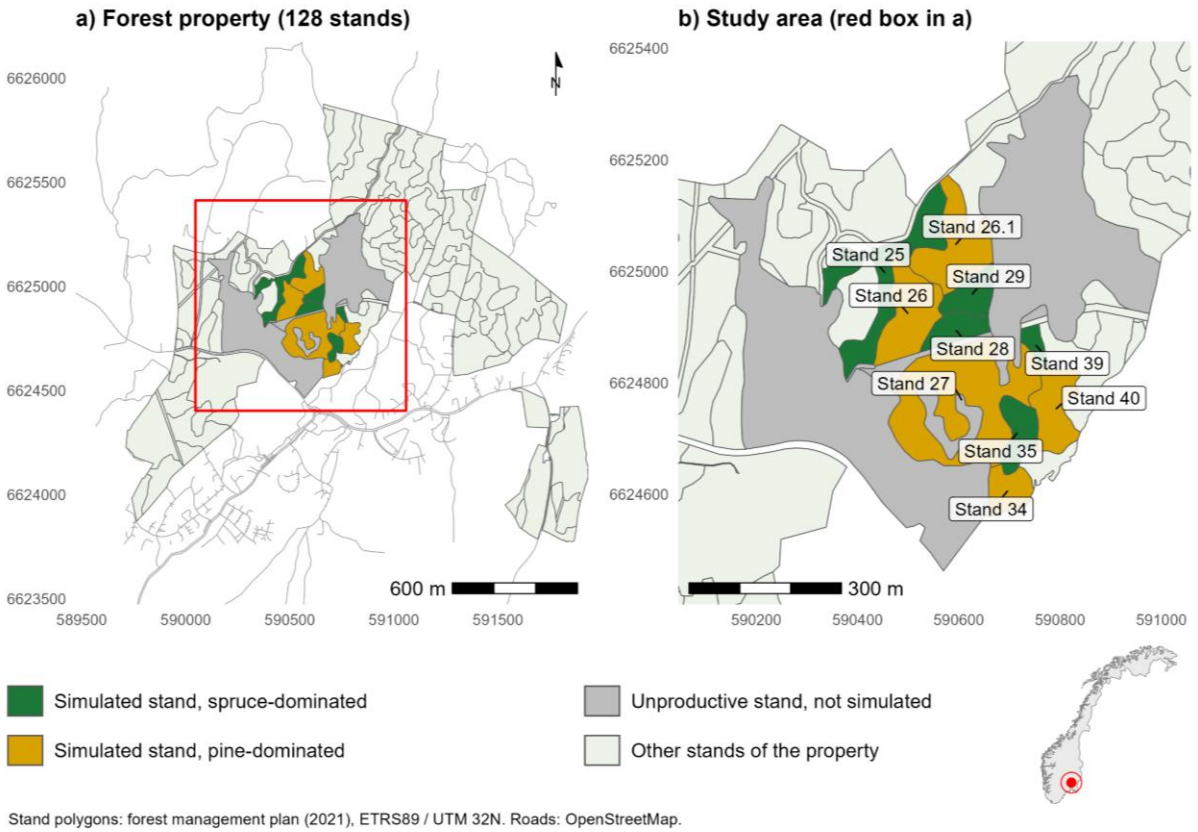


Figure 3. The LL North forest property. (a) Overview of the property, comprising 128 stands delineated in the 2021 forest management plan. The red box indicates the study area. (b) Detail of the study area, showing the 10 productive stands included in the simulations, coloured by dominant species and labelled with their stand identifiers from the management plan (e.g., 26.1 denotes sub-stand 1 of stand 26). Dark grey indicates stands classified as unproductive in the plan and excluded from the simulations. Pale green indicates other stands within the property, which will be included at a later stage of the project.

Six management regimes were simulated for the study area (Table 6): set-aside (SA), business-as-usual (BAU), carbon sink (CS), intensive management (INT), continuous cover forestry (CCF) and mixed-species regeneration (MULT). They were taken from the regimes defined for Norwegian forests by Vergarechea et al. (2023, 2026). BAU represents the even-aged management currently practised in Norway: clear-felling at a rotation age set by site index, followed by planting or natural regeneration. CS, INT and MULT keep the even-aged system. CS extends the BAU rotation age by 40 % with the aim of increasing carbon storage in the forest, INT increases the management intensity through thinning and fertilisation, and MULT replaces spruce replanting with a 50/50 mixture of spruce and pine or birch. In all clear-cutting regimes (BAU, CS, INT and MULT) the 10 largest non-spruce trees per hectare are retained at final felling, as required by the Norwegian PEFC standard. CCF replaces clear-felling with repeated selective harvests, and SA leaves the forest unmanaged as a reference.

All regimes were simulated for 100 years (2026–2126) in 5-year periods under the RCP4.5 climate scenario. Not every regime is suitable for every stand: each one has rules

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on dominant species, site index and development class, so the regimes cover different parts of the study area (Table 5). SA, BAU and CS apply to all 10 productive stands (12.84 ha), INT to 8 stands (10.31 ha; the two stands with site index 8 are excluded), MULT to the 5 stands on spruce sites (4.07 ha) and CCF to the 4 spruce-dominated stands in development class IV–V (3.39 ha).

Table 6. Simulation scenarios for the LL North property. Stands = number of productive stands (out of 10) to which each regime applies; regimes cover different areas, so indicators are compared per hectare. Retention trees = the 10 largest non-spruce trees per hectare left standing at final felling (Norwegian PEFC standard). INT is not applied to the two poorest sites (SI 8); CCF only to spruce-dominated stands in development class IV–V; MULT only to stands on spruce sites.

ID	Silvicultural system	Stands (area)	Key parameters	Difference to BAU
BAU	Even-aged, clear-cut	10/10 (12.84 ha)	Final felling at rotation age by site index (70–110 yr), 10 retention trees/ha; replanting (spruce) or seed-tree regeneration (pine); no thinning	-
CS	Even-aged, extended rotation	10/10 (12.84 ha)	As BAU, rotation age extended by 40 % (98–154 yr)	Later final felling, higher carbon stock in the forest
INT	Even-aged, intensive	8/10 (10.31 ha)	As BAU plus one thinning (1/3 of volume), fertilization before final felling and denser, faster replanting	Thinning, fertilization, faster regeneration
CCF	Continuous cover	4/10 (3.39 ha)	Selective harvest of trees > 15 cm dbh every 15 yr (max. 30 % of their basal area); underplanting of spruce	No clear-cut
MULT	Even-aged, mixed-species regeneration	5/10 (4.07 ha)	As BAU, replanting with 50 % spruce and 50 % pine/birch	Mixed-species regeneration
SA	No management	10/10 (12.84 ha)	-	Process protection

2.2 Modelling framework

Different modeling frameworks were used to develop the forest management simulations and obtain insights about the best alternative for each LL and owner. Regardless of the internal workflow and philosophy of each simulation platform, it is important to highlight that predictive models are subject to error, which means their results should be interpreted as a reference and not as an absolute truth. It is important to bear in mind that, as the simulation horizon increases, potential errors also increase, simply due to their cumulative effect. Details about each specific platform are presented in this section.

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LL South

The simulations were carried out using the SIMANFOR platform (Bravo et al., 2005; available at www.simanfor.es). SIMANFOR is a freely available cloud platform that allows flexible silvicultural simulations adapted to the needs of each user, targeting different ecosystem services according to the management goal. Previous studies have shown its utility for inspecting the impact of different silvicultural prescriptions (Vázquez-Veloso et al., 2025) focusing not only for timber production, but also for carbon sequestration (Martín Ariza et al., 2017), mushrooms and pine cone production (de la Parra Peral et al., 2017), and even a joint evaluation of the trade-offs among different ecosystem services, species mixtures and silvicultural guidelines (Vázquez-Veloso et al., 2025) (see more related publications here).
SIMANFOR can support the implementation of different forest growth models at different detail levels (stand, size-class and individual tree). Among the models available on the platform, both the *IBEROPT (original)* and the *Pinea Sistema Central (PINEA)* were used for this deliverable as they perfectly match the species (*Pinus pinaster* and *P. pinea*) and region (Segovia, Spain) conditions of the LL South living labs. For this, it incorporates empirical models to estimate individual-tree dynamics (growth, mortality and ingrowth), as well as metrics related to volume, biomass, carbon, competition, diversity and structure, providing users an output with multiple indicators.
Simulation periods were established at 30 and 80 years for *P. pinaster* and *P. pinea*, respectively, according to the initial stand age and rotation period established.

LL Central

The latest version of the climate-sensitive forest gap model ForClim (version 4.1; Marano et al. 2025, Marano et al. 2026) was applied, as it has been extensively tested and validated for Central European forest conditions (Huber et al. 2021, Mina et al. 2017, Nögel et al. 2026). ForClim allows simulating mixed and uneven-aged stands, accounts for climate change impacts, and represents a broad range of established silvicultural systems (Rasche et al. 2011, Thrippleton et al. 2020). It is further well suited to simulate the potential natural vegetation (PNV) as well as climate-driven shifts in tree species composition (Huber et al. 2021, Gutiérrez et al. 2016, Takolander et al. 2019). The model currently includes 32 tree species, which constrains the representation of some species present in the properties.

Forest stands are represented in ForClim by independent patches with a size of 400 m^2. To account for stochasticity, the forest inventory of each property was extended to 100 patches following the approach of Thrippleton et al. (2020), taking into consideration the species and diameter distribution of the inventory.

The simulations covered a 70-years period (2025–2095). Climate input consisted of a historical baseline (1981–2010) (MeteoSwiss, 2026) and an ensemble of ten climate

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models under RCP4.5 and RCP8.5 (CH2018, 2018). The climate data for the German properties were extracted from CH2018 grid cells close to the border at similar elevation to be complementary to the Swiss model ensemble.

Management simulation in ForClim covered the defined management scenarios for the properties (see Table 2), including a modification to cover the objective of protecting habitat trees. The strategy selected the ten largest trees per hectare, which are then excluded from all management interventions. They are counted as habitat trees once they reach a dbh of at least 60 cm. Additionally, simulations for the PNV were conducted to derive suitable species for the planting scenarios on the two German properties. These simulations started from bare ground and ran for 1000 years under an end-of-century climate. Therefore, the climate data from the last 15 years (2084-2099) of the CH2018 models was randomly resampled.

Based on the ForClim output, biodiversity and ecosystem service indicators were calculated (Blattert et al. 2024), linking to multifunctionality assessments and to business models developed in WP3. The indicators covered three groups, representing the main forest functions for LL Central: timber production (timber harvested, increment), carbon sequestration (wood products & substitution, forest carbon stock) and proxies for biodiversity (habitat trees, deadwood, tree species diversity), as these represent the central forest services in LL Central. The indicator values were averaged over the 70-year simulation period (see Figure 5).

LL East

Stand-level simulations (SIMANFOR)

SIMANFOR (Bravo et al., 2025) was used with the dynamic stand model for Romania based on the mathematical-auxological growth and yield tables of Giurgiu and Drăghiciu (2004). Each pure, even-aged cohort is described by age, stem density, quadratic mean diameter, basal area, dominant height, growing stock and thinning yield. The supplied series begin in 2025 at age 15, advance in five-year steps and reach rotations of 70–110 years. Thinning events are prescribed by age, using either stem density or basal area as the extraction criterion.

The age of the final thinning varies in the actual runs: 80 years for fir (*Abies* sp.) and beech (*Fagus sylvatica*), 60 for spruce (*Picea abies*) and 50 for pine (*Pinus sylvestris*). Thereafter, standing volume increases through natural growth without further commercial thinning until the simulation ends. The stand-level model implemented into SIMANFOR does not represent spatial gaps, recruitment of new cohorts, tree-level habitat retention, or species-mixture changes; consequently no distinct CON/CVA/PRO growth curves should be inferred from the identical outputs.

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Tree-level simulations (ForestFuture Portal)

ForestFuture is a Python/Streamlit decision-support prototype linked to georeferenced individual-tree inventories. ForestFuture is publicly accessible as an interactive web application at https://forest-future.replit.app/. The source code will be released as open-source software on GitHub to support transparency, reproducibility and further development. Species-specific age trajectories from the Romanian yield tables are interpolated and applied as relative dbh, height and volume increments to the individual measured trees. The tree positions and initial size differences are preserved, while programmed management events select specific trees for removal. For group shelterwood, trees are removed in spatial clusters and regeneration cohorts are introduced into openings; alternative objectives use different tree-ranking and habitat-retention rules. The user can select a 20 to 100-year horizon and five- or ten-year steps. For example, ForestFuture currently schedules group-shelterwood regeneration as an initiation cut of approximately 30% of basal area at the pathway final age, a gap-expansion cut of about 35% after 15 years and a final release of about 30% after a further 15 years. Irregular shelterwood and conservation pathways follow different event schedules. These phase timings, target removals and gap-selection constants are explicit prototype rules derived from the pathway library rather than directly measured local regeneration responses.

The portal reports timber and standing volume, retained habitat trees and deadwood, three tracked carbon pools (living trees, deadwood and harvested wood products), a transparent structural-biodiversity proxy, owner cash flows, net present value (NPV), peak financing requirement and a weighted scenario ranking. Carbon conversions follow IPCC-style stock accounting and financial outputs depend on user-defined costs, prices and discount rate. ForestFuture is a yield-table-informed scenario-screening model, not a calibrated mechanistic individual-tree competition or regeneration model; its spatial gap and tree-selection heuristics still require Living Lab validation (Giurgiu and Drăghiciu, 2004; MMAP, 2022; IPCC, 2019).

LL North

For Living Lab North, stand development was simulated with an individual-tree growth simulator implemented in *SiTree* (Antón-Fernández and Astrup 2022), an open-source R framework. The simulator draws on data from the permanent 250 m^2 plots of the Norwegian National Forest Inventory (NFI) and has previously been applied to project forest development at the national scale under alternative management regimes (Blattert et al. 2023, Toraño Caicoya et al. 2023, Vergarechea et al. 2023, Vergarechea et al. 2026).

Tree growth and mortality were projected in five-year intervals using nearest-neighbour imputation. At each simulation step, each tree was assigned the observed increment and survival status (alive or dead) of the most similar reference tree in a database of NFI remeasurements. Height increment was derived from the imputed volume increment

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through the volume functions. Similarity was determined based on site index (SI), diameter at breast height (dbh), latitude, basal area of larger trees (bal) and total stand basal area (G). The reference database comprised NFI measurements collected in 2005–2017 and their remeasurements five years later (up to 2022), the same data used in the most recent national projections. Ingrowth was estimated using an analogous imputation procedure at the plot level.

The imputed five-year increments therefore remained within the range observed in the reference database. Where no sufficiently similar reference tree was available, published Norwegian individual-tree models were used instead (Bollandsås 2007; Bollandsås and Næsset 2009; Smith 2014, 2016). Tree volume was calculated for trees with a dbh of at least 5 cm using Norwegian species-specific volume functions (Braastad 1966; Brantseg 1967; Vestjordet 1967). Because *SiTree* and its growth and mortality models were developed for NFI plots of about 250 m^2, the tree-level inventory of each stand was divided into a regular grid of 250 m^2 cells based on the tree coordinates, and each cell with trees was simulated as one plot (367 cells in total). All cells of a stand share the stand attributes of the management plan (SI, age, development class, dominant species), and results were summed back to the stand and to the study area. Final felling is decided at stand level and therefore affects all cells of a stand at the same time; thinning is decided cell by cell.

Management was simulated with regime-specific rules. Each regime is defined by a table of treatments by site index, species and development class (rotation age, thinning rules, regeneration method and waiting time, fertilisation; Table 6). None of the stands lies in a protected area, so no environmental harvest restrictions apply. Simulations covered a 100-year period (2026–2126), divided into 20 five-year intervals, with one run per management regime and a fixed random seed. Climate change was included through its effect on site index under the RCP4.5 scenario. The SI of each stand was increased over time following the trajectory projected for the nearest NFI plot by a climate-sensitive site index model (Antón-Fernández, C 2016). Climate effects on mortality and disturbances were not included.

Six forest ecosystem service (FES) indicators were derived from the simulation outputs using indicator functions, adapted to the study area (Vergarechea et al. 2023, Vergarechea et al. 2026):

- **Harvested timber volume (m^3/ha):** merchantable volume under bark, after accounting for harvesting losses.
- **Net timber value (NOK/ha):** gross timber revenue minus harvesting and transport costs, without discounting. Revenue was calculated using average assortment prices for 2019 from Statistics Norway, assuming a sawlog-to-pulpwood ratio of 55:45 for conifers and allocating all birch timber to pulpwood.

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- **Carbon stored in harvested wood products (t CO_2/ha):** carbon stocks in wood products, expressed as CO_2, calculated using half-lives of 35 years for sawn wood and 25 years for wood-based panels.
- **Carbon stored in the standing forest (t CO_2/ha):** carbon stocks estimated from individual-tree biomass and expressed as CO_2.
- **Ecological hotspots:** indicators of habitat features, including large birch and aspen trees (dbh > 40 cm), old spruce and pine stands (> 150 and > 200 years, respectively), and large broadleaved trees (dbh > 20 cm). These were expressed as tree densities (trees/ha) and the proportion of cells meeting the relevant criteria.
- **Tree species diversity:** the Shannon diversity index of the basal-area share of each species, calculated for each 250 m^2 cell and averaged across cells.

Indicators were calculated for each stand and five-year period. Where applicable, values were expressed per hectare of the area to which each management regime applied, as the regimes covered different parts of the study area. Tree species diversity and cell proportions were reported as dimensionless indicators.

2.3 Data

Data used as input for simulation purposes were extracted from each LL target stand. The forest inventory carried out in every LL is detailed in this section, consistently including tree species identification as well as dbh and height measurements. Additional information, such as environmental and climate data, was used to complement the forest inventory data. Further details for each LL are provided below.

LL South

Input data for LL South were collected from two representative pine stands in Segovia (Spain): a *Pinus pinaster* Ait. stand located in Dehesa Mayor, and a *Pinus pinea* L. stand in Cuéllar. Forest inventory measurements were captured using a LiDAR Hand-held Laser Scanning (HLS) within circular sample plots of 15 m radius. Due to the empirical nature of the growth and yield models applied for these species, external climate variables were extracted from WorldClim (Fick and Hijmans, 2017; Harris et al., 2020) to assess mushroom productivity for the *P. pinaster* stand according to the model requirements. The key baseline dasometric characteristics summarizing the stand conditions prior to simulation are provided in Table 7 below.

Table 7. Main stand dasometric variables for LL South. ID is the unique plot identifier; T is the average stand age (years); N is the stand density (trees/ha); dg is the stand quadratic mean diameter (cm); G is the stand basal area (m^2/ha); Ho is the stand dominant height (m); V is the stand volume over bark (m^3/ha); Wa is the stand aboveground biomass (t/ha); C is the total carbon stock of the stand, including roots (t/ha).

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ID	T	N	dg	G	Ho	V	Wa	C
P. pinaster	70	396.83	38.46	46.09	21.69	425.85	205.67	131.84
P. pinea	60	158.73	29.79	11.07	10.99	61.73	54.32	35.97
P. pinea (mix stand)	80	458.76	22.53	18.29	14.51	112.91	99.65	65.32

LL Central

The initialisation of the forest properties within ForClim requires the spatial information on the area of interest (i.e. stand boundary), forest inventory data (dbh and tree species) and various environmental data, including the digital elevation, soil data and climate data (CH2018, 2018); see also section 2.2.

The forest inventory was based on different data sources. The overall aim was to have representative initialisation data of the small private forest owners areas of interest within their property. The areas were jointly identified with the local LL representatives, who were in exchange with the forest owners. The different forest data sources were:

- Full inventory: all trees have been measured within the representative forest area, either by a manual full inventory or by a photogrammetry approach (Hristova et al 2025, Hristova et al. 2026), which was developed within this project allowing precise data collection of small forest properties.
- Inventory sample plots: To represent the larger forest area of the Citizens' Community Aesch, data collected by systematic permanent inventory was used being able to represent the whole forest area
- Planting list: the information on the planted trees (amount and species) after a disturbance was used as input. The list was provided by the private forest owner.

The soil data for Swiss properties was taken from Baltensweiler et al. (2024), and for the German properties from the BK50 soil map of the LGRB (LGRB 2015). These data were used to calculate the plant-available water holding capacity of each forest area using the *rforclim* package (Hiltner & Marano 2025). The water holding capacity was integrated over the full 0–200 cm profile for all properties. In the case of the German soil data, the lowest soil horizon in the data (95 cm), was extended to 200 cm, to be complementary to the Swiss data.

Table 8. Forest inventory basis for each property

Property	Type	Source	Area (ha)	Details	Parameters	Date
P1	Full-inventory	Photogrammetry	0.52	360° Camera, Insta360, collected by	dbh, tree species, position	17.02.2025

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				WSL (Hristina Hristova)		
P2	Full-inventory	Manual	0.51	Collected by WaldbeiderBasel(Andreas Gabriel)	dbh, tree species	31.08.2026
P3	Sample plots	Manual	Each 2.34 (≈156 represented)	WaldbeiderBasel, 100 x 200 m grid, 300 m^2, 78 sample plots	dbh, tree species, position	2023
P4	Full-inventory	Manual	0.32	Collected by Forstkammer Badenwürttemberg (Britta Hars)	dbh, tree species	02.07.2026
P7	Planting list	-	1.39	Planting lists, derived from forest owner	Number of trees of each tree species	December 2025 (planting)

LL East

SIMANFOR was initialised with four representative Romanian stand records (inventory year 2025, age 15; pure stands, high production/quality class I). The baseline data include tree density, quadratic mean diameter, basal area, dominant height and standing volume, which are projected using the corresponding species model. These illustrative stand inputs do not describe the georeferenced Cobor inventory used by ForestFuture.

Table 9. Initial stand characteristics for the four SIMANFOR simulations (N = stand density; dg = quadratic mean diameter; G = basal area; Ho = dominant height; V = volume over bark).

Species (plot ID)	Age (years)	N (trees/ha)	dg (cm)	G (m^2/ha)	Ho (m)	V (m^3/ha)
Fagus sylvatica (1)	15	3,830.10	5.62	9.50	10.73	67.74
Abies alba (2)	15	7,715.58	3.46	7.27	7.10	59.55
Picea abies (3)	15	4,722.42	5.79	12.42	7.92	74.56
Pinus sylvestris (4)	15	3,421.33	5.83	9.14	9.45	83.71

For ForestFuture, the Cobor Forest demonstration was initialised from a georeferenced tree inventory acquired during Small4Good activities. It contains 9,642 mapped trees over an estimated 23.45 ha, equivalent to 411 trees/ha, with an initial mean dbh of 26.6 cm, dg of 30.4 cm, G of 29.9 m^2/ha and V of 318.3 m^3/ha (7,465 m^3 in total). The editable species mapping in the recorded demonstration contains *Fagus sylvatica*, *Quercus petraea* and *Carpinus betulus*; the initial Shannon diversity index is 0.11.

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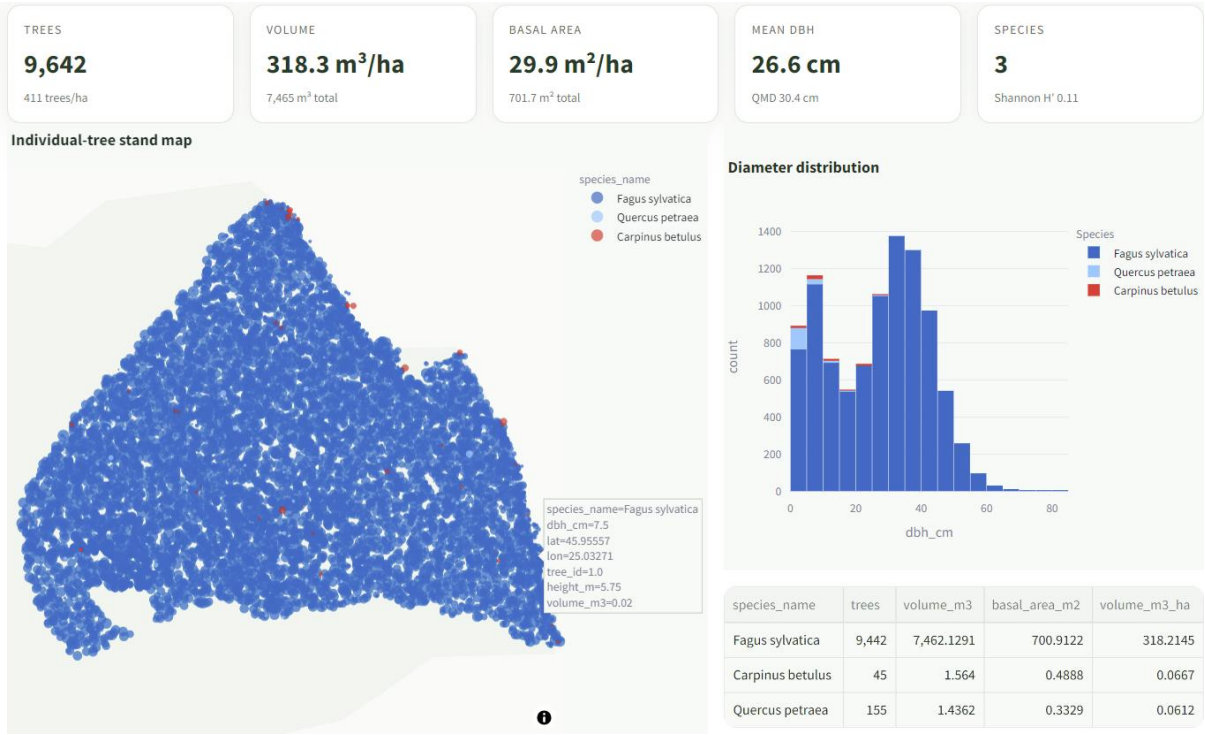


Figure 4. Cobor Forest demonstration on ForestFuture Portal.

The ForestFuture input combines tree coordinates, species/code, dbh, height, tree volume and optional age with the Romanian BAU pathway database and species-growth table. Where height or volume is unavailable, the application applies explicitly simplified fallback equations. The 23.45 ha figure is estimated geometrically from the point inventory and should be replaced by the legal parcel area for operational assessment. The recorded example uses 70 €/m^3 timber price, 32 €/m^3 harvesting costs, 1,800 €/ha regeneration costs and a 3% discount rate; these are editable demonstration assumptions, not field-estimated project-wide economic parameters.

LL North

Simulations were initialised by combining two data sources: a tree-level inventory derived from remote sensing and stand attributes obtained from the owner's forest management plan (Table 10). Individual trees were detected from UAV laser scanning data acquired in 2026 with a DJI Zenmuse L3 scanner mounted on a DJI Matrice 400 (1535 nm wavelength, 0.25 mrad beam divergence, up to 16 returns per pulse), flown at 80 m above ground level. The point clouds were pre-processed with the open-source Point Data Abstraction Library (PDAL), including buffered tiling and voxelisation. Individual trees were then segmented in NIBIO's ForestSens platform (https://forestsens.com) with the SegmentAnyTree v2 model (Wielgosz et al. 2024, 2026); the segmented tiles were merged to avoid counting trees more than once. Tree height was measured directly from the individual-tree point clouds, whereas dbh and

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species class (spruce, pine or birch) were predicted for each tree with the 4Heads model (Xiang et al., in review), available in the same platform. In total, 9,510 trees were detected in the 16 stands of the study area, 8,035 of them in the 10 productive stands. Of these, 56 % were classified as birch, 24 % as pine and 20 % as spruce, a higher share of birch than suggested by the management plan, which classifies all ten productive stands as pine- or spruce-dominated.

SI, stand age, development class and dominant species were obtained from the forest management plan. For the simulations, development class was recalculated from SI and stand age using the classification rule implemented in the simulation pipeline. The remote-sensing inventory provided the initial tree population for the simulations starting in 2026. Before initialisation, the six unproductive stands were excluded because they lacked the numeric site index values required by the growth models. A minimum dbh threshold of 5 cm was also applied, excluding 530 trees from the productive stands. The final simulation dataset therefore comprised 7,505 trees across ten stands with a total mapped area of 12.84 ha. However, the tree inventory covered only part of the stand polygon in five of these stands (25, 26.1, 34, 39 and 40).

Additional variables required by the simulation pipeline but unavailable in the management plan—vegetation type, soil type (mineral or peat), harvesting cost and transport-cost region—were assigned from the nearest NFI plot with the required information in the 2018–2022 inventory cycle. Given the small extent of the study area (approximately 370 × 400 m) relative to the NFI grid spacing, all cells were assigned values from the same plot, located approximately 4.6 km away. These included mineral soil, a harvesting cost of approximately 195 NOK/m^3 and the transport-cost region Østlandet. For the four stands fully covered by the tree inventory, the simulated standing volume at the start of the simulation (2026) was 60–89 % of the volume reported in the management plan (2021). In the five stands only partly covered by the inventory (25, 26.1, 34, 39 and 40), it was only 6–40 %, so their results should be interpreted with caution. This comparison provides a consistency check between the two data sources, although the different reference years and inventory methods should be considered when interpreting the discrepancies.

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Table 10. Details about LL North data sources related to this deliverable.

Data	Source	Details	Variables used	Date
Tree inventory	UAV LiDAR point cloud. Pre-processing with PDAL (buffered tiling, voxelization); individual-tree segmentation with SegmentAnyTree via NIBIO's ForestSens API; tiles merged so that each tree is counted once	9,510 trees detected in 16 stands, 8,035 in the 10 productive stands	Position (UTM 32N); height measured from the point cloud; dbh and species (spruce / pine / birch) predicted per tree with the 4Heads model	2026
Stand attributes	Owner's forest management plan	16 stands, 10 productive	Site index (H40), stand age, development class, dominant species, area	2021
Growth, mortality and ingrowth reference data	Norwegian NFI permanent plots (250 m2)	Re-measured plots, nearest-neighbour imputation	5-year diameter increment, survival, ingrowth	NFI cycles 2005–2009, 2010–2014 and 2015–2019
Site and cost attributes	Nearest NFI plot (approx. 4.6 km)	One donor plot for the whole property; transport region assigned directly	Vegetation type, mineral/peat soil, harvesting cost (approx. 195 NOK/m3), transport region (Ostlandet)	NFI cycle 2018–2022
Timber prices	Statistics Norway (SSB)	Average roundwood prices for sale; sawlog and pulpwood by species	NOK/m3	2019

Building on the dataset described above, the following section presents the simulation results for LL North across the evaluated management regimes.

2.4 Results

This chapter presents the detailed results of the modeling approaches for each Living Lab. Given the diversity of stands, modeling frameworks, and silvicultural guidelines applied, each section focuses on the results with the greatest relevance and impact for the respective site.

LL South

Pinus pinaster: main stand-level variables

Stand density progressively diverged across all four silvicultural itineraries. The unmanaged control maintained the highest tree stocking throughout the rotation,

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concluding at approximately 370 trees/ha. In contrast, the managed scenarios reduced final density to a narrow range between 210 and 230 trees/ha, with the lowest density recorded under bau (210 trees/ha) following its heavy initial harvest.

Thinning type provided a marked influence on individual tree growth and stem dimensions. The moderate scenario, driven by progressive thinnings from below that selectively removed suppressed and smaller trees, consistently sustained the highest quadratic mean diameter throughout the rotation. It attained a final diameter of approximately 52 cm. The remaining scenarios followed comparable, lower trajectories: bau recovered from its early dominant-tree removals to reach 48 cm, followed by wildfire (47 cm), whereas the unthinned control exhibited the lowest diameter (45 cm) due to persistent stand competition and stem stagnation (see Figure 21 in Annex I).

Basal area dynamics clearly distinguished the conservation of growing stock among regimes. As expected, the unmanaged control accumulated the highest basal area across the entire cycle. Among the harvested itineraries, the moderate regime preserved substantially more basal area than the other alternatives, ending at 48 m^2/ha compared with 40 m^2/ha under wildfire and 38 m^2/ha under bau (see Figure 22 in Annex I). This confirms that gradual, low-intensity thinning preserves stand capital while promoting individual diameter increment.

Dominant height proved largely insensitive to the thinning regimes, varying within a narrow window of 24.5 to 25.2 m at the end of the rotation across all four scenarios (see Figure 23 in Annex I).

Pinus pinaster: timber production, biomass, and carbon stocks

Standing wood volume, aboveground biomass, and carbon pools closely mirrored basal area trajectories. The control scenario retained the largest in-situ timber volume and carbon reservoir at rotation end as no timber was extracted; however, this standing stock consisted of a greater number of smaller-diameter stems.

Among the managed options, the moderate thinning regime achieved the highest standing volume, biomass, and carbon storage at harvest (Table 11). Conversely, wildfire and bau yielded nearly identical, lower final standing volumes, reflecting either heavier cumulative biomass removals (bau) or systematic fuel-reduction thinnings (wildfire) that limited residual stand accumulation.

Pinus pinaster: non-timber forest products

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Annual edible mushroom production increased with stand age across all scenarios, yet management created dramatic divergences in production patterns and yield magnitude. The moderate scenario demonstrated an extraordinary capacity to stimulate fungal fruiting, exhibiting pronounced production pulses early in the rotation and around stand age 85. It peaked at an estimated 1,600 kg/ha/year at the end of the simulation, nearly doubling the yields of bau (900 kg/ha/year) and wildfire (800 kg/ha/year), while outperforming the dense control (660 kg/ha/year) by far (see Figure 24 in Annex I). These findings highlight that the canopy openness and basal area levels maintained under moderate thinning create optimal microclimatic and host conditions for sporocarp production. Nevertheless, these empirical models were not originally calibrated for long-term rotations and strongly rely on weather conditions (held constant across simulations); consequently, trajectories capture solely the relative influence of forest management, and absolute yield values should be interpreted with caution

Estimated annual resin production exhibited a downward trajectory across all scenarios as stands aged. Because region-specific empirical models accounting for thinning-induced resin stimulation are currently lacking in the literature, resin yield was estimated using a constant average rate (3 kg/tree) according with the literature available. Consequently, production directly reflected residual tree density. The control maintained the highest yields throughout, ending at 1.1 t/ha/year. In contrast, the managed scenarios registered step-wise decreases following each cutting operation, ending at 0.70 t/ha/year (wildfire), 0.65 t/ha/year (moderate), and 0.60 t/ha/year (bau) (see Figure 25 in Annex I).

Table 11. Simulated cumulative and standing wood volume (over bark), aboveground biomass, and carbon stocks at the end of the rotation under different management scenarios for P. pinaster in LL South.

Scenario	Accumulated wood volume (standing + extracted) (m^3/ha)	Standing wood volume (m^3/ha)	Accumulated aboveground biomass (standing + extracted) (t/ha)	Standing aboveground biomass (t/ha)	Accumulated carbon (standing + extracted) (t/ha)	Standing carbon (t/ha)
bau	600	410	280	190	180	125
control	625	625	300	300	190	190
moderate	600	500	290	240	185	160
wildfire	625	425	290	200	185	130

Pinus pinea: main stand-level variables

In the stone pine simulations, stand density remained constant at 160 trees/ha under the control scenario, reflecting the absence of an empirical mortality model for this species in the platform. Across the managed itineraries, stocking was reduced over time, ending at 105 trees/ha under bau (which applied four light systematic thinnings every 15 years

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while protecting 30% of the largest trees), 100 trees/ha under pine cones (a single thinning from below at age 115), and 80 trees/ha under wildfire (a low-intensity thinning at age 110).

Quadratic mean diameter followed virtually identical trajectories across all scenarios up to age 110, after which cutting interventions triggered marked divergence. The heavy opening in wildfire stimulated the strongest diameter response, reaching 62 cm by age 140. The pine cones scenario followed with 57 cm, whereas the bau and unmanaged control remained clustered at approximately 50 cm (see Figure 26 in Annex I).

Basal area peaked in the control scenario at 31 m^2/ha. Following their single interventions, wildfire and pine cones exhibited active basal area recovery, both converging at approximately 25 m^2/ha at rotation end. In contrast, the repetitive entries under bau progressively control growing capital, concluding with the lowest basal area (21 m^2/ha) characteristic of this stone pine stands (see Figure 27 in Annex I).

Dominant height developed steadily towards 23–24 m under control, bau, and pine cones. Conversely, the wildfire scenario experienced an apparent sharp decline to 19 m at age 110 (see Figure 28 in Annex I). This was an effect of the low stand density combined with allometric variability: thinning from below removed several slender, relatively tall individuals that had small diameters, altering the composition of the 100 thickest trees/ha that define dominant height.

Pinus pinea: timber production, biomass, and carbon stocks

Standing wood volume, aboveground biomass, and carbon stocks were highest under control due to total tree preservation. Among the active silvicultural regimes, pine cones retained the largest volume and biomass at rotation end, followed by wildfire (Table 12). The bau scenario consistently yielded the lowest standing stock, a consequence of repeated harvests over the 140-year horizon.

Pinus pinea: non-timber forest products (pine cones and pine nuts)

Healthy pine cone biomass and nut production patterns were tightly linked to residual tree density. In the control, yields remained flat throughout the simulation (0.21 t/ha/year of cones and ~47,000 nuts/ha/year). Managed itineraries exhibited step-wise decreases synchronized with thinning entries (see Figure 29 in Annex I).

Among managed regimes, pine cones maintained the highest yields (0.16 t/ha/year of cones and 38,000 nuts/ha/year), demonstrating that a targeted late thinning from below preserves a productive canopy while improving individual crown vigor. The wildfire scenario yielded 0.15 t/ha/year (35,000 nuts/ha/year), while bau recorded the lowest

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yields (0.12 t/ha/year and 30,000 nuts/ha/year), as frequent thinnings diminished the cone-bearing tree pool without sufficient recovery intervals.

Table 12. Simulated cumulative and standing wood volume (over bark), aboveground biomass, and carbon stocks at the end of the rotation under different management scenarios for P. pinea in LL South.

Scenario	Accumulated wood volume (standing + extracted) (m^3/ha)	standing wood volume (m^3/ha)	Accumulated aboveground biomass (standing + extracted) (t/ha)	standing aboveground biomass (t/ha)	Accumulated carbon (standing + extracted) (t/ha)	standing carbon (t/ha)
bau	275	215	210	160	130	100
control	320	320	240	240	145	145
pine cones	300	255	230	200	140	120
wildfire	300	245	235	200	140	120

Pinus pinea: stand structure, diversification, and biodiversity (*Quercus ilex* integration)

Introducing *Quercus ilex* into the understory at stand age 80 revealed two key ecological and productive findings.

- Compatibility with pine cone production: diversification did not compromise fruit yield. In fact, simulated healthy cone biomass and nut yields increased across all scenarios compared with pure stands. At age 140, cone production reached 0.32, 0.20, 0.18, and 0.17 t/ha/year under control, bau, pine cones, and wildfire, respectively (corresponding to 72,000, 45,000, 41,000, and 39,000 nuts/ha/year). Notably, bau improved its relative performance, shifting from the lowest-yielding regime in pure stands to the second-highest in the mixed stand.
- Silvicultural thinning rules versus biodiversity persistence: in pure pine stands, species diversity indices were uniformly zero. When *Q. ilex* was introduced, species diversity (Shannon H', Simpson, Margalef, Pielou) only persisted under the control (H'=0.64) and BAU (H'=0.63) scenarios. However, under wildfire and pine cones, diversity indices dropped back to zero. This divergence occurred because thinning from below strictly targets smaller diameter classes, inadvertently felling the young *Q. ilex* cohort and eliminating species diversification.
- Structural complexity: where *Q. ilex* survived (control and bau), diameter and height variability increased drastically, with CV (Coefficient of Variation) in dbh jumping from ~28% to over 100% and CV in height from ~19% to 82–85%. In contrast, regimes with lower-tier thinning prevented vertical stratification, illustrating that standard thinning algorithms must be adjusted when managing mixed, multi-layered stands to avoid eradicating secondary species.

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LL Central

The simulation results for LL Central were analysed using indicators for the forest ecosystem services timber production and carbon sequestration, and proxies for biodiversity. Overall, the silvicultural management scenarios had a stronger effect on the indicator values than the climate scenarios. Indicators, however, decreased in the majority of properties and investigated services under climate change. An exception was deadwood, which tended to increase, particularly under RCP8.5.

Timber production

Timber harvested volume and forest increment are jointly used to assess the sustainability of each silvicultural management scenario. Sustainable timber production is particularly important for small private forest owners; therefore harvest should not exceed the increment. None of the simulated scenarios exceeded this threshold on any property. However, both potential future harvests and increment decreased substantially under RCP8.5.

Carbon sequestration

The potential for carbon storage in harvested wood products and the substitution of fossil fuels and non-timber construction materials were directly linked to harvest intensity and therefore followed the same pattern as timber harvest volumes. Carbon storage in forest biomass was highest under the no-management scenario (NO) in all cases except P7. The overall carbon sequestration potential of each management scenario can be assessed by combining both carbon indicators, i.e. carbon stored in the forest and carbon stored in the harvested wood products, including substitution effects.

Proxies for biodiversity

Deadwood volumes were highest under NO in most properties, while differences among scenarios including harvest activities were rather small. The number of large trees (dbh ≥ 60 cm), used as a proxy for habitat trees, differed strongly between NO and the managed scenarios, especially in P2 and P3. The effect of habitat tree protection was clearly evident. Under climate change, fewer habitat trees could be retained throughout the simulation period, suggesting that additional trees would need to be selected over time to meet biodiversity funding criteria. Tree species diversity remained stable across climate scenarios and most management scenarios (see Annex I). However, NO resulted in lower tree species diversity in established stands (property P1 - P4). An exception was property P7, where natural regeneration in the disturbed area increased tree species diversity compared with management scenarios involving artificial planting.
Detailed results on the basal area development by per tree species under the different management and climate change scenarios for each property is shown in Annex I.

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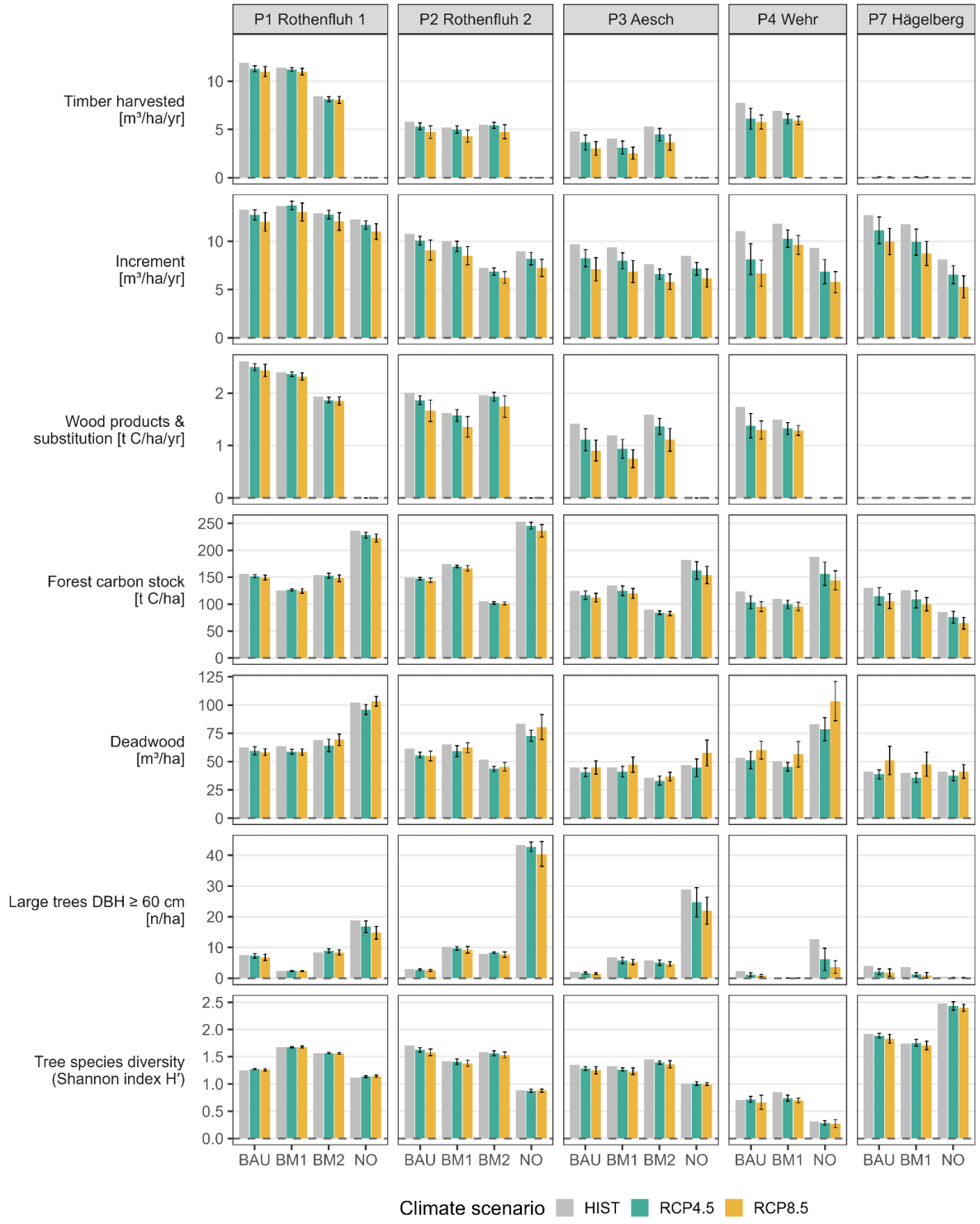


Figure 5. Biodiversity and ecosystem service indicators for the five forest properties under four management scenarios (BAU, BM1, BM2, NO) and three climate scenarios (HIST, RCP4.5, RCP8.5), averaged over the period 2025–2095. Results for the climate change scenarios are presented as the mean ± 1 standard deviation (SD) across ten CH2018 climate models.

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Dashboard for communication with SFO

The manifold results for the different properties in the central LL were summarised and illustrated in an interactive dashboard (Figure 6), which allows to elaborate the alternative effects of management and climate change scenarios on biodiversity and ecosystem service groups as well as the underlying indicators to measure them. The intention is to provide small forest owners an understanding on how their forests contribute to the forest multifunctionality. The dashboard was amongst other used during a workshop in the Central LL in November 2026, where the simulations results of selected properties were presented to the small forest owners.



Figure 6. Dashboard summarising and illustrating the simulation effects of management and climate change scenarios on biodiversity and ecosystem service groups as well as the underlying indicators. Shown are the changes in carbon pools for the property one (Rothenfluh, Switzerland).

LL East

SIMANFOR: stand development and thinning yields

All four stands accumulated volume over their respective rotations, with stepwise reductions at commercial thinnings and subsequent recovery through increment (Figure 7). In the supplied exports, the last commercial thinning occurs at age 80 in beech and fir, age 60 in spruce and age 50 in pine. Cumulative thinning yields were 426.8, 489.6, 422.6

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and 216.7 m^3/ha, respectively. Because initial densities and rotation ages differ, the final stocks are descriptive species-specific projections rather than directly controlled comparisons of species productivity.

Table 13. SIMANFOR projections at the end of each species-specific rotation, with cumulative thinning yields computed from the supplied simulation workbooks (N = stand density; dg = quadratic mean diameter; G = basal area; Ho = dominant height; V = volume over bark).

Species	Final age	N (trees/ha)	dg (cm)	G (m^2/ha)	Ho (m)	V (m^3/ha)	Thinnings (m^3/ha)
Fagus sylvatica	110	1,298.45	43.56	205.75	40.06	913.74	426.78
Abies alba	110	3,189.84	49.53	653.72	40.75	1,106.40	489.62
Picea abies	100	1,734.07	45.08	296.46	40.96	1,138.06	422.58
Pinus sylvestris	70	1,824.27	29.40	133.74	31.15	744.44	216.73

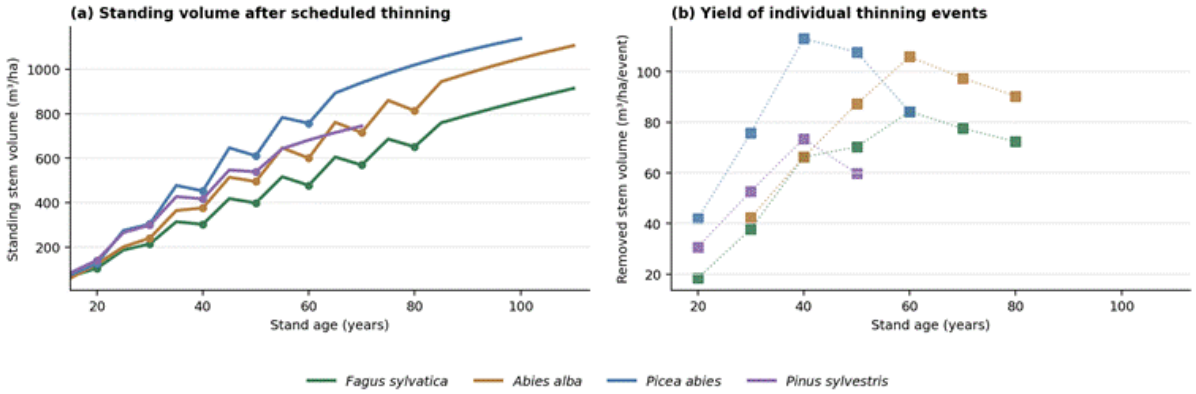


Figure 7. Stand-level Romanian BAU trajectories from SIMANFOR: (a) volume remaining after each scheduled thinning, and (b) volume removed during individual thinning events. Each species has a different rotation age.

ForestFuture: mixed-stand alternatives

The recorded Cobor demonstration compared a Romanian group-shelterwood BAU pathway (RI-HM-FAG-PRO-01: final age 110 years, 9-year thinning interval, 13.125% basal-area thinning, 85% natural regeneration, three retained trees/ha and 12 m^3/ha deadwood target) against biodiversity- and carbon-oriented options. Over a 100-year simulation with five-year steps, BAU received the highest weighted decision score (67.3) under the selected user preferences. The carbon alternative had the greatest final carbon stock (803.7 t CO_2/ha) and standing volume (622.8 m^3/ha), while the biodiversity alternative had the highest structural-biodiversity score (81.2/100; Figure 8).

Table 14. ForestFuture results for the recorded Cobor example; NPV and peak capital requirement are euro values for the simulated stand and depend on the illustrative cost assumptions and owner weights.

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Scenario	Decision score	NPV (€)	Peak capital (€)	Final volume (m^3/ha)	Final carbon (t CO_2/ha)	Biodiversity (%)
BAU	67.3	42,839	2,533	534.9	731.3	69.3
Carbon sink	51.3	−23,768	70,043	622.8	803.7	55.3
Biodiversity	43.5	−25,382	51,867	351.7	515.2	81.2

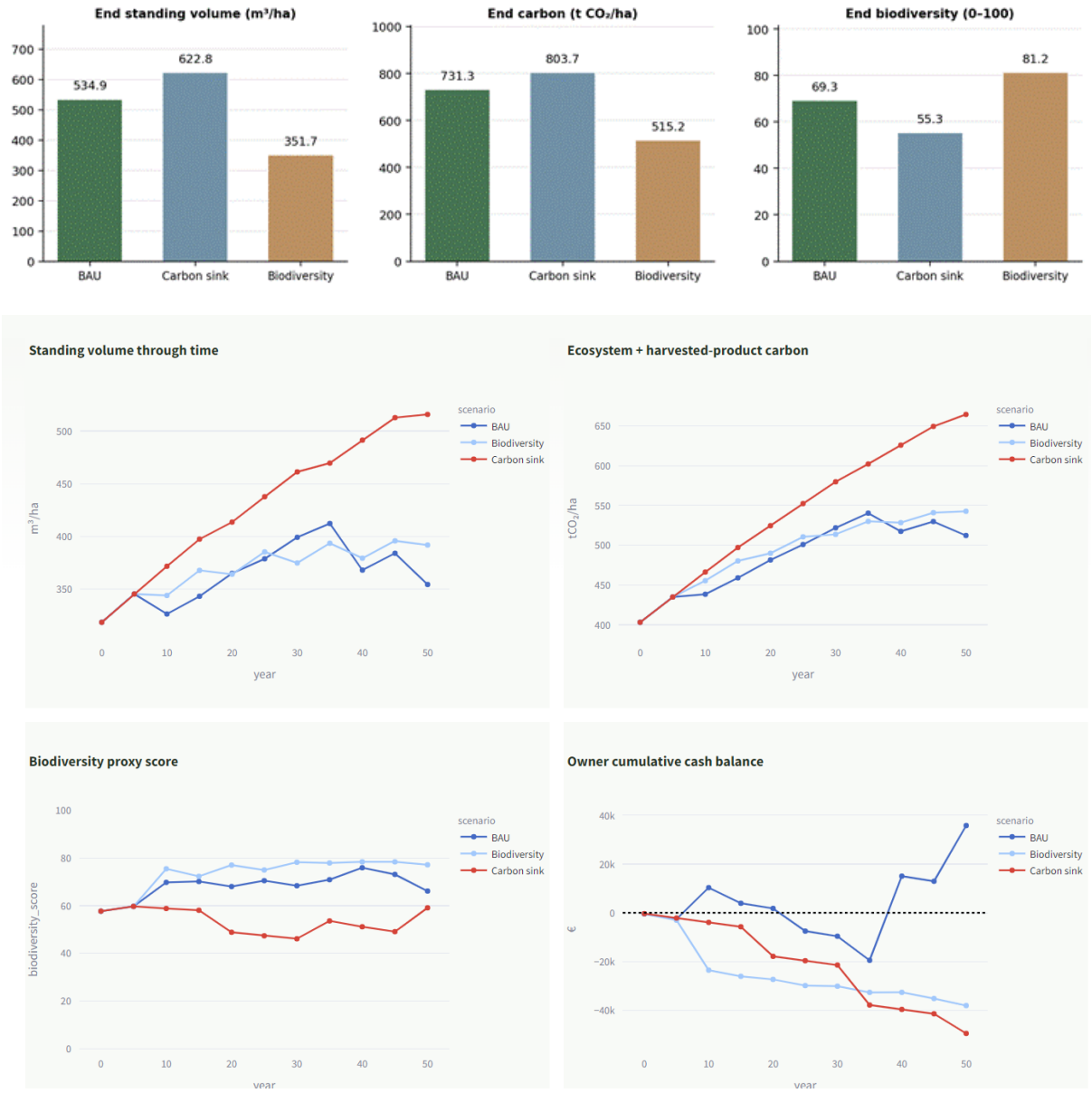


Figure 8. ForestFuture end-of-horizon comparison for the same mapped Cobor stand: standing stock, tracked carbon and the modelled structural-biodiversity proxy.

Unlike the aggregate stand-level runs, ForestFuture also identifies the individual trees removed or retained and the position of regeneration gaps. Figure 9 illustrates the initiation and expansion phases of the same group-shelterwood pathway, with standing

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trees, past/current removals, protected elements and young regeneration visually distinguishable. This spatially explicit representation is the main complement to the yield-table trajectories, not an independent validation of regeneration success.



Figure 9. ForestFuture tree-level maps illustrating (a) the initiation cut and (b) gap-expansion phase within a Romanian group-shelterwood BAU pathway. Dashed circles indicate simulated openings; regeneration symbols are illustrative, not measured regeneration densities. Source: LL East ForestFuture Portal.

Both tools deserve a joint interpretation and highlight their limitations. The two approaches answer different questions: SIMANFOR describes reference stand growth and intermediate wood yields, whereas ForestFuture explores spatial treatment decisions and owner-oriented trade-offs. The stand-level numerical values, especially high late-rotation basal area in some pure-stand runs, require plausibility checks before site-specific prescription; ForestFuture biodiversity scores, spatial gap rules and hypothetical carbon/economic assumptions likewise require calibration. Neither dataset provides a directly comparable, climate-forced prediction for every management regime.

LL North

Stand development and harvests

The six regimes represent alternative management trajectories for the same forest. Each is simulated independently over 100 years, starting from the forest conditions recorded in the 2026 inventory. Within each stand, differences among regimes therefore reflect management effects alone. As most stands are already mature, the even-aged regimes (BAU, INT and MULT) concentrate final fellings early in the simulation. Under BAU, two-thirds of the productive area undergoes final felling within the first five-year period. Standing volume consequently declines sharply, reaching a minimum of approximately 20–30 m^3/ha around 2056, before recovering as the regenerated stands grow. By 2126, standing volume reached 280 m^3/ha under INT, 226 m^3/ha under MULT and 216 m^3/ha under BAU (Figure 10). CS follows a similar trajectory, but final fellings are delayed by 5–10 years in the oldest pine stands and by 30–40 years in the spruce stands. Consequently, the regenerated stands are still relatively young at the end of the simulation, with a standing volume of 109 m^3/ha. Under CCF, clear-felling is excluded, and the four spruce stands are harvested at 15-year intervals, with each intervention removing 12–28% of standing volume. Despite these periodic removals, standing volume increases from 75 to

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293 m^3/ha over the simulation period. Under SA, where no harvesting occurs, standing volume increases steadily from 96 to 413 m^3/ha.

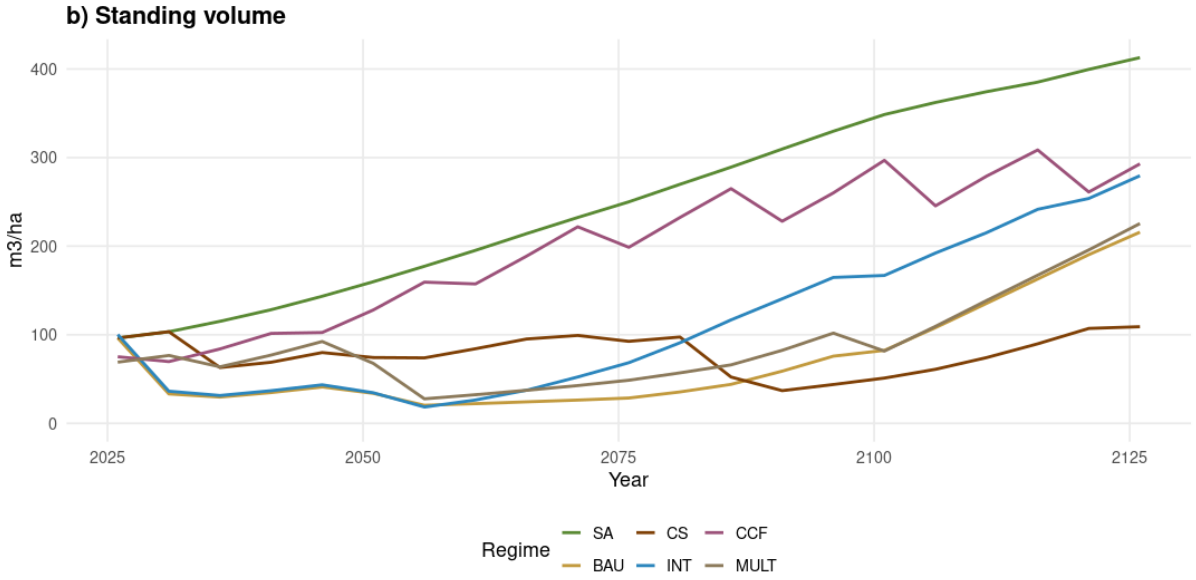


Figure 10. Standing volume (m^3/ha, stem volume under bark) in the study area over the simulation period (2026–2126) under the six management regimes. Values are per hectare of the area to which each regime applies: SA, BAU and CS cover all 10 productive stands (12.84 ha), INT 8 stands (10.31 ha), MULT the 5 stands on spruce sites (4.07 ha) and CCF the 4 spruce-dominated stands (3.39 ha).

These differences also shape the flow of timber and income over time (Figure 11). Under the even-aged regimes most of the harvest comes from a single final felling per stand, concentrated in the first decades and followed by a long period with little harvest. CCF instead provides smaller but regular harvests and keeps a continuous forest cover throughout the period.

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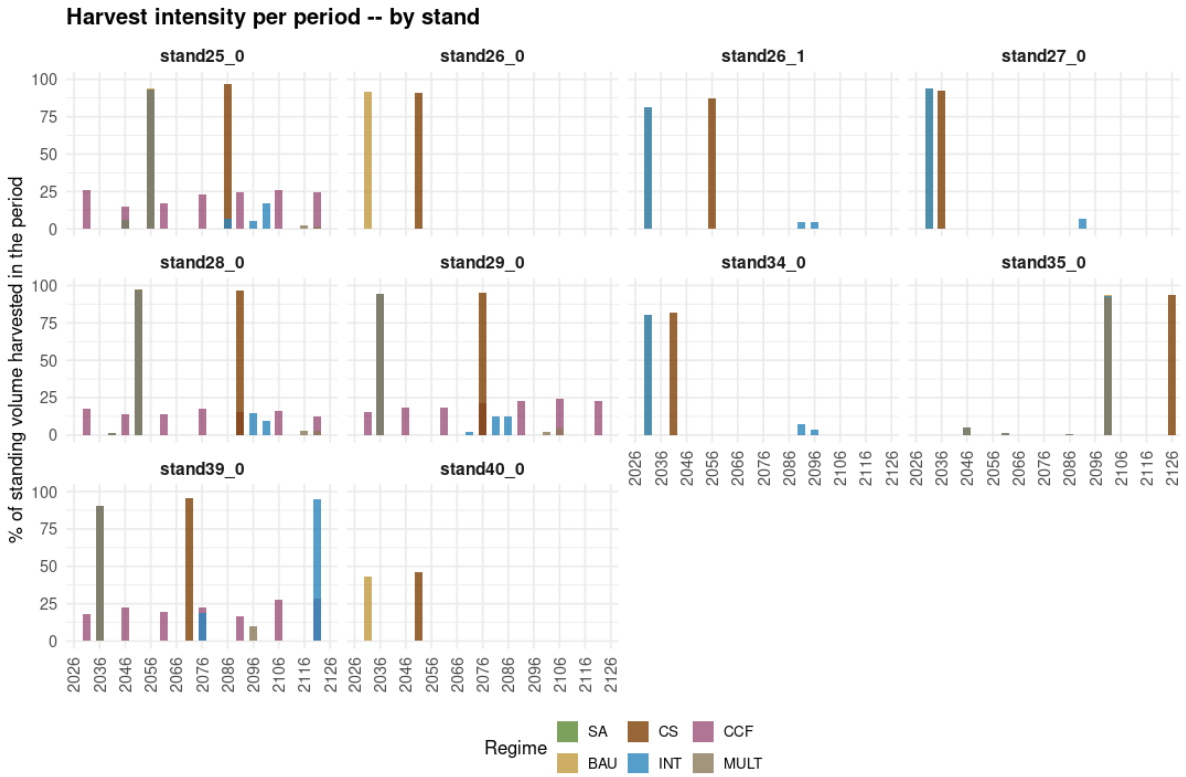


Figure 11. Harvest intensity per stand and 5-year period under the five managed regimes (harvested volume as a percentage of the standing volume before the cut). Each colour is a separate simulation of the same stand. Bars close to 100 % are final fellings (retention and seed trees remain standing); lower bars are thinnings (INT, MULT) or selective harvests (CCF). Missing bars indicate that the regime does not apply to that stand.

Timber production

Over the 100 years CCF yields the largest harvest per hectare of its own area (311 m^3/ha and about 50,000 NOK/ha), followed by CS (180 m^3/ha), MULT (166 m^3/ha), INT (156 m^3/ha) and BAU (114 m^3/ha). These averages, however, refer to different stands: CCF applies only to the four spruce-dominated stands on good sites, whereas the other regimes also include the less productive pine stands. On those four stands, CS (330 m^3/ha) and CCF (311 m^3/ha) give similar harvests, well above INT (209 m^3/ha), MULT (147 m^3/ha) and BAU (141 m^3/ha). CCF also shows the highest net volume production (harvest plus change in standing volume, 5.6 m^3/ha/yr), because its regular harvests remove trees before they die and the underplanted spruce keeps the stands growing (Figure 12).

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Carbon

The carbon stock in the forest is highest under SA, which increases from 216 to 578 t CO_2/ha (393 t CO_2/ha on average over the 100 years; Figure 11). Among the managed regimes, the ranking depends on whether the end year or the whole period is considered. In 2126, CCF (423 t CO_2/ha) and INT (393 t CO_2/ha) hold the most carbon, followed by MULT (358), BAU (313) and CS (160 t CO_2/ha), the only regime that ends below its initial level because its regenerated stands are still young. Averaged over the period, however, CCF keeps by far the most carbon (308 t CO_2/ha, against 120–169 t CO_2/ha in the even-aged regimes), because it never removes the whole canopy, whereas the even-aged regimes lose most of their stock at the early final fellings and only rebuild it towards the end. This average ranking also holds on the four stands where CCF applies (308 against 139–193 t CO_2/ha). The carbon stored in harvested wood products is small compared with the forest stock (below 2 t CO_2/ha on average).

Biodiversity

Under BAU, CS and INT the number of hotspot trees falls to almost zero (3–11 trees/ha) and tree species diversity drops from about 0.7 to about 0.25 (Figure 11), because the final fellings remove most of the old trees and the new stands are dominated by one planted species. MULT behaves differently: its mixed planting raises species diversity to 0.84 in 2126, the highest value of all regimes, and its retained broadleaved trees keep the number of hotspot trees close to the initial level. Without management, both indicators increase (352 hotspot trees/ha and a Shannon index of 0.75 in 2126). CCF keeps much of the species diversity (0.54) and shows the largest increase in hotspot trees (714 trees/ha); this last value should be interpreted with caution, because the indicator is based on stand age and also counts young trees in stands that are never clear-felled.

Interpretation and limitations

No single regime performs best across all indicators. In this mature forest, the principal trade-off is between early timber revenues and the retention of carbon and biodiversity: even-aged regimes with single-species replanting (BAU, CS and INT) concentrate timber production in the first few decades, at the expense of old trees and tree species diversity, whereas SA retains the largest carbon stock but generates no timber income. CCF combines high harvest volumes per hectare with high carbon stocks. However, its applicability is restricted to the four spruce-dominated stands on productive sites, so it cannot be considered a direct alternative for the property as a whole. MULT demonstrates the potential of mixed-species replanting to maintain tree species diversity while achieving timber yields comparable to INT. Extending the rotation (CS) postpones carbon losses but does not result in a higher carbon stock at the end of the 100-year simulation period. This time horizon also truncates the even-aged rotations, limiting the assessment of their full-cycle outcomes.

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These findings should be interpreted as an initial application of the approach. The analysis covers a 12.84 ha subset of the property, and the regimes apply to different sets of stands. Although results are expressed per hectare, differences in stand characteristics constrain direct comparisons. Climate change is represented solely through changes in site index under a single scenario (RCP4.5), and growth in regenerated stands may be somewhat overestimated. In addition, five stands were only partially covered by the tree inventory. Excluding these stands preserves the main contrasts among regimes but alters the relative rankings of MULT, INT and BAU and changes absolute indicator values by up to approximately 40%.

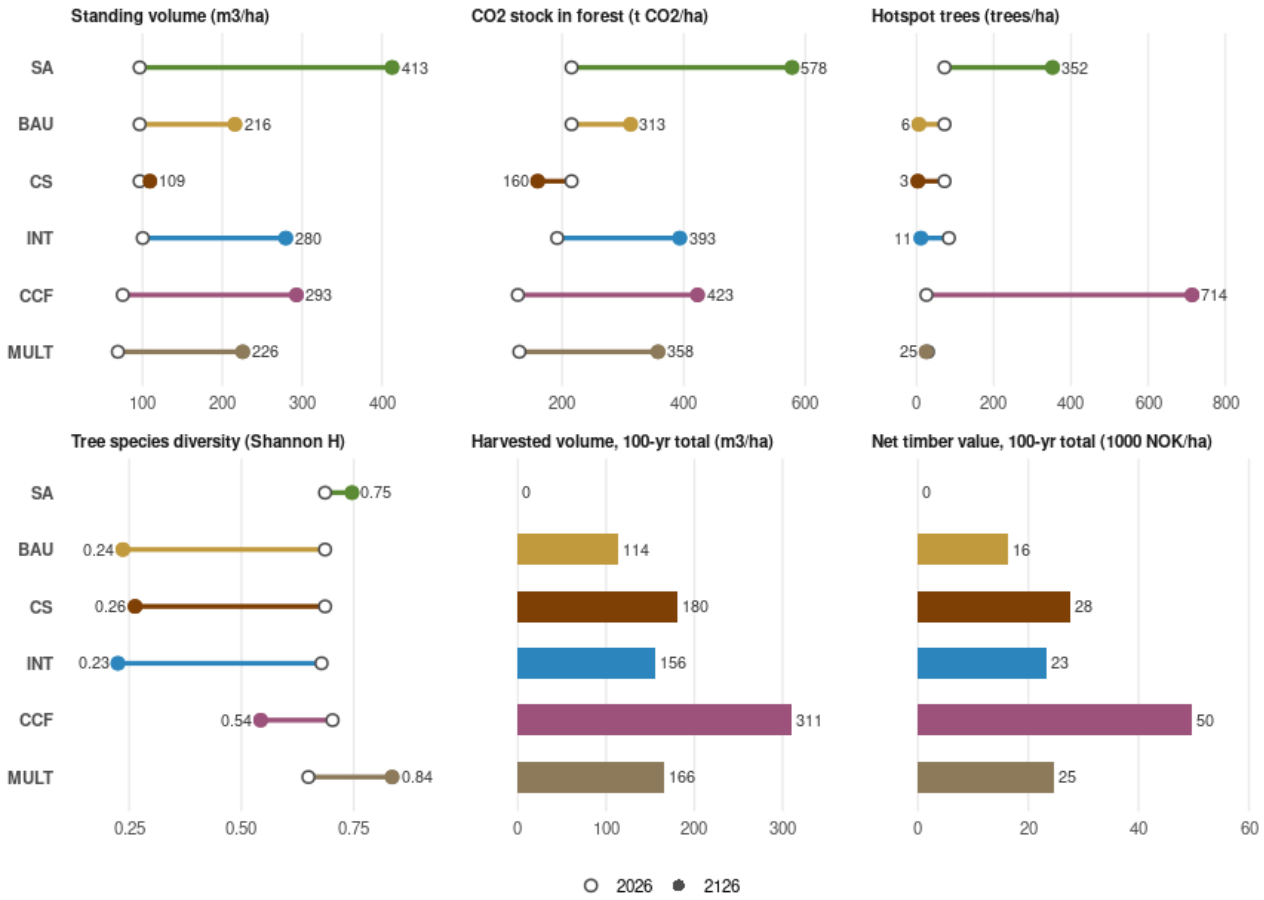


Figure 12. Comparison of the six management regimes at the start (2026, open circles) and the end (2126, filled circles) of the simulation for all the analyzed indicators. Values are per hectare of the area to which each regime applies. Starting values differ between regimes because INT, MULT and CCF apply to only part of the stands. The number of hotspot trees under CCF is overestimated, because the indicator is based on stand age.

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3. Conclusions

The four LL presented here highlight the importance of combining site-specific silviculture with a matching business model to support small forest owners. While no single prescription is adequate everywhere, the approach is common across the LLs in North, East, Central and South Europe. These results demonstrate that one-size-fits-all EU frameworks are insufficient for small owners and regionally differentiated guidelines and flexible support schemes must be proposed. In all LL we observed the trade-off between the short-term income (timber, mushrooms, pine nuts) and long-term ecological value (carbon stock, biodiversity). Each LL resolves this trade-off differently and even each owner must adapt the regional orientation to their own situation.

Climate change compounds this trade-off, shifting the productive and ecological baseline on which any prescription is built. The availability of climate-sensitive models is therefore essential, given the impact of climate change on ecosystem service provision and forest productivity. This reinforces the importance of designing silvicultural guidelines adapted to projected situations and flexible enough to incorporate adaptive management as conditions evolve. Yet even the most robust simulations, such as those conducted here over 70–100 year horizons, only reach owners through technical support grounded in local realities. Bridging this gap requires advisory services embedded in local ownership realities.

These findings feed directly into the forthcoming policy brief on multifunctional forest management, connecting owner-level practices with EU policy frameworks and science-based knowledge. Ultimately, science-based guidelines are only as effective as the extension services and capacity-building programmes that bring them to owners. The shortage of accessible, locally embedded technical support remains the critical implementation gap to implement political frameworks and complement science-based guidelines.

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5. Annexes

5.1 Annex I: Supplementary graphs

LL Central

Basal area development for all properties

Property P1: Rothenfluh 1

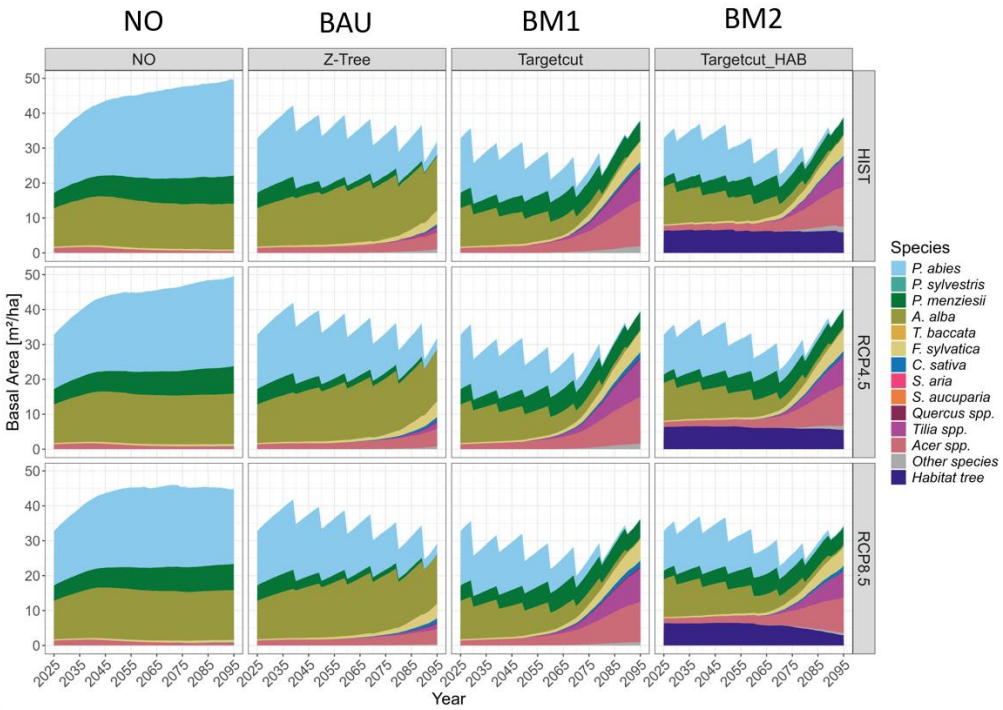


Figure 13. Simulated basal area development (m^2/ha) by tree species in P1 (Rothenfluh 1) for each management and climate scenario. The ten protected trees per hectare in BM2 are shown separately as habitat trees, irrespective of species.

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Property P2: Rothenfluh 2

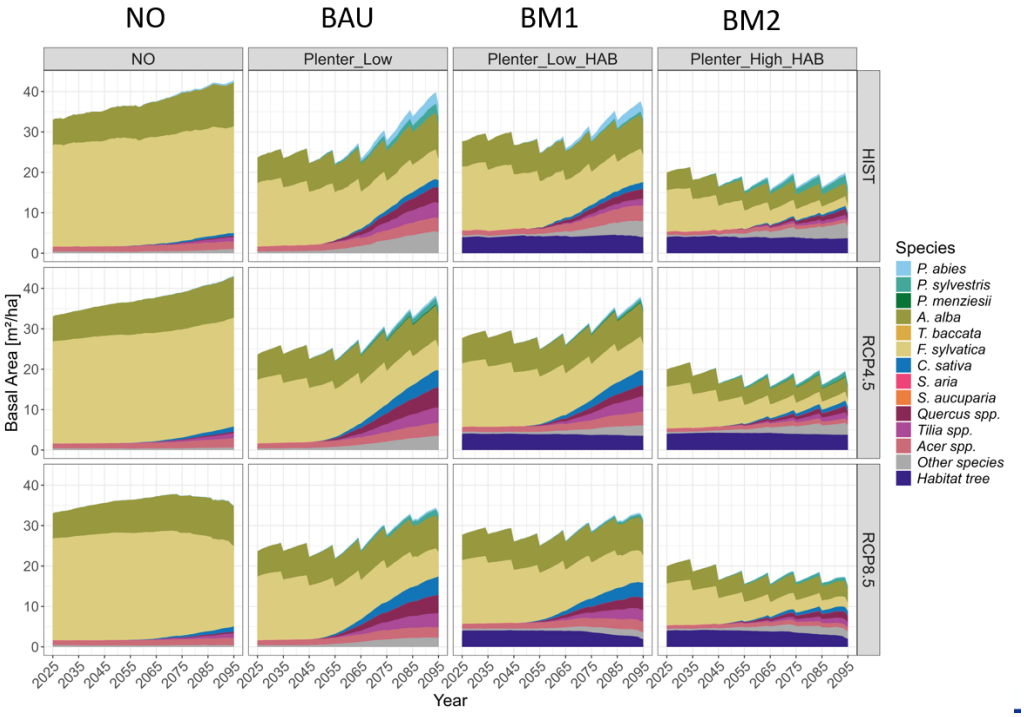


Figure 14. Simulated basal area development (m^2/ha) by tree species in P1 (Rothenfluh 2) for each management and climate scenario. The ten protected trees per hectare in BM1 and BM2 are shown separately as habitat trees, irrespective of species.

Property P3: Aesch

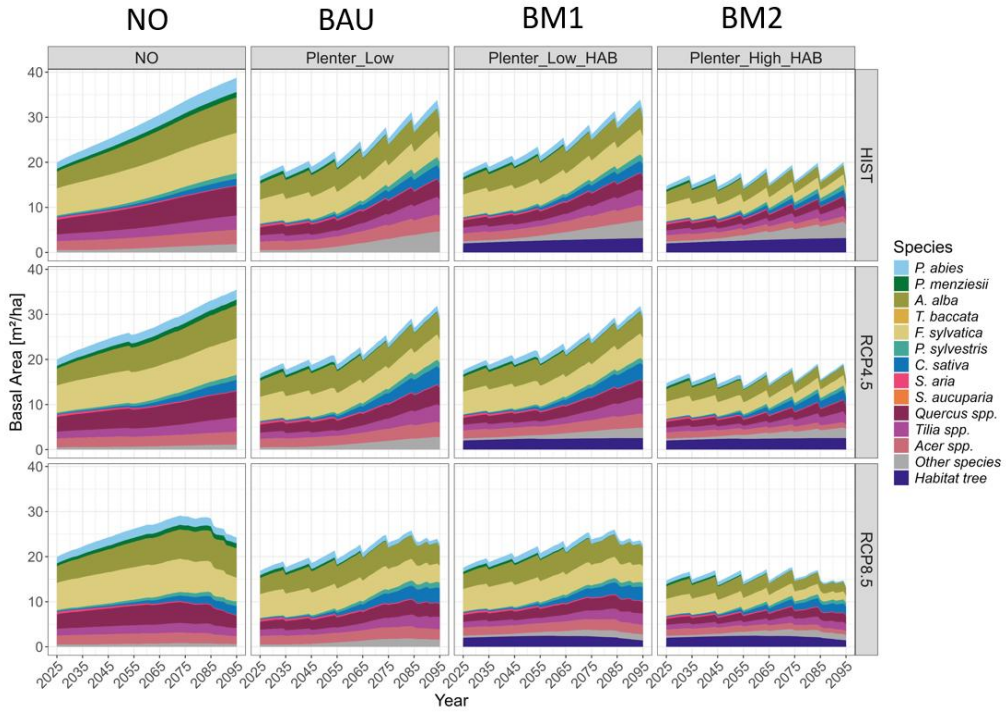


Figure 15. Simulated basal area development (m^2/ha) by tree species in P1 (Rothenfluh 2) for each management and climate scenario. The ten protected trees per hectare in BM1 and BM2 are shown separately as habitat trees, irrespective of species.

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Property P4: Wehr

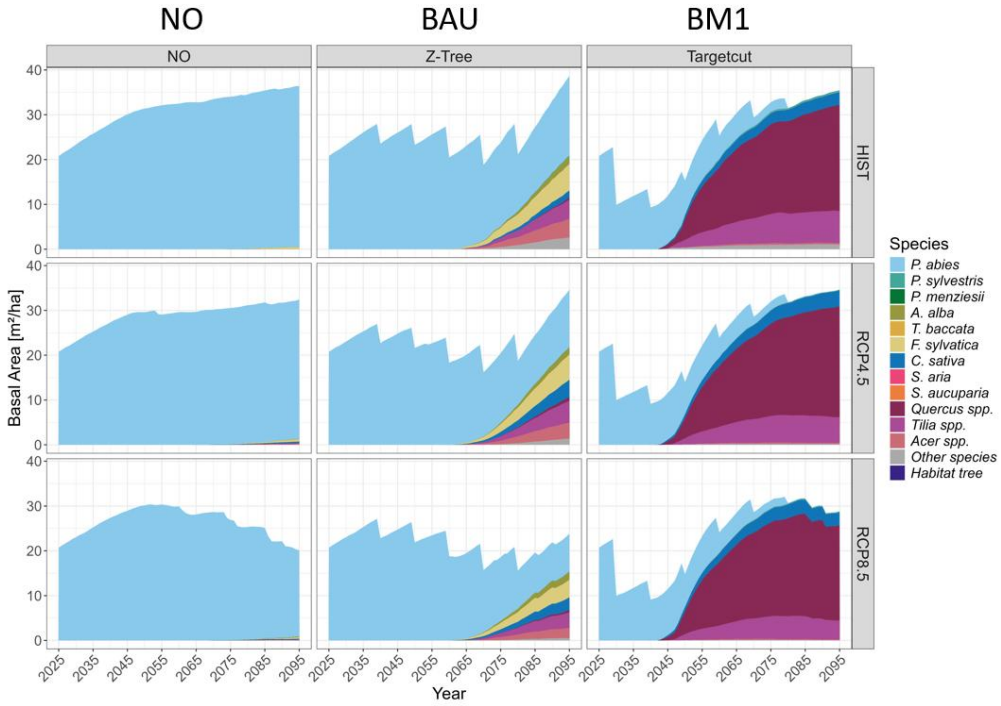


Figure 16. Simulated basal area development (m^2/ha) by tree species in P4 (Wehr), stand 1, for each management and climate scenario.

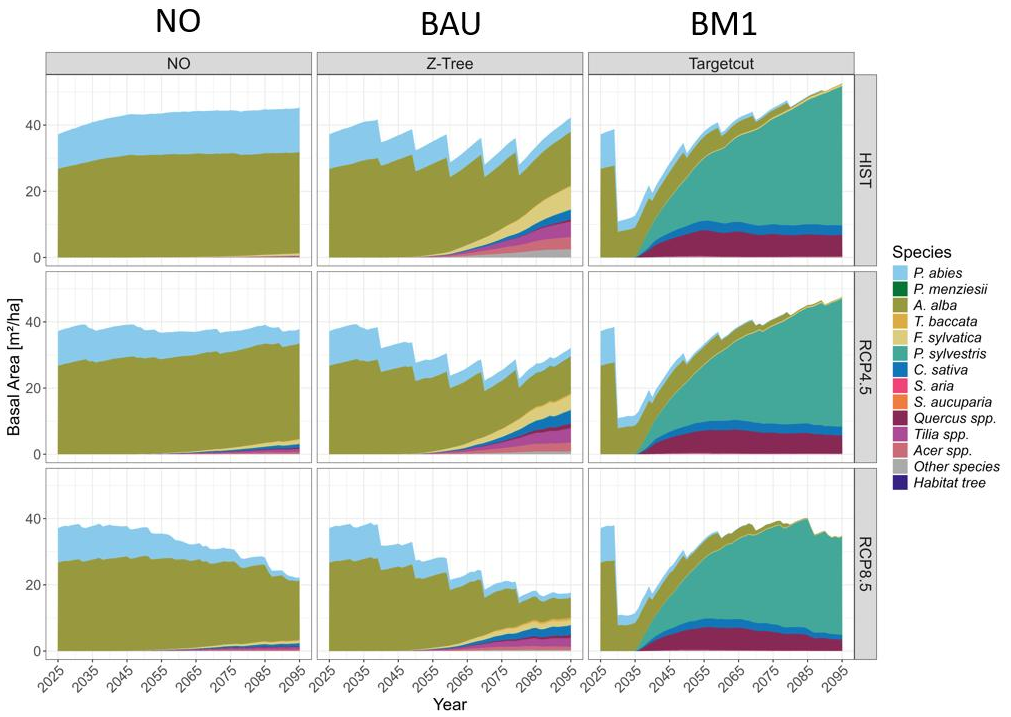


Figure 17. Simulated basal area development (m^2/ha) by tree species in P4 (Wehr), stand 2, for each management and climate scenario.

Property P7: Hägelberg

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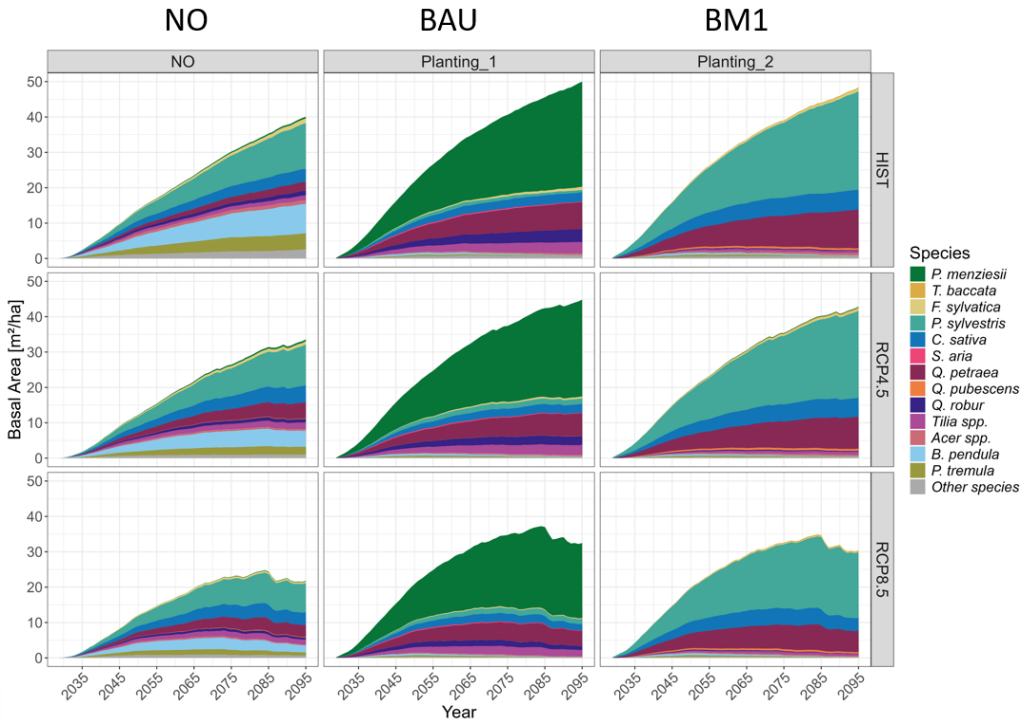


Figure 18. Simulated basal area development (m^2/ha) by tree species in P7 (Hägelberg) for each management and climate scenario.

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LL North

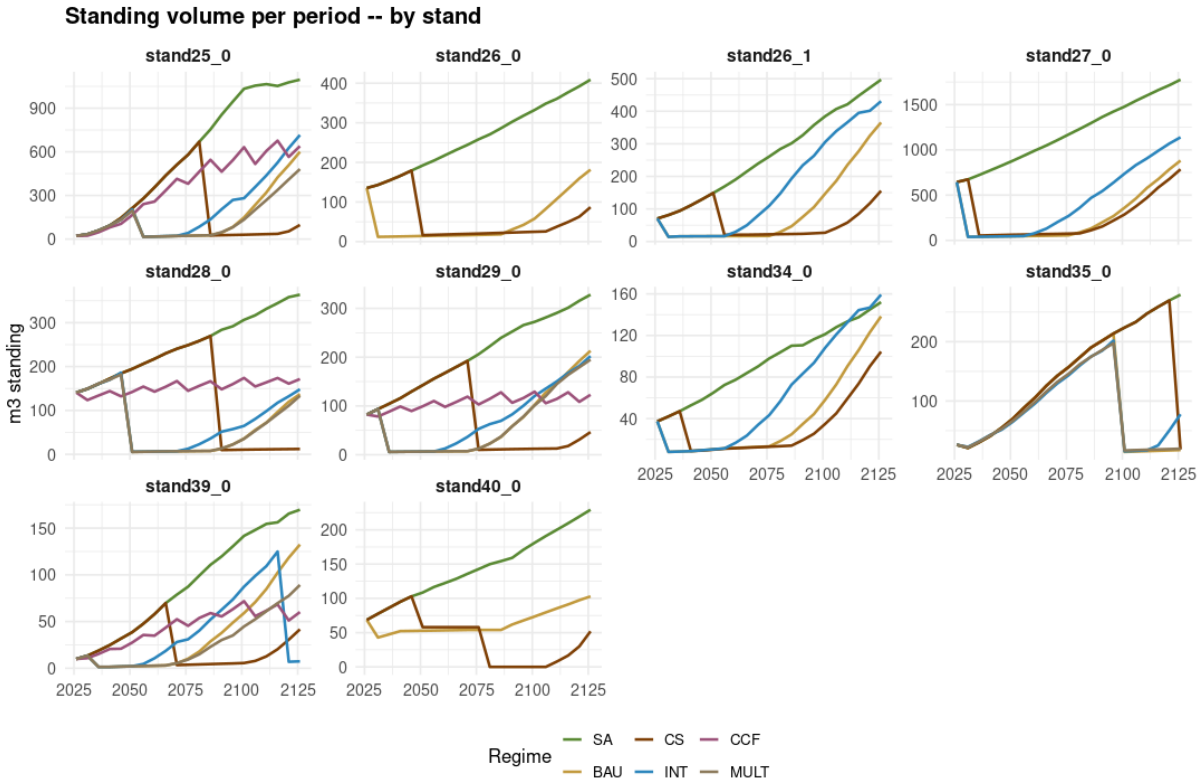


Figure 19. Standing stem volume (m^3, under bark) per stand over the simulation period (2026–2126) under the five management regimes: set-aside (SA), business-as-usual (BAU), carbon sink (CS), intensive (INT) and continuous cover forestry (CCF). Sharp drops correspond to final fellings, and the saw-tooth pattern under CCF to selective harvests every 15 years. Not all regimes apply to every stand (INT: 8 of 10 stands; CCF: the 4 spruce-dominated stands), and the y-axis scale differs between panels.

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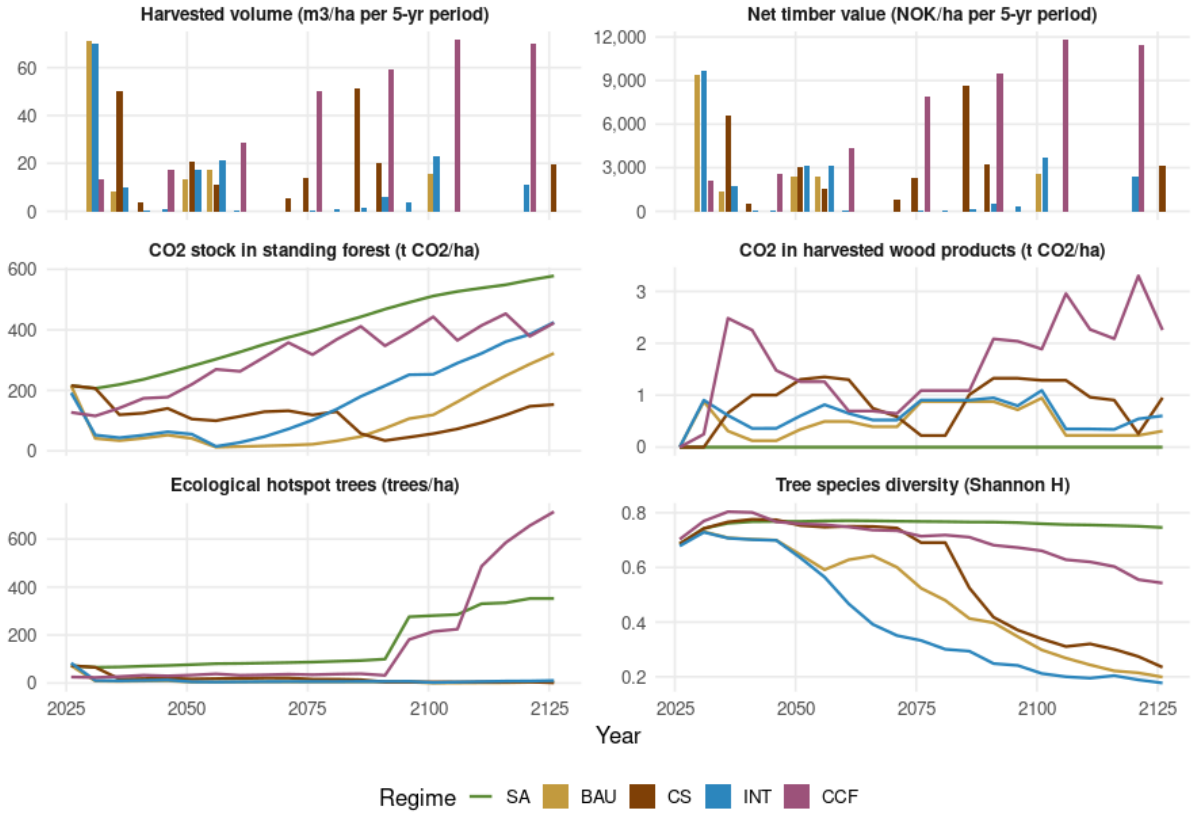


Figure 20. Ecosystem service indicators under the five management regimes, 2026–2126, as absolute totals. The regimes cover different areas (SA, BAU and CS 12.84 ha; INT 10.31 ha; CCF 3.39 ha), so totals are not directly comparable; per-hectare values are given in Figure 10.

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LL South

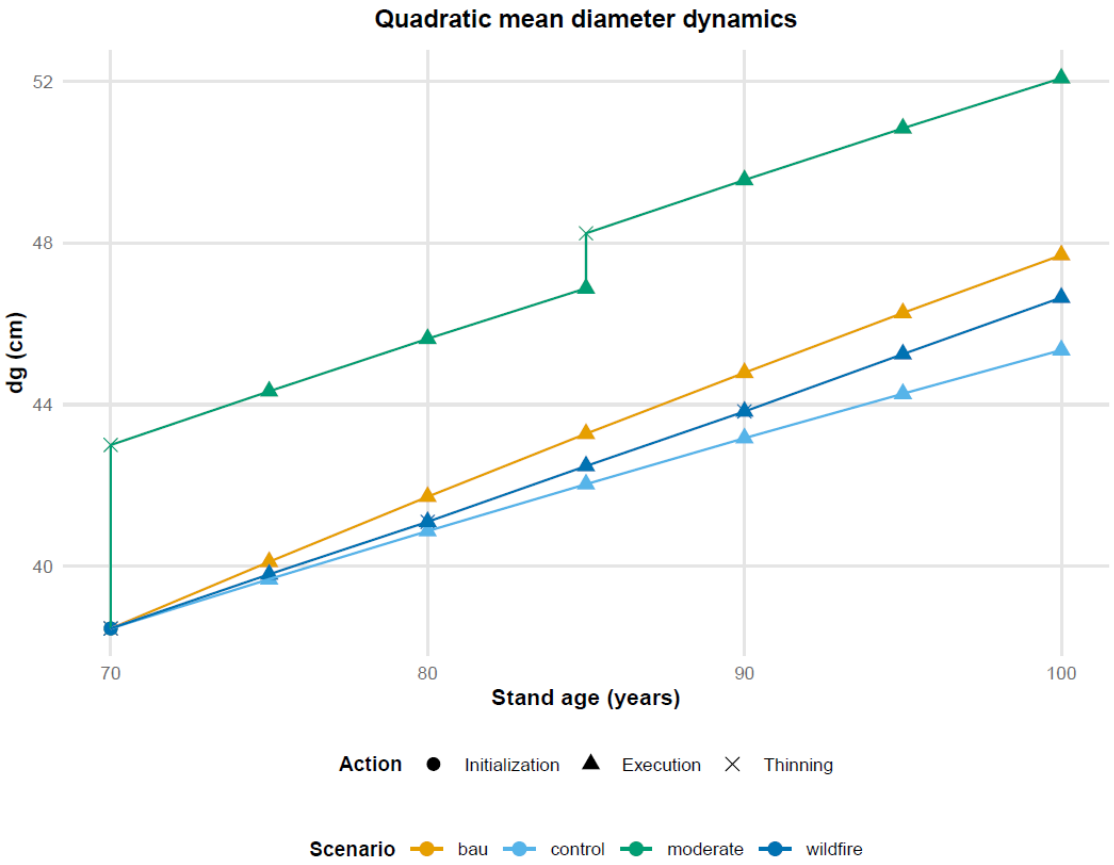


Figure 21. Evolution of quadratic mean diameter (cm) under the four silvicultural management scenarios in the Pinus pinaster stand.

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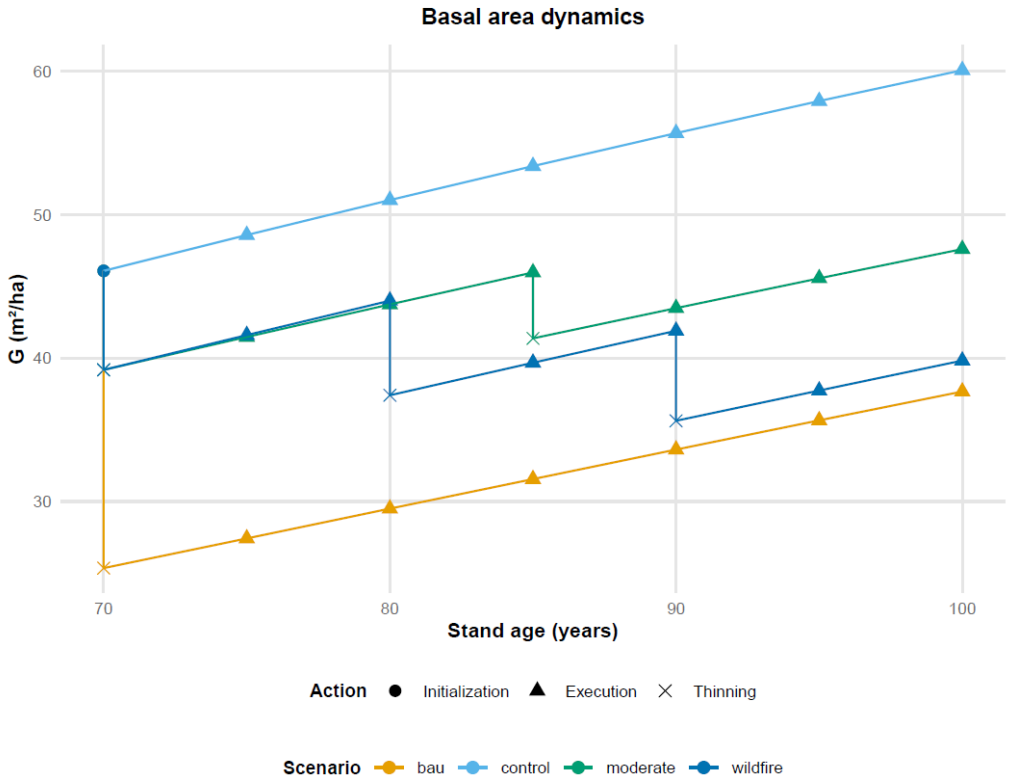


Figure 22. Evolution of basal area (m^2/ha) under the four silvicultural management scenarios in the Pinus pinaster stand.

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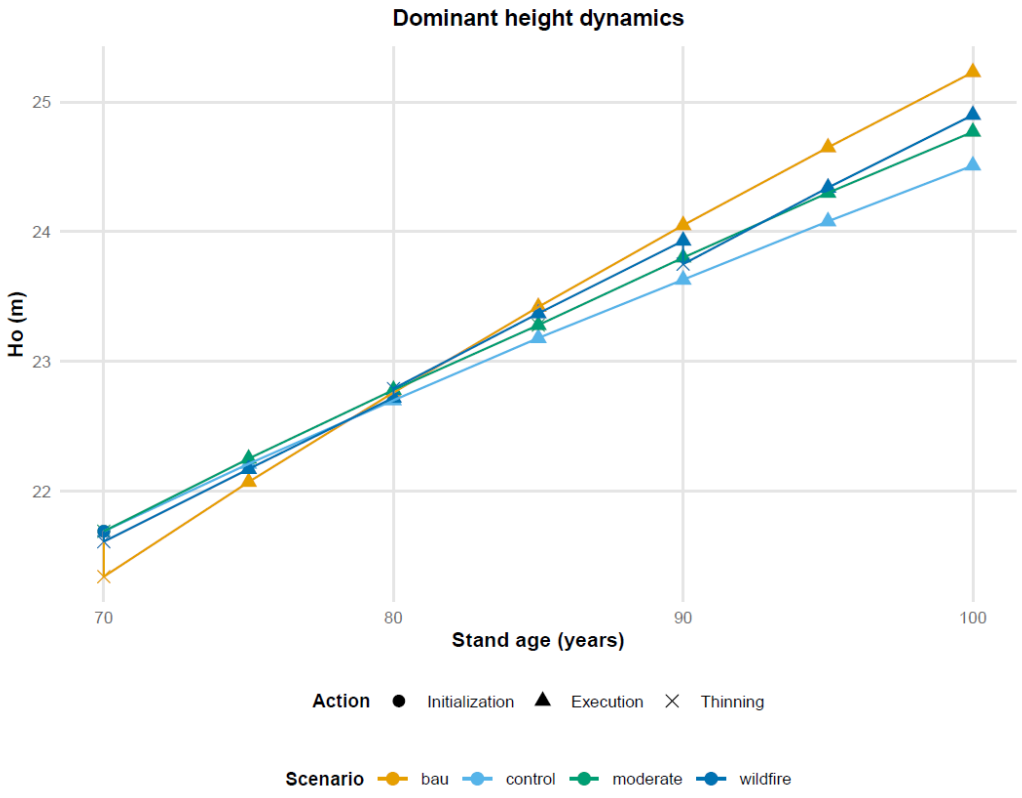


Figure 23. Evolution of dominant height (m) under the four silvicultural management scenarios in the Pinus pinaster stand.

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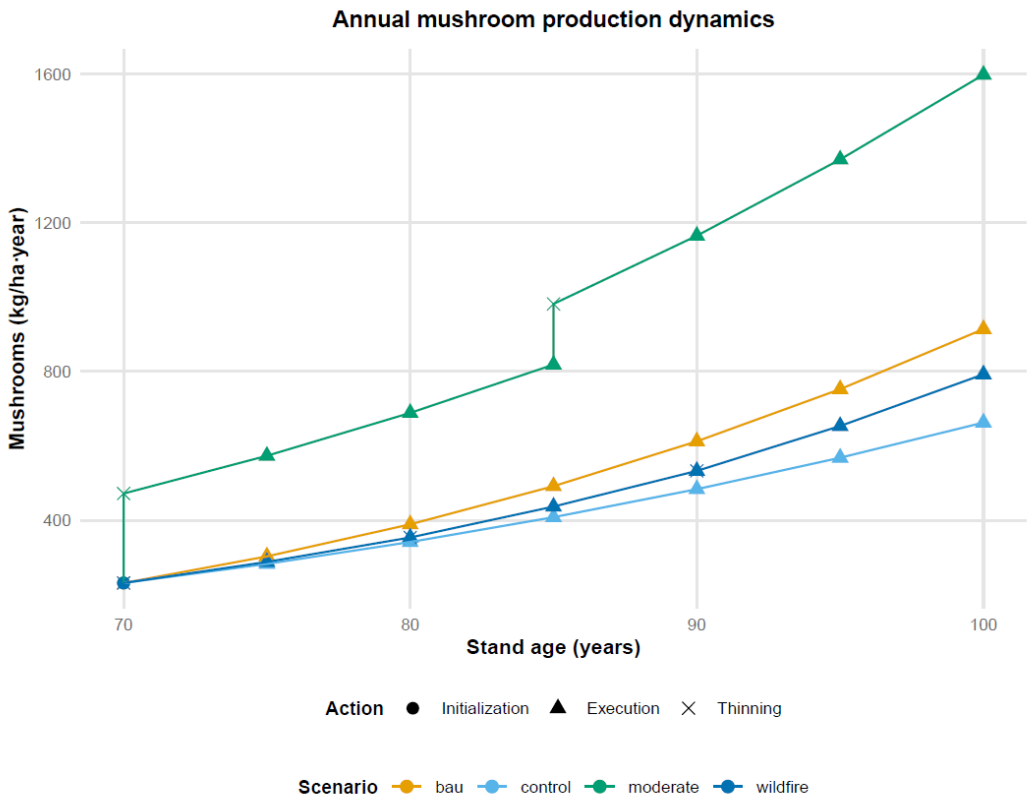


Figure 24. Evolution of estimated annual mushroom production (kg/ha/year) under the four silvicultural management scenarios in the Pinus pinaster stand.

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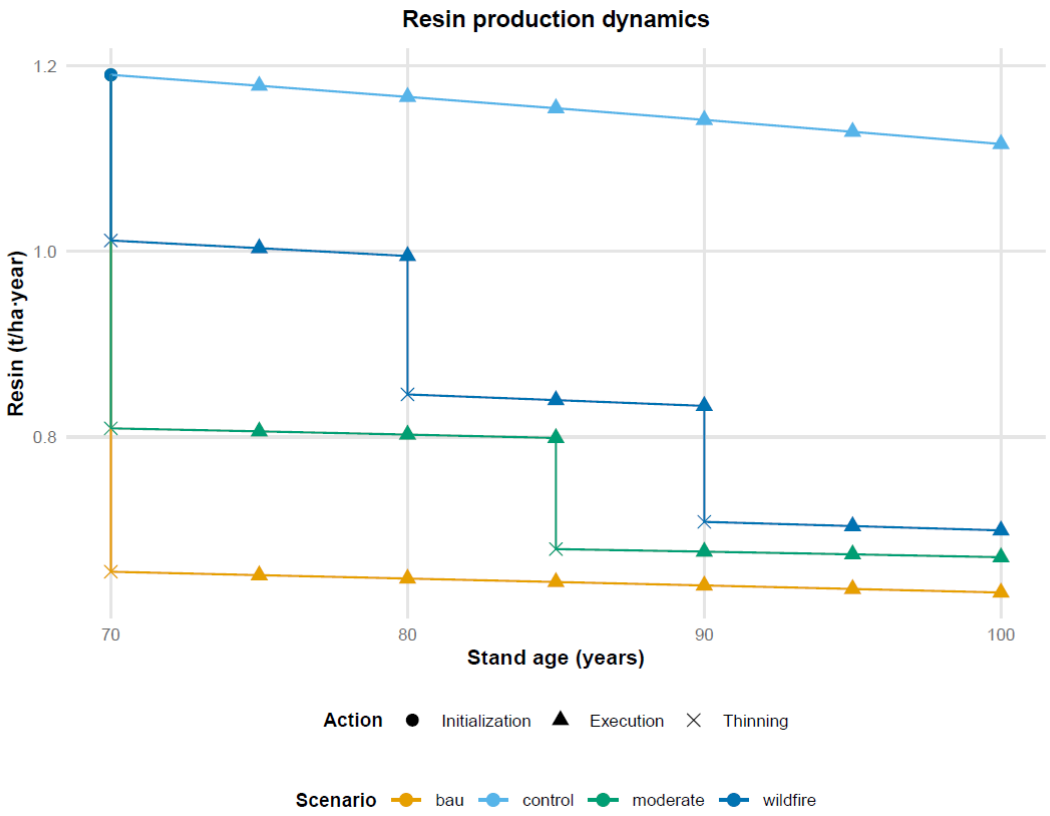


Figure 25. Evolution of estimated annual resin production (t/ha/year) under the four silvicultural management scenarios in the Pinus pinaster stand.

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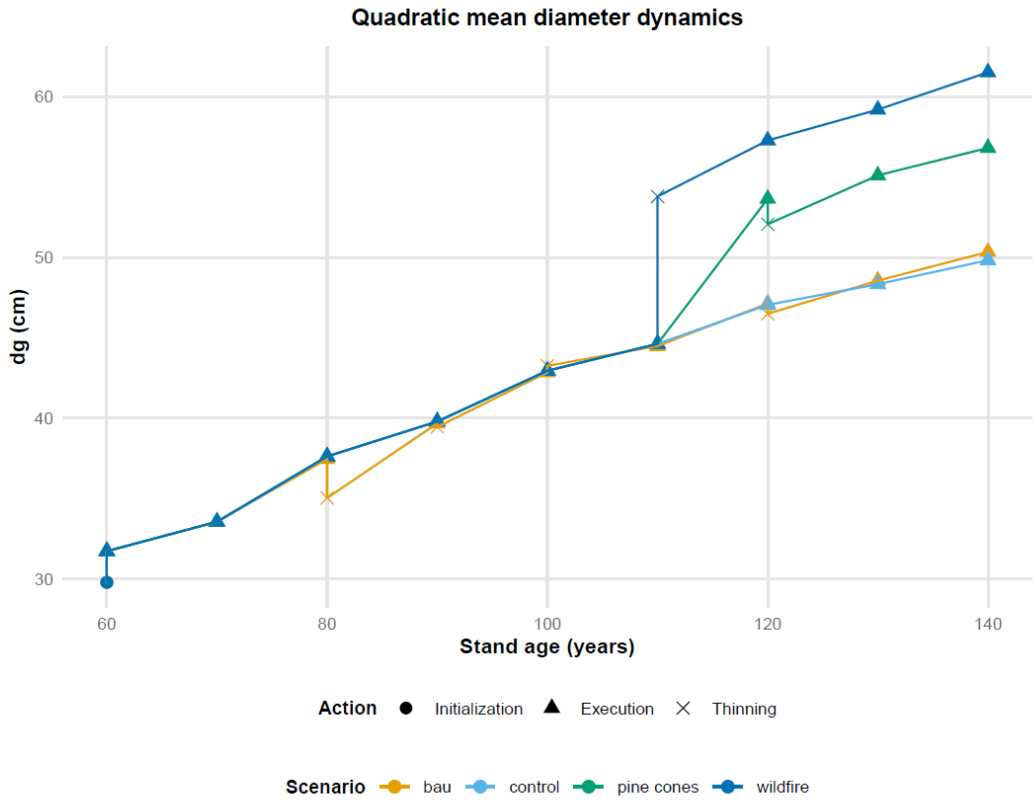


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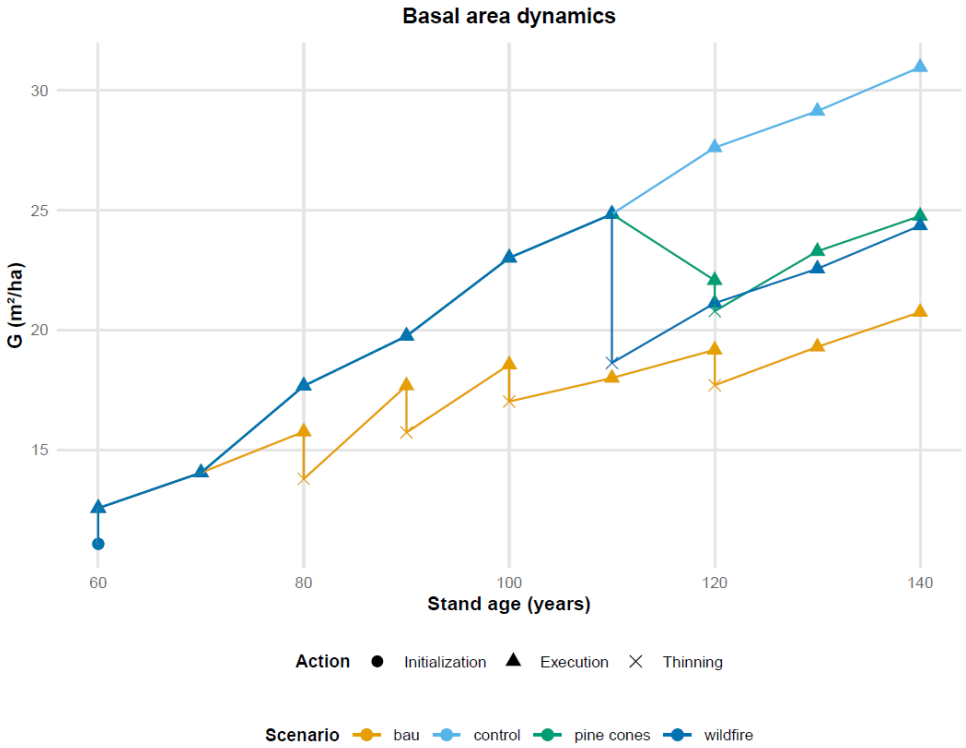


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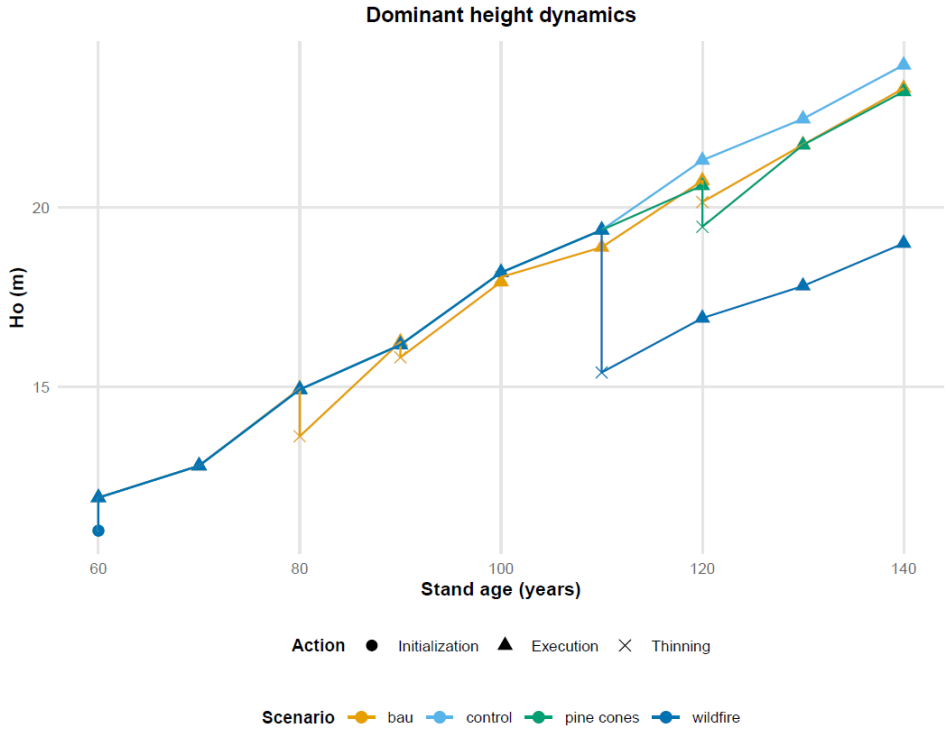


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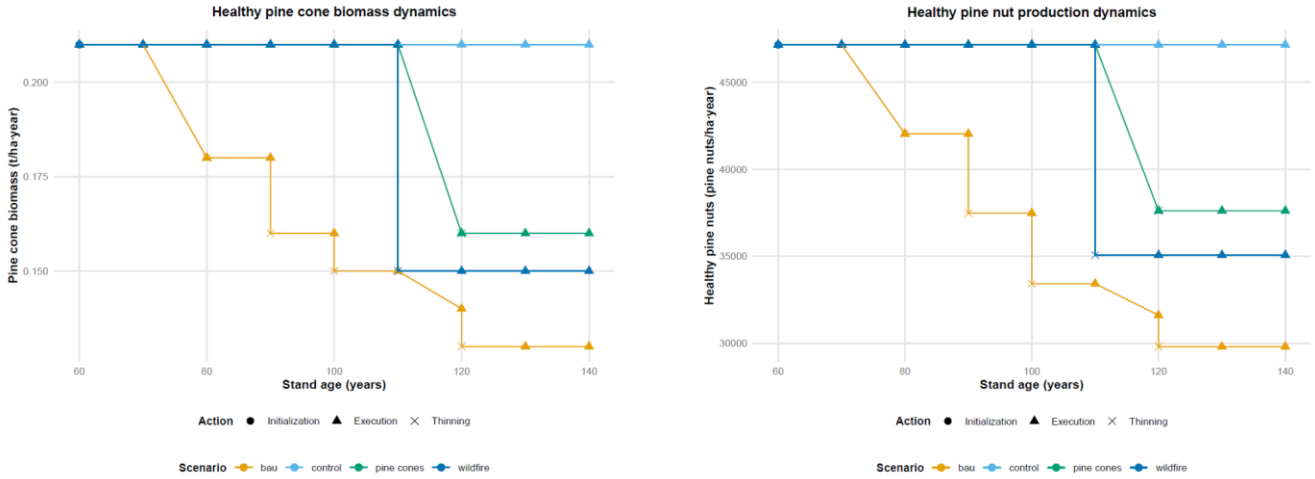


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