FORWARD PROJECTIONS OF LONG TERM EFFECTS OF FOREST RESTORATION IN VYSOČINA REGION, CZECH REPUBLIC

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Photo cover: Vysočina forest restoration pilot. September 2024. Photo by GJ Nabuurs

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EXECUTIVE SUMMARY

Vysočina Region in the Czech Republic with 219 000 ha of forest has been heavily affected by bark beetle attacks since 2017. Therefore, the restoration focuses on regenerating forests by establishing new mixed forest stands (including 3 and more tree species in each forest stand) with an increased rate of natural regeneration of pioneer species like Betula, Populus, Alnus and Salix. Also, in some stands spruce will be replaced by other tree species (Fagus sylvatica, Abies spp., Quercus spp. and Acer spp.). The restoration of Vysočina North Moravia also aims to improve the biodiversity. Projections are made with the EFISCEN-Space model under a moderate climate change scenario of RCP4.5.

Disturbance Scenarios (1) intense Ips and (2) moderate Ips lead to substantial volume loss in coming decades and a totally changed forest resource by 2040–2060. While a recovery period occurs in both scenarios, by 2100, standing volumes remain significantly (250 and 330 m³/ha) lower than in the baseline scenario (450 m³/ha). In the baseline, assuming very limited influence of bark beetle, diameters of harvested trees increase from currently mostly 40–60 cm to 60+ diameters.

Forest structure shifts toward smaller trees and more broadleaved species in both *Ips* scenarios. While in (1) intense *Ips* scenario, volume and increment decrease to approximately 50 % of the Baseline in 2100, in (2) moderate *Ips* scenario, the reduction of spruce is partially substituted by an increased share of other conifers such as Douglas fir, *Quercus* spp. and long lived broadleaved. These drastic restoration scenarios stipulated by large calamities lead to unsustainable developments for several decades, and large volumes of harvestable wood in the coming decades. This seems almost unavoidable, although the speed at which it occurs can be influenced and moderated by management. In the longer term, less wood will be available and assortments changing drastically. Early adaptation and keeping bark beetle outbreaks under control to slow down the transformation, is advisable.

DEMO INFORMATION

Vysočina Region is located on both sides of the historical border between Bohemia and Moravia (also called Bohemian-Moravian Highlands). The transformation of virgin forests (dominated by *Fagus sylvatica*, *Abies alba* and *Picea abies*) started with medieval colonisation and continued to the period of industrialisation in the 19th and 20th century.

Systematic introduction of monocultural spruce management dates back to the 18th century. The transformation of forest ecosystems resulted in a 70% representation of Norway spruce, the almost complete absence of natural forests, the eradication of predators and an imbalance between the forest environment and game numbers.

Nowadays, forests cover approximately 30% of the region; in the past, the area was characterised by relatively healthy woodlands compared to other parts of the country due to lower air pollution. Spruce silviculture was very effective and with relatively low rates of calamity fellings during the 20th century. The region is also important for agricultural production (both plant and animal), winter and summer recreation and water retention (the main European watershed passes through).

Currently, the area is dominated by non-native forest plantations of spruce within an agricultural landscape. The ownership of the land is shared among different actors, such as the Forest of the Czech Republic (Lesy České republiky s.p.), private owners and Military Forests of the Czech Republic.

Since 2017 the Norway spruce forests in Vysočina North Moravia have been heavily affected by calamities of European spruce bark beetle (*Ips typographus*). Therefore, the restoration focuses on regenerating forests by establishing new mixed forest stands (including 3 and more tree species in each forest stand) with increased rate of natural regeneration of pioneer species like *Betula*, *Populus*, *Alnus* and *Salix*. Besides, in some stands spruce will be replaced by other tree species (*Fagus sylvatica*, *Abies* spp., *Quercus* spp. and *Acer* spp.). The restoration of Vysočina North Moravia also aims to improve the biodiversity and provide better access to other ecosystem services such as wood production, carbon storage, biodiversity, soil protection, recreation and water provision.

In stands degraded after the bark beetle calamity, salvage logging took place. Mostly degraded mature, 80- to 120-year-old, forest stands. Occasionally, young spruce stands were heavily infested. It is estimated that in the region of Vysočina more than 20% of all conifers were harvested (of which 95% was salvage felling). Affected trees were removed, and sites were prepared for artificial and natural regeneration. Different soil and site preparation techniques were used concerning site conditions and the actual amount of wood residues. Admixed trees and hotspots of natural regeneration were retained. Tree species mostly endangered by browsing (broadleaved and *Abies alba*) are protected mainly through fencing.

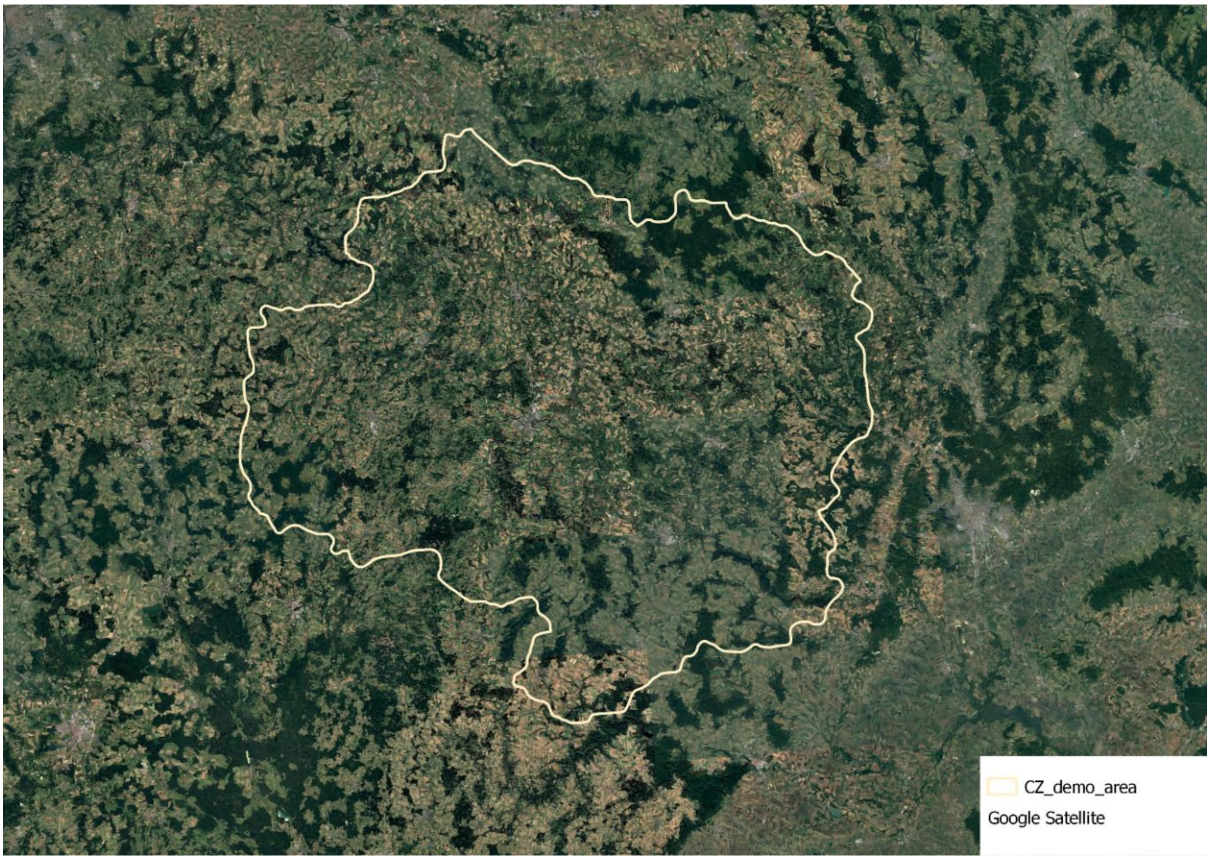

Figure 1. Aerial view on study region Vysočina with 219000 ha of forest, represented by 1097 NFI plots.

MODEL DESCRIPTION

EFISCEN-Space model

EFISCEN-Space is an empirical European forest model that simulates development of forest resources under varying scenarios of forest management and climate change. It keeps track of the development of the diameter distribution of 20 tree species (groups) for individual plot locations (Schelhaas et al., 2022). The diameter distribution changes over time due to the growth of trees (simulated by the growth of trees to a larger diameter class), the removal of trees due to natural (background) mortality or harvest, and the occurrence of new trees (ingrowth) in lowest diameter classes. The EFISCEN-Space model is initialised on tree-wise observations from forest inventories, usually National Forest Inventories (NFIs), and driven by environmental datasets with pan-European coverage (Nabuurs et al., 2007, Schelhaas et al., 2022, Filipek et al., In prep). These data are used to initialize forest structure and are the basis for the model's detailed and dynamic (i.e. sensitive to forest structure) simulation of growth (Schelhaas et al., 2018). Growth is related to the current forest structure (plus the abiotic predictors), and as incorporated here under a RCP 4.5. scenario for all 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 the growth is modulated to annual downscaled weather under RCP4.5 with the global climate model (GCM) MPI-ESM1-2-LR. This results in growth being influenced by the climate as predicted under this RCP.

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). Calamity mortality as happened in region in near past, was simulated as extra harvesting pressure, to arrive at a correct initial growing stock. This is an indirect manner of simulating salvaging. In the runs in the current study natural disturbances (bark beetle) were assumed to take place but were implemented as extra harvesting pressure. There is no bark beetle module.

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

SCENARIO DESCRIPTION

EFISCEN-Space scenarios

All runs are made from the year 2025 to 2100. As our input NFI cycle was for the years 2011-2015 we first had to bring the forest resource information to the initial year 2025.

While the normal harvest for state forest administration Vysočina was around 700 000 m^3/y, in the calamity years it rose to over 3.5 million m^3/year in state forest only. See graph below. This we implemented to arrive at a real growing stock in 2025.

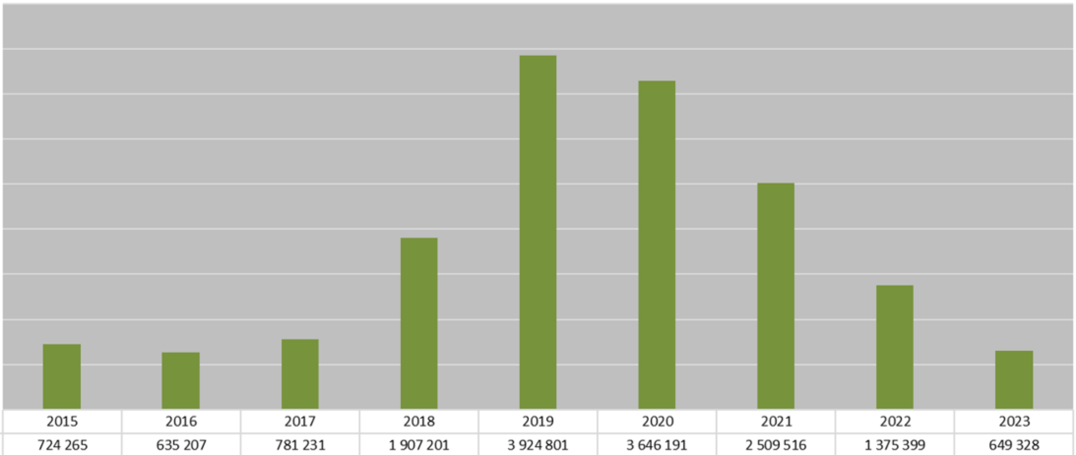

Figure 2. Calamity harvest over time in state forest only in study region. In all forests, the highest damage was in 2020 and reached 8.66 million m^3.

We applied this with a high harvesting routine and brought the volume down from (NFI 2011–2014) 420.3 +-14.1 m^3/ha to 377 m^3/ha in 2025. This was very close to the realistic value. Note that we applied it evenly over the region. Only later in calamity runs, plots were overlayed on calamity areas and those plots obtained calamity management (see example map in Figure 3).

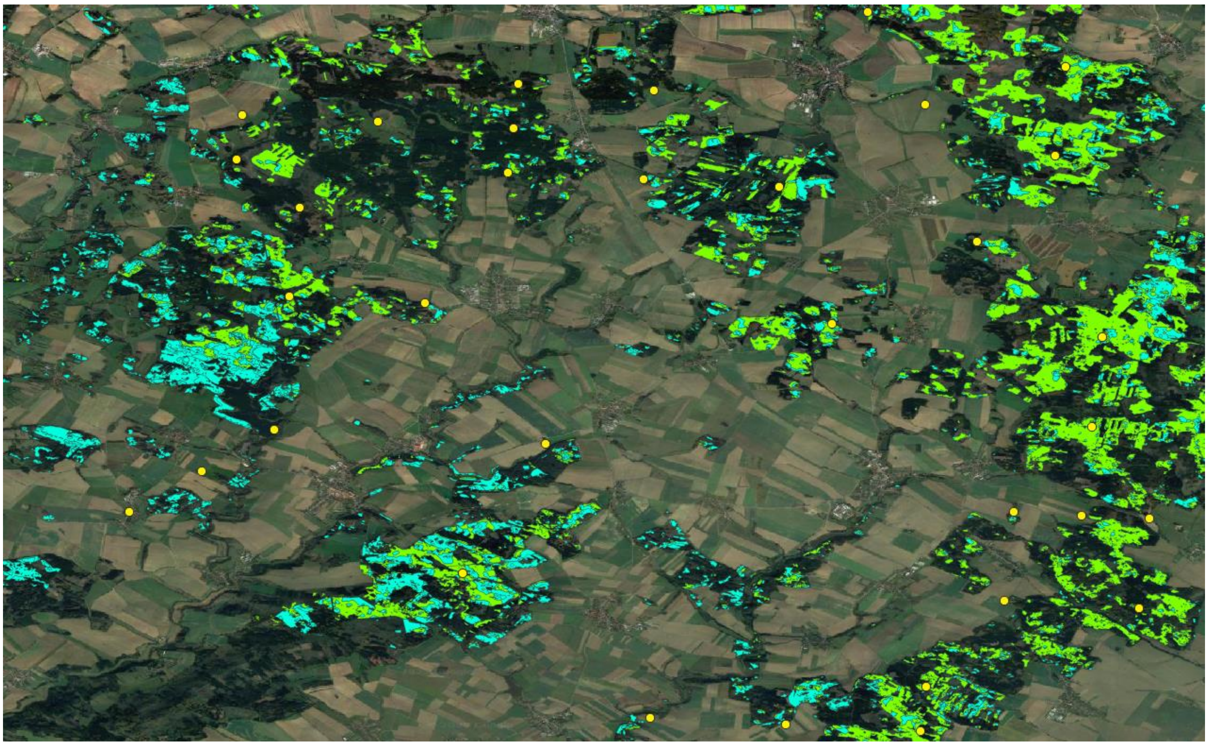

Figure 3. Example map of affected calamity areas (colour by year) and the plot locations (small yellow dots, jiggered). Those plots that are in calamity areas were given the Calamity management, see scenarios.

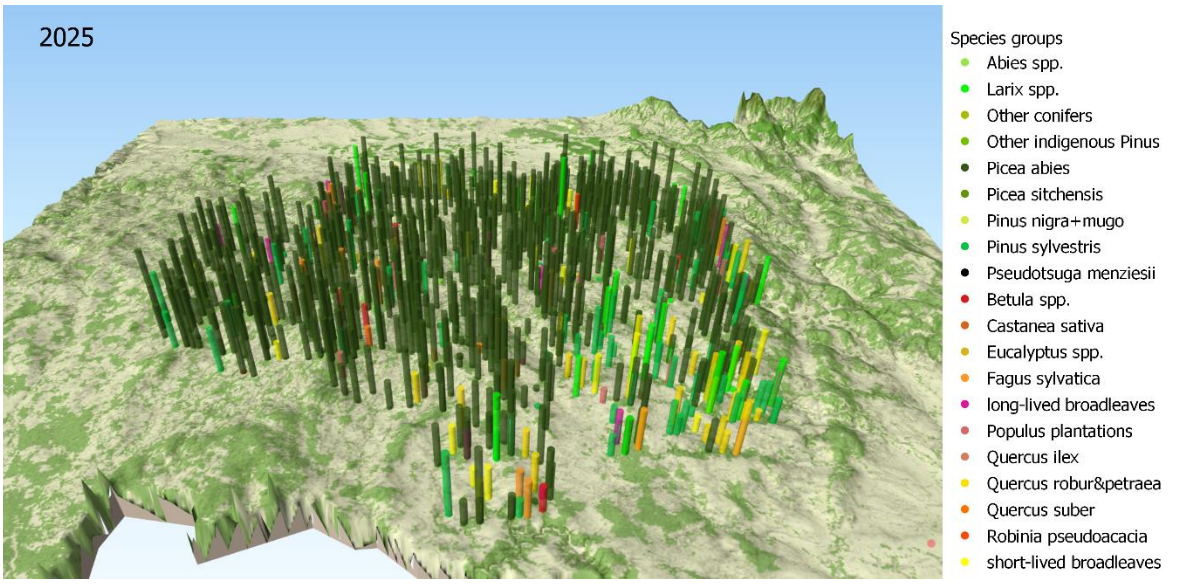

Figure 4: 3D view on state of forest in 2025 in Vysocina region represented by 1097 NFI plots. The height of the bar depicts the growing stock, the colour the main tree species; the dark green showing a very much spruce dominated forest estate.

1. Baseline (BAU)

In this first baseline scenario, the Czech NFI data are used to produce projections of typical forest management practices as of 2025 under a what if scenario where bark beetle (*Ips typographus*) calamity will not occur in the future in the Czech Republic.

Additionally, under this scenario, the management of conifer stands for timber production, which reflects typical approaches with rotation periods of around 110 years and 75% of spruce in regeneration. Since for Czech Republic we only had one NFI available at the time of model set up, the management regimes are derived from German repeated sets of NFIs.

Table 1: Probability of cutting by either clearcut or thinning per management rule. Probability per plot is determined by thresholds as Dq10 and basal area. Shape of cutting denotes with a positive value an emphasis on large diameter trees, with a negative value an emphasis on small diameter trees.

regime	rule	shape_ of_ cutting	maxiter	Cutting _intensity	Cutting nterval	Value Min	valueMax	Action Variable	probability
unmanaged	no	0	10	0	12	0	0	basalArea10	0
Germany_Alpine_Beech	clearcut1	0	10	0	12	-1	0	Dq10	0
Germany_Alpine_Spruce	clearcut1	3	10	0.902904	12	40	60	Dq10	0.021148
Germany_Alpine_Abies	clearcut1	0	10	0.971875	12	-1	55	Dq10	0.135593
Germany_Atlantic_Continental_ShortlivedBr	clearcut1	-1	10	0.957042	12	-1	35	Dq10	0.06553
Germany_Atlantic_Continental_LonglivedBr	clearcut1	0	10	0.959769	12	-1	55	Dq10	0.076794
Germany_Atlantic_Continental_Oak	clearcut1	-0.5	10	0.952053	12	-1	40	Dq10	0.043113
Germany_Atlantic_Continental_Poplar	clearcut1	-1	10	0.941924	12	-1	45	Dq10	0.035928
Germany_Atlantic_Continental_Beech	clearcut1	0	10	0.944707	12	-1	60	Dq10	0.045625
Germany_Atlantic_Continental_Birch	clearcut1	0	10	0.968892	12	-1	35	Dq10	0.062598
Germany_Atlantic_Continental_Pine	clearcut1	0	10	0.908142	12	-1	50	Dq10	0.019095
Germany_Atlantic_Continental_Douglas	clearcut1	0	10	0.934071	12	-1	40	Dq10	0.072131
Germany_Atlantic_Continental_Spruce	clearcut1	3	10	0.952902	12	35	50	Dq10	0.03
Germany_Atlantic_Continental_Larch	clearcut1	0	10	0.928395	12	-1	40	Dq10	0.02557
Germany_Atlantic_Continental_Abies	clearcut1	0	10	0.986645	12	-1	40	Dq10	0.313231
Germany_Alpine_Beech	clearcut2	0	10	0.939281	12	0	-1	Dq10	0.023529
Germany_Alpine_Spruce	clearcut2	5	10	0.924202	16	60	-1	Dq10	0.03
Germany_Alpine_Abies	clearcut2	0	10	1	12	55	-1	Dq10	0.333333
Germany_Atlantic_Continental_ShortlivedBr	clearcut2	0	10	0.955888	12	35	-1	Dq10	0.1139
Germany_Atlantic_Continental_LonglivedBr	clearcut2	0	10	0.990684	12	55	-1	Dq10	0.117978
Germany_Atlantic_Continental_Oak	clearcut2	0	10	0.916509	12	40	-1	Dq10	0.02194
Germany_Atlantic_Continental_Poplar	clearcut2	0	10	0.937006	12	45	-1	Dq10	0.064516

Germany_Atlantic_Continental_Beech	clearcut2	0	10	0.961519	12	60	-1	Dq10	0.098765
Germany_Atlantic_Continental_Birch	clearcut2	0	10	0.964204	12	35	-1	Dq10	0.228571
Germany_Atlantic_Continental_Pine	clearcut2	0	10	0.961297	12	50	-1	Dq10	0.04908
Germany_Atlantic_Continental_Douglas	clearcut2	0	10	0.967619	12	40	-1	Dq10	0.128834
Germany_Atlantic_Continental_Spruce	clearcut2	5	10	0.972915	16	50	-1	Dq10	0.03
Germany_Atlantic_Continental_Larch	clearcut2	0	10	0.924167	12	40	-1	Dq10	0.072874
Germany_Atlantic_Continental_Abies	clearcut2	0	10	0.980485	12	40	-1	Dq10	0.267332
Germany_Alpine_Beech	thin1	0	10	0.351485	12	-1	30	basalArea10	0.166667
Germany_Alpine_Spruce	thin1	0.5	10	0.342388	12	20	35	basalArea10	0.155063
Germany_Alpine_Abies	thin1	0	10	0.363088	12	-1	35	basalArea10	0.4
Germany_Atlantic_Continental_ShortlivedBr	thin1	-1	10	0.395576	12	-1	25	basalArea10	0.170455
Germany_Atlantic_Continental_LonglivedBr	thin1	-0.5	10	0.374578	12	-1	30	basalArea10	0.384766
Germany_Atlantic_Continental_Oak	thin1	-1	10	0.322705	12	-1	40	basalArea10	0.436947
Germany_Atlantic_Continental_Poplar	thin1	-1	10	0.439552	12	-1	25	basalArea10	0.283871
Germany_Atlantic_Continental_Beech	thin1	-1	10	0.354189	12	-1	30	basalArea10	0.527912
Germany_Atlantic_Continental_Birch	thin1	-1	10	0.438172	12	-1	15	basalArea10	0.089928
Germany_Atlantic_Continental_Pine	thin1	-1	10	0.377791	12	-1	20	basalArea10	0.302411
Germany_Atlantic_Continental_Douglas	thin1	-1	10	0.401877	12	-1	20	basalArea10	0.325581
Germany_Atlantic_Continental_Spruce	thin1	-1	10	0.36032	12	18	30	basalArea10	0.3
Germany_Atlantic_Continental_Larch	thin1	-2	10	0.409652	12	-1	20	basalArea10	0.398734
Germany_Atlantic_Continental_Abies	thin1	-1	10	0.396234	12	-1	30	basalArea10	0.496994
Germany_Alpine_Beech	thin2	-1	10	0.328878	12	30	-1	basalArea10	0.315789
Germany_Alpine_Spruce	thin2	-1	10	0.226327	12	35	-1	basalArea10	0.15
Germany_Alpine_Abies	thin2	0.5	10	0.32875	12	35	-1	basalArea10	0.571429
Germany_Atlantic_Continental_ShortlivedBr	thin2	-1	10	0.317252	12	25	-1	basalArea10	0.336158
Germany_Atlantic_Continental_LonglivedBr	thin2	-1	10	0.324019	12	30	-1	basalArea10	0.560288
Germany_Atlantic_Continental_Oak	thin2	-2	10	0.265162	12	40	-1	basalArea10	0.609447
Germany_Atlantic_Continental_Poplar	thin2	-3	10	0.299041	12	25	-1	basalArea10	0.409836
Germany_Atlantic_Continental_Beech	thin2	-1	10	0.324937	12	30	-1	basalArea10	0.691004
Germany_Atlantic_Continental_Birch	thin2	-1	10	0.363582	12	15	-1	basalArea10	0.346154
Germany_Atlantic_Continental_Pine	thin2	-1	10	0.311536	12	20	-1	basalArea10	0.616595
Germany_Atlantic_Continental_Douglas	thin2	-2	10	0.346742	12	20	-1	basalArea10	0.781579
Germany_Atlantic_Continental_Spruce	thin2	-1	10	0.304189	12	30	-1	basalArea10	0.3

Germany_Atlantic_Continental_Larch	thin2	-2	10	0.336925	12	20	-1	basalArea10	0.714163
Germany_Atlantic_Continental_Abies	thin2	-1	10	0.327606	12	30	-1	basalArea10	0.782631

Implementing this BAU scenario allows comparisons with the Restoration #1 scenario that reflects new approaches resulting from the stand-replacing disturbance of bark beetle and adaptation measures reflecting changing climatic characteristics and increasing risk of drought damage.

2. Restoration scenario #1 Intense *Ips* calamity

In Vysočina region with 219000 ha of forest (repr by 1097 NFI plots) a calamity regime was applied on 447 plots (95000ha). A rather drastic restoration regime is then the only option.

Restoration action #1 aims to establish more diverse, mixed forest ecosystems adapted to changing environmental conditions after bark-intense and continued beetle calamity in spruce monocultures. Accordingly, forest restoration activities will include the restoration of former Norway spruce stands by using ingrowth of broadleaved species only.

Table 2. No of trees planted per year per species in felled areas when under a certain basal area.

Betula spp	500
Castanea	400
Beech	800
Quercus spp	500
Short lived broadleaves	400
Long lived broadleaves	400

Moreover, in forests where spruce remains the dominant species, regeneration will follow the same pattern stimulated with additional ingrowth of birch and other broadleaved but with a generally shorter rotation period as an adaptive measure to mitigate the risk of large-scale bark beetle infestations. The target harvest diameter for Norway spruce typically does not exceed 50 cm.

3. Restoration scenario #2 Moderate *Ips* calamity

Restoration action #2 aims to establish diverse, mixed forest ecosystems as well but under assumption that the *Ips* calamity - #2 moderate *Ips* will be more moderate, and there will be more planting of coniferous species like fir and Douglas fir, next to some broadleaves as well. In forest stands where spruce is the dominant species, shorter rotation period as an adaptive measure to mitigate the risk of large-scale bark beetle infestations will be applied. The target harvest diameter for Norway spruce typically does not exceed 50 cm.

PROJECTION RESULTS

EFISCEN-Space

1. Baseline (BAU)

In the baseline scenario (BAU), the average volume per hectare (m³/ha) gradually increases from 2020 to around 2080 (assuming no major bark beetle outbreak), after which it slightly declines to values close to 450 m³/ha. Total volume (Mm³) follows the same trend. Gross annual increment (m³/ha/yr) shows a continuous decrease from 9.5 to 5.3 m³/ha/yr from 2026 to 2100. Accordingly, the total increment (Mm³) follows the same declining trend (Figure 5).

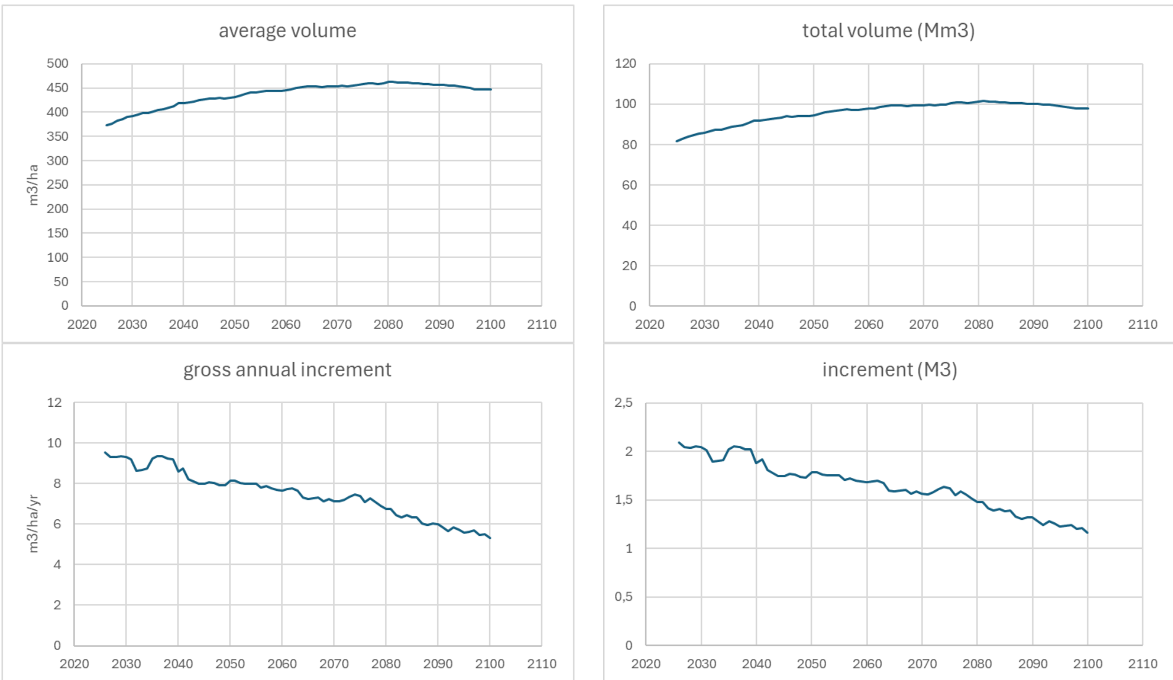

Figure 5. The average total volume per hectare (m³/ha), total volume (Mm³), gross annual increment (m³/ha/yr) and total increment (Mm³) from 2026 to 2100 under the baseline (BAU) scenario.

The average harvested volume per hectare (m³/ha/yr) varies greatly year-to-year but remains within a relatively stable range of around 5.1 m³/ha/yr. The same is true for total annual harvest, with a long-term average of 1.1 Mm³. The average mortality remains stable with values around 1.4 m³/ha/yr, corresponding to an annual total mortality of 0.3 Mm³ (Figure 6). The proportion of average harvested volume per hectare (m³/ha/yr), average mortality (m³/ha/yr) and gross annual increment (m³/ha/yr) is shown in Figure 7.

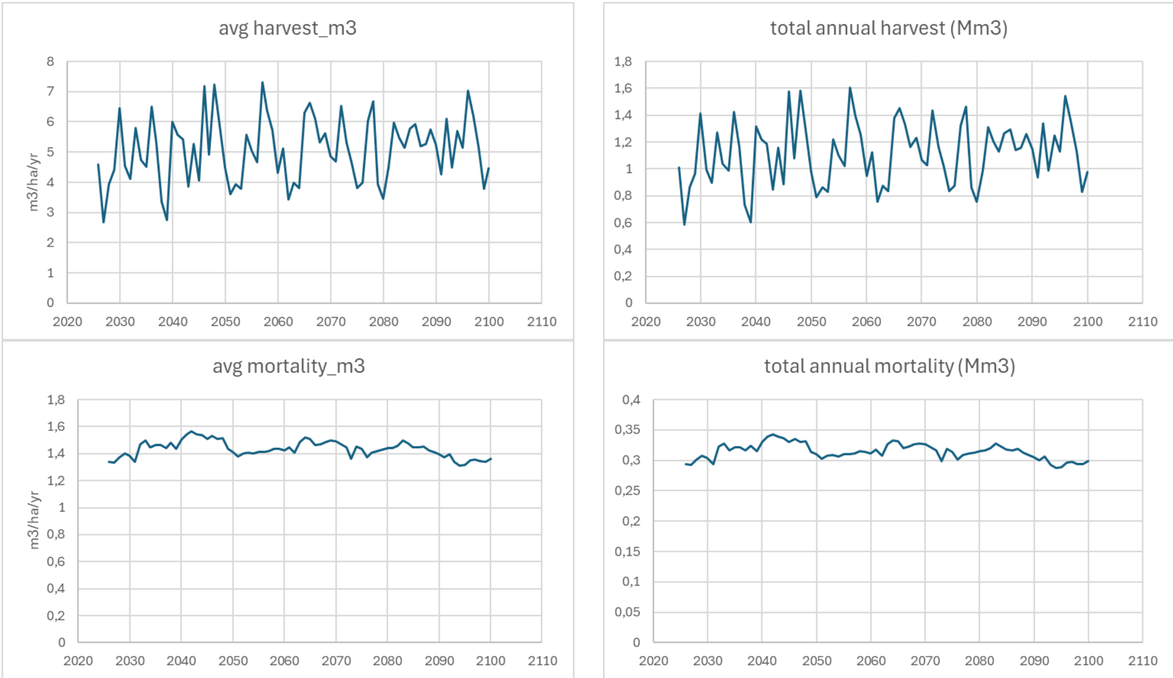

Figure 6. The average harvested volume per hectare (m³/ha/yr), total annual harvest (Mm³), average mortality (m³/ha/yr) and annual total mortality (Mm³) from 2026 to 2100 under the baseline (BAU) scenario.

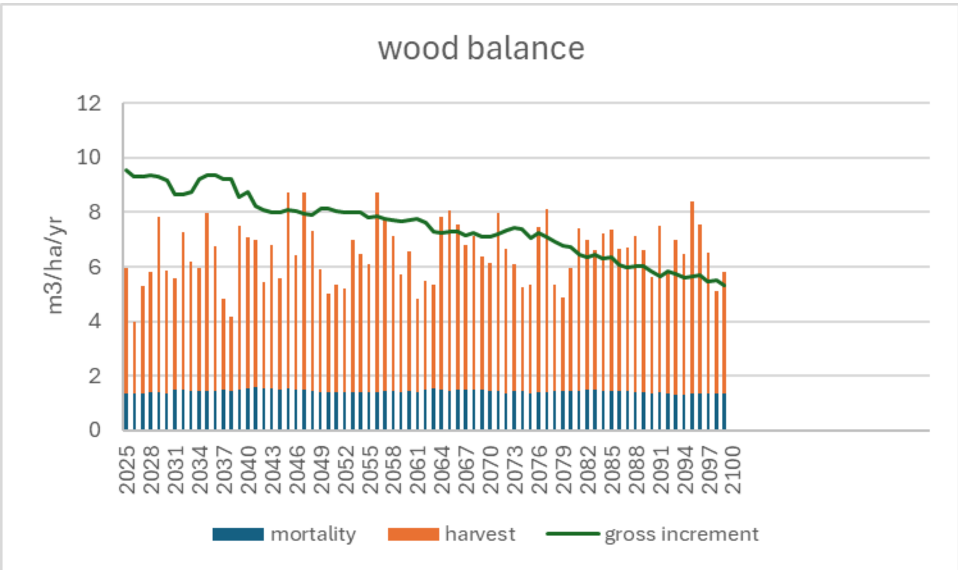

Figure 7. The proportion of average harvested volume per hectare (m³/ha/yr), average mortality (m³/ha/yr) and gross annual increment (m³/ha/yr) under the baseline (BAU) scenario.

Figure8 represents the development of total standing stock (m³/ha) over time, categorized by diameter classes and coniferous and broadleaved species. Conifers dominate in volume across all classes from 2026 to 2100. The peak of the total standing volume shifts to larger diameter classes from the 40–50 cm dbh class in 2025 to the 70–80+ cm dbh class in 2100. This is because with a moderate felling intensity in BAU the accrual of wood continues over time. In reality, probably more felling intensity would be shifted to medium and large size diameters in order to avoid this. This dynamic shifting of harvesting pressures over time during simulation is not possible at the moment.

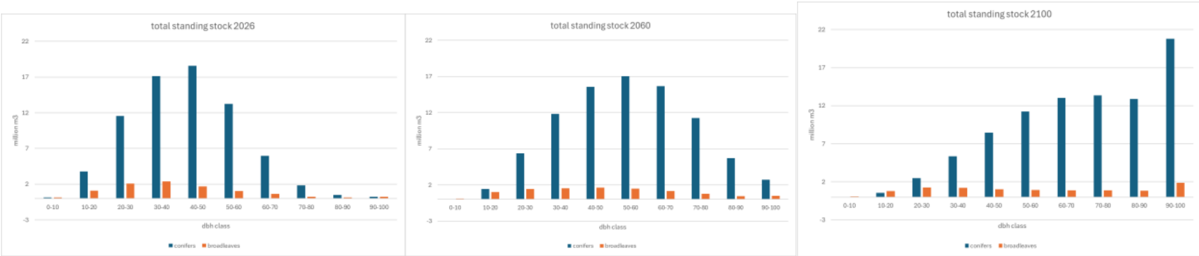

Figure 8. Development of total standing stock (m³/ha) from 2025 to 2100, categorized by diameter classes, comparing coniferous and broadleaved species under the baseline (BAU) scenario.

The development of total harvest (m³/ha) from 2026 to 2100 categorized by diameter classes and species groups (coniferous and broadleaved) is given in Figure 9. The dominance of coniferous species in total harvested volumes is evident, along with a significant shift toward larger diameter classes by 2100.

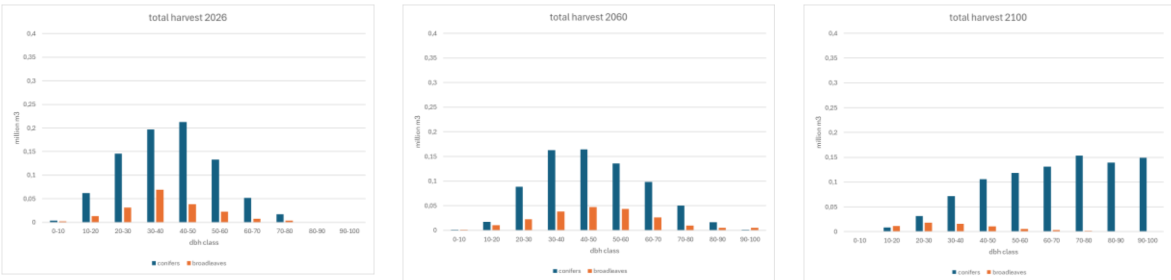

Fig. 9. Total harvest (m³/ha) from 2026 to 2100 categorized by diameter classes, comparing coniferous and broadleaved species under the Baseline (BAU) scenario.

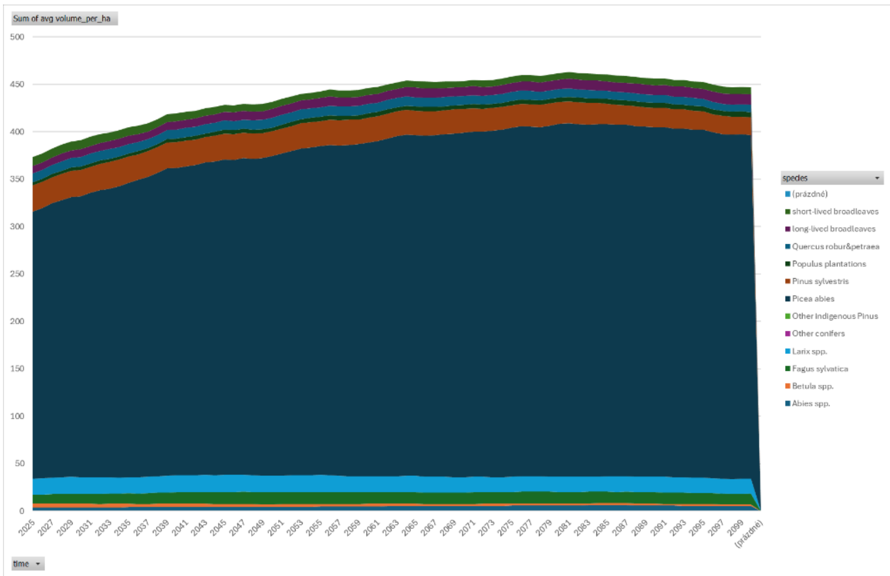

Figure 10. Average standing volume per hectare (m³/ha) from 2025 to 2100, broken down by tree species under the baseline (BAU) scenario.

2. Restoration scenario #1 intense *Ips*

In the #1 intense *Ips* scenario the average volume per hectare (m³/ha) significantly decreases from 2026 to around 2043, after which it starts to grow until it reaches average volume of approximately 250 m³/ha. Total volume (Mm³) follows the same trend. Gross annual increment (m³/ha/yr) shows a steep decline followed by a recovery period from 2040 to 2060 (with values around 8.0 m³/ha/yr), and then a general decrease to 2.9 m³/ha/yr by 2100. Accordingly, the total increment (Mm³) follows the same trend (Figure 11).

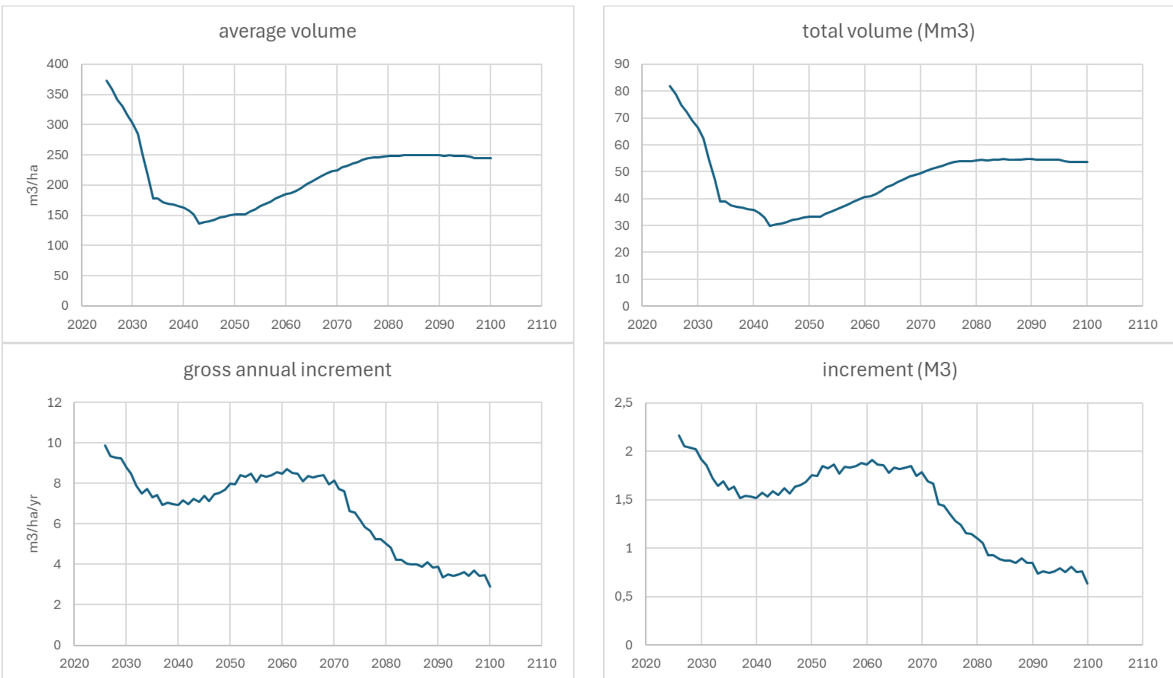

Figure 11. The average total volume per hectare (m³/ha), total volume (Mm³), gross annual increment (m³/ha/yr) and total increment (Mm³) from 2026 to 2100 under the #1 intense Ips scenario.

The average harvested volume per hectare (m³/ha/yr) peaks in 2032 with 44.8 m³/ha/yr as a result of intense bark-beetle infestation. This is followed by a steep drop with values since 2070 constantly below 2.0 m³/ha/yr. The total annual harvest follows the same trend. The average mortality decreases significantly until 2040, then increases to values from 1.0 to 1.2 m³/ha/yr, corresponding to an annual total mortality of 0.2–0.25 Mm³ (Figure 12). The mortality starts increasing again after 2040 because the growing stock volume (and density) increases again after 2040. Most of this density related mortality happens in spruce forest. The proportion of average harvested volume per hectare (m³/ha/yr), average mortality (m³/ha/yr) and gross annual increment (m³/ha/yr) is shown in Figure 12.

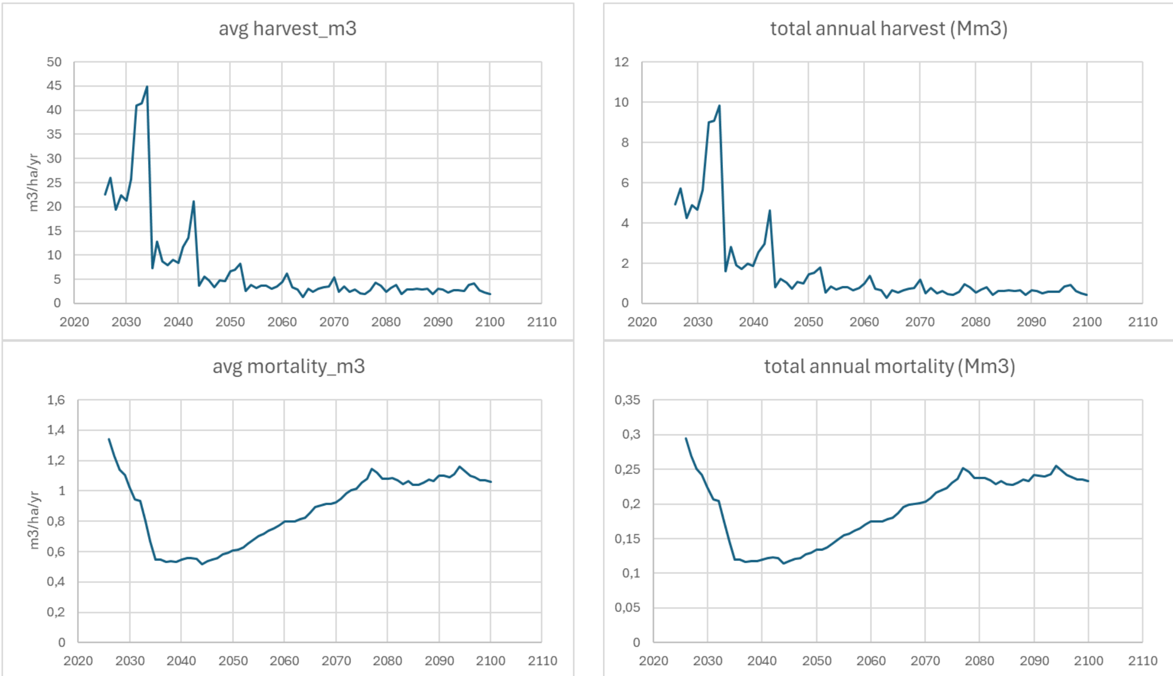

Figure 12. The average harvested volume per hectare (m³/ha/yr), total annual harvest (Mm³), average mortality (m³/ha/yr) and annual total mortality (Mm³) from 2026 to 2100 under the #1 intense Ips scenario.

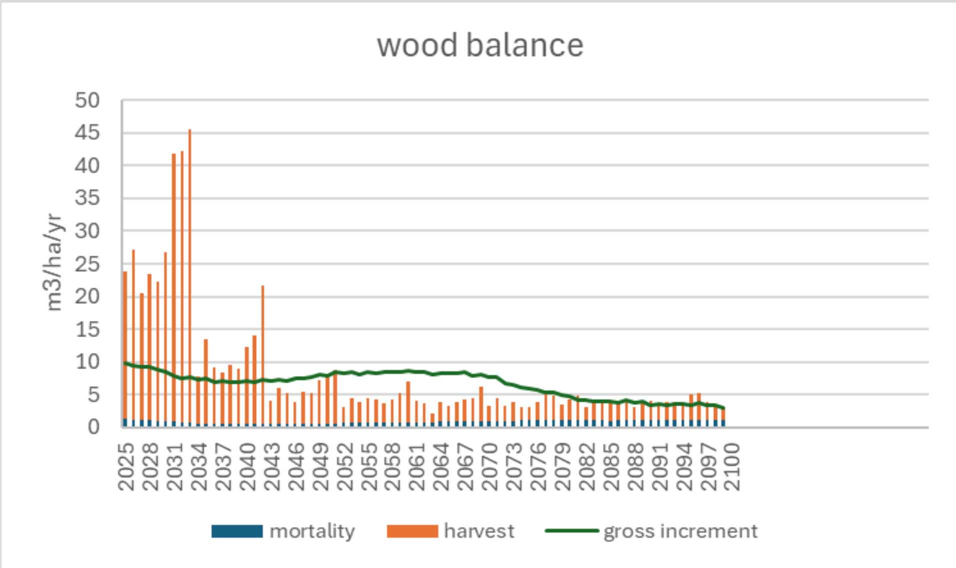

Figure 13. The proportion of average harvested volume per hectare (m³/ha/yr), average mortality (m³/ha/yr) and gross annual increment (m³/ha/yr) under the #1 intense Ips scenario.

Figure 14 represents the development of total standing stock (m³/ha) over time, categorized by diameter classes, comparing coniferous and broadleaved species. Conifers dominate in volume across all classes in 2026, in 2060 broadleaved species start to dominate up to the bhd of 30 cm, in 2100 up to the dbh of 40 cm. In higher dbh classes, the proportion of both species groups is balanced. The peak of the total standing volume shifts to smaller diameter classes from the 40–50 cm dbh class in 2025 to the 10–20 cm dbh class in 2100.

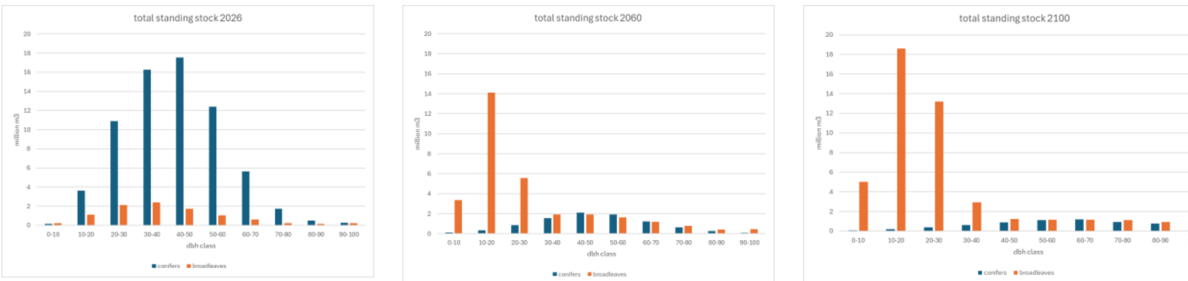

Figure 14. Development of total standing stock (m³/ha) from 2026 to 2100, categorized by diameter classes, comparing coniferous and broadleaved species under the #1 intense Ips scenario. A totally changed forest composition has already occurred by 2060.

The development of total harvest (m³/ha) from 2026 to 2100, categorized by diameter classes and species groups (coniferous and broadleaved), is shown in Figure 15. The increasing proportion of broadleaved species in total harvested volumes is evident, along with a significant shift toward smaller diameter classes by 2100.

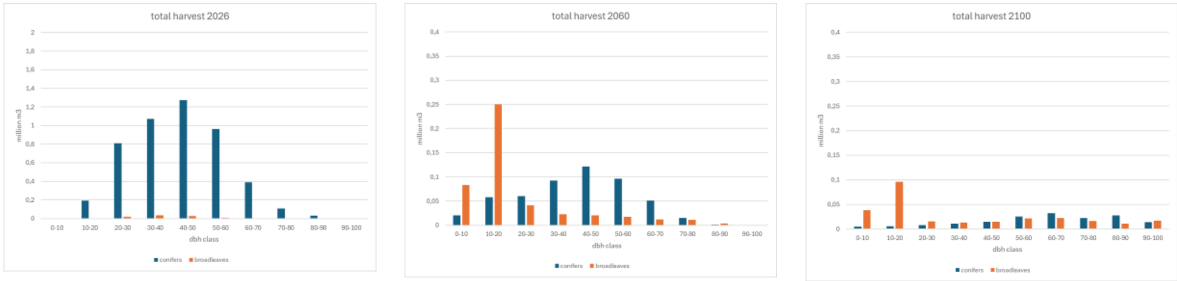

Figure 15. Total harvest (m³/ha) from 2026 to 2100 categorized by diameter classes, comparing coniferous and broadleaved species under the #1 intense Ips scenario.

This is also confirmed by Figure 16, which shows a increasing and consistently high volume of broadleaves, mainly beech, and only a minor presence of coniferous.

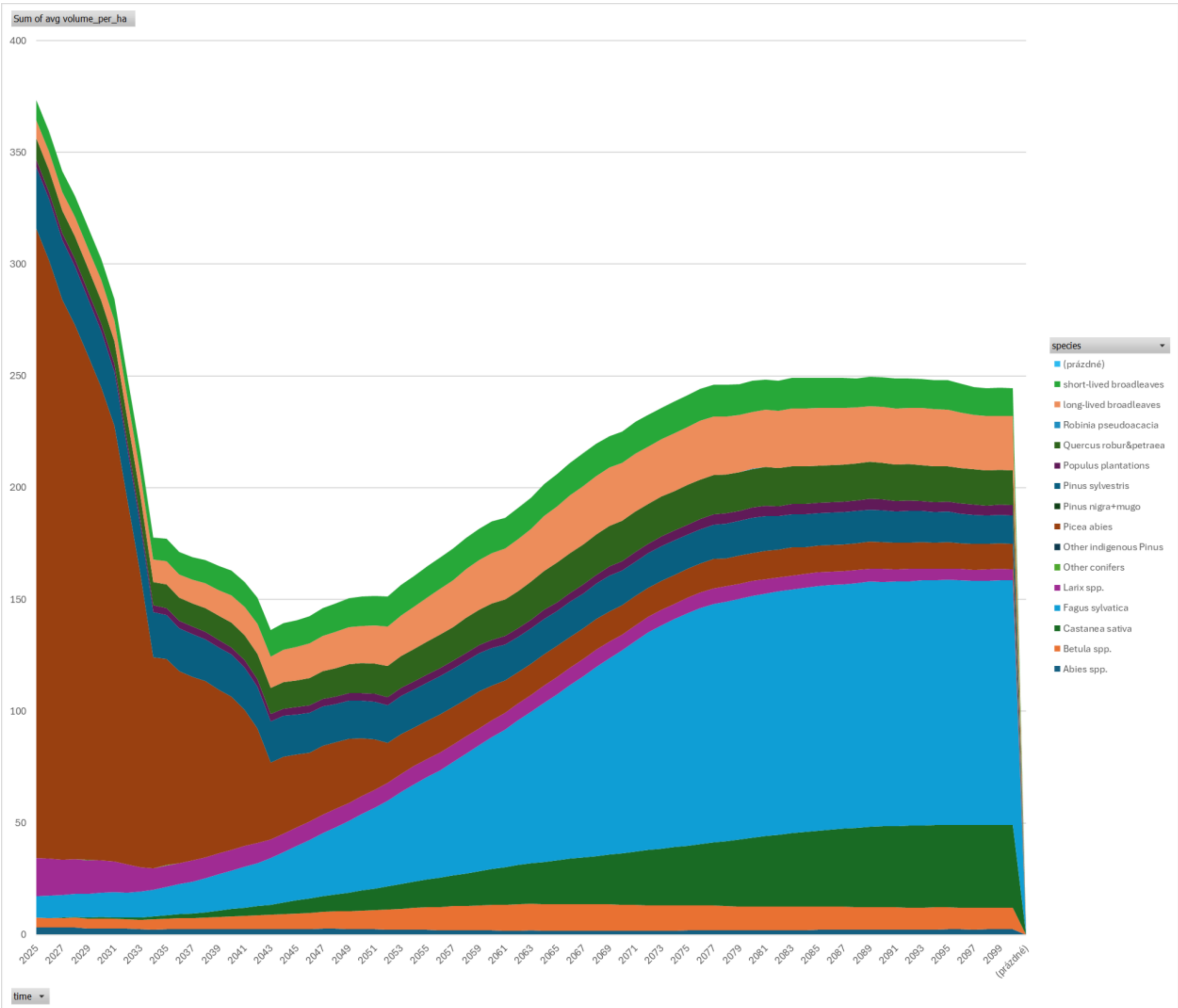

Figure 16. Average standing volume per hectare (m³/ha) from 2025 to 2100, broken down by tree species under the #1 intense Ips scenario.

SUPERB
Upscaling Forest Restoration

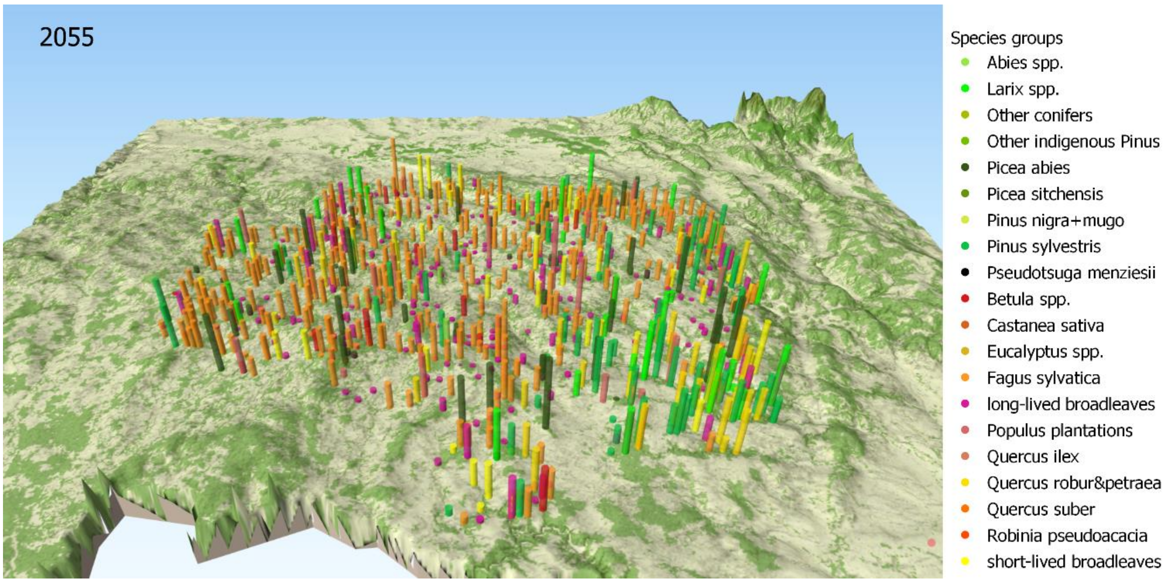

Figure 17. State of forest resources in 2055.

3. Restoration scenario #2 moderate *Ips*

In the #2 moderate *Ips* scenario the average volume per hectare (m^3/ha) significantly decreases from 2026 to around 2043, after which it starts to grow until it reaches average volume of approximately 330 m^3/ha. Total volume (Mm^3) follows the same trend. Gross annual increment ($m^3/ha/yr$) shows a decline followed by a recovery period from 2040 to 2070 (with values around 11.0 $m^3/ha/yr$), and then a general decrease to 5.0 $m^3/ha/yr$ by 2100. Accordingly, the total increment (Mm^3) follows the same trend (Figure 18).

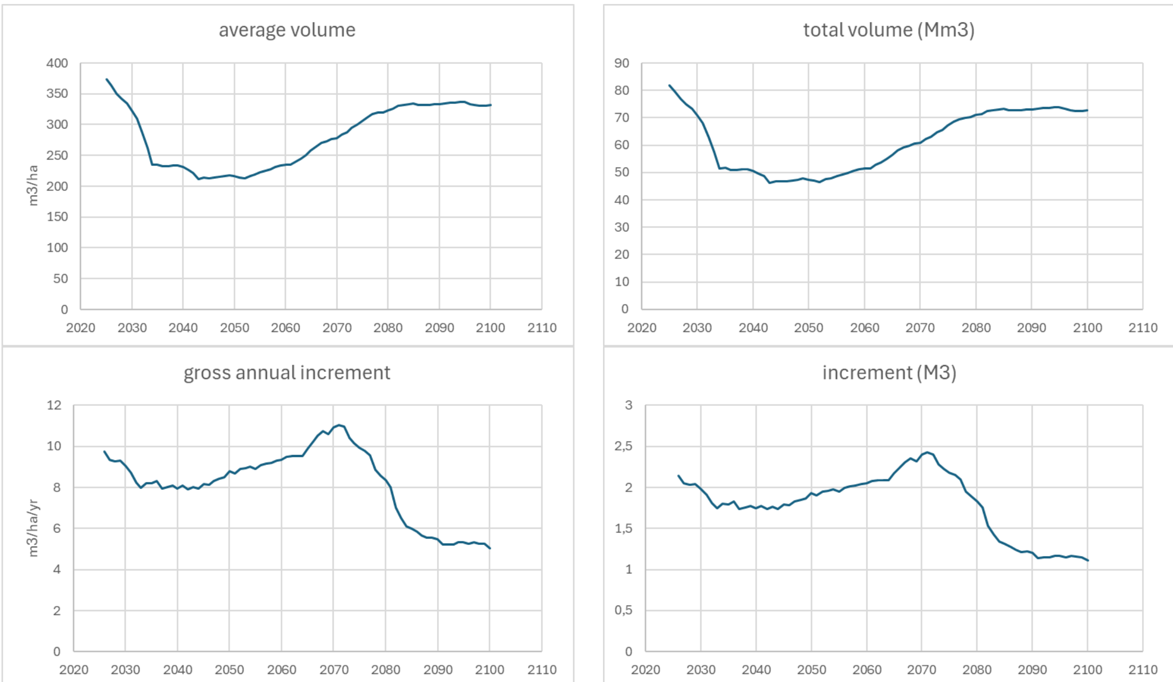

Figure 18. The average total volume per hectare (m^3/ha), total volume (Mm^3), gross annual increment ($m^3/ha/yr$) and total increment (Mm^3) from 2026 to 2100 under the #2 moderate Ips scenario.

The average harvested volume per hectare (m³/ha/yr) peaks in 2032 with 35.0 m³/ha/yr as a result of bark-beetle infestation. This is followed by a steep drop with values since 2060 constantly around 5.0 m³/ha/yr. The total annual harvest follows the same trend. The average mortality decreases until approximately 2050, then increases to values mostly below 0.8 m³/ha/yr, corresponding to an annual total mortality of less than 0.2 Mm³ (Figure 19). The proportion of average harvested volume per hectare (m³/ha/yr), average mortality (m³/ha/yr) and gross annual increment (m³/ha/yr) is shown in Figure 19.

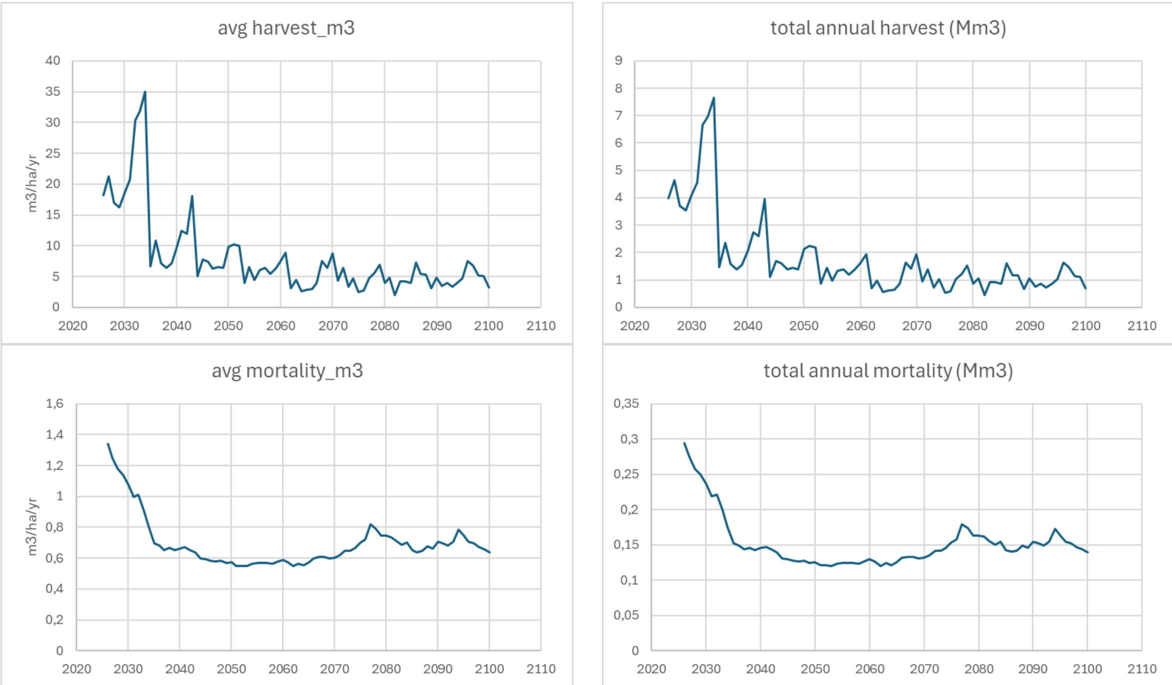

Figure 19. The average harvested volume per hectare (m³/ha/yr), total annual harvest (Mm³), average mortality (m³/ha/yr) and annual total mortality (Mm3) from 2026 to 2100 under the #2 moderate Ips scenario.

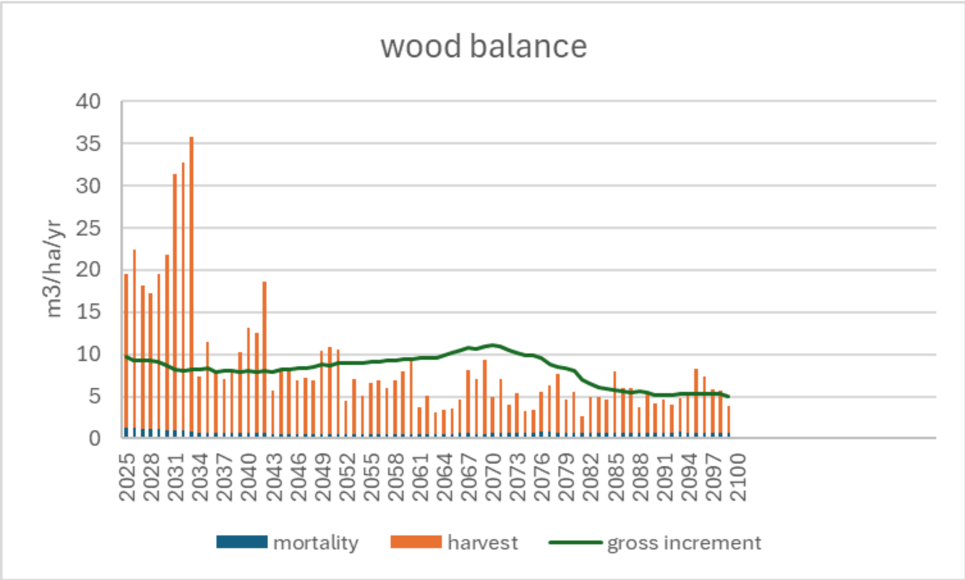

Figure 20. The proportion of average harvested volume per hectare (m³/ha/yr), average mortality (m³/ha/yr) and gross annual increment (m³/ha/yr) under the #2 moderate Ips scenario.

Figure 21 represents the development of total standing stock (m³/ha) over time, categorized by diameter classes, comparing coniferous and broadleaved species. Conifers dominate in volume across all classes in 2026, in 2060 broadleaved species start to dominate up to the dbh of 30 cm, in 2100 up to the dbh of 40 cm. In higher dbh classes, the proportion of both species groups is more balanced. The peak of the total standing volume shifts to smaller diameter classes from the 40–50 cm dbh class in 2025 to the 20–30 cm dbh class in 2100.

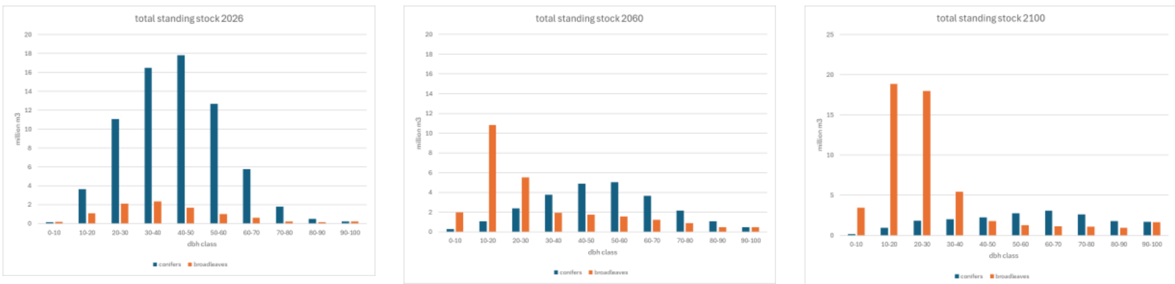

Figure 21. Development of total standing stock (m³/ha) from 2026 to 2100, categorized by diameter classes, comparing coniferous and broadleaved species under the #2 moderate Ips scenario.

The development of total harvest (m³/ha) from 2026 to 2100, categorized by diameter classes and species groups (coniferous and broadleaved), is shown in Figure 22. The increasing proportion of broadleaved species in total harvested volumes is evident, along with a significant shift toward smaller diameter classes by 2100.

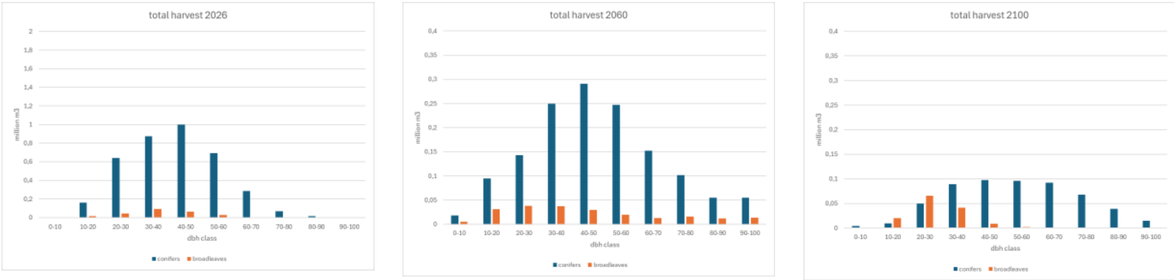

Figure 22. Total harvest (m³/ha) from 2026 to 2100 categorized by diameter classes, comparing coniferous and broadleaved species under the #2 moderate Ips scenario.

This is also confirmed by Figure 23 and Figure 24, which shows a consistently high volume of broadleaves, mainly beech, but still important share of spruce, pine and a constantly increasing share of Douglas fir.

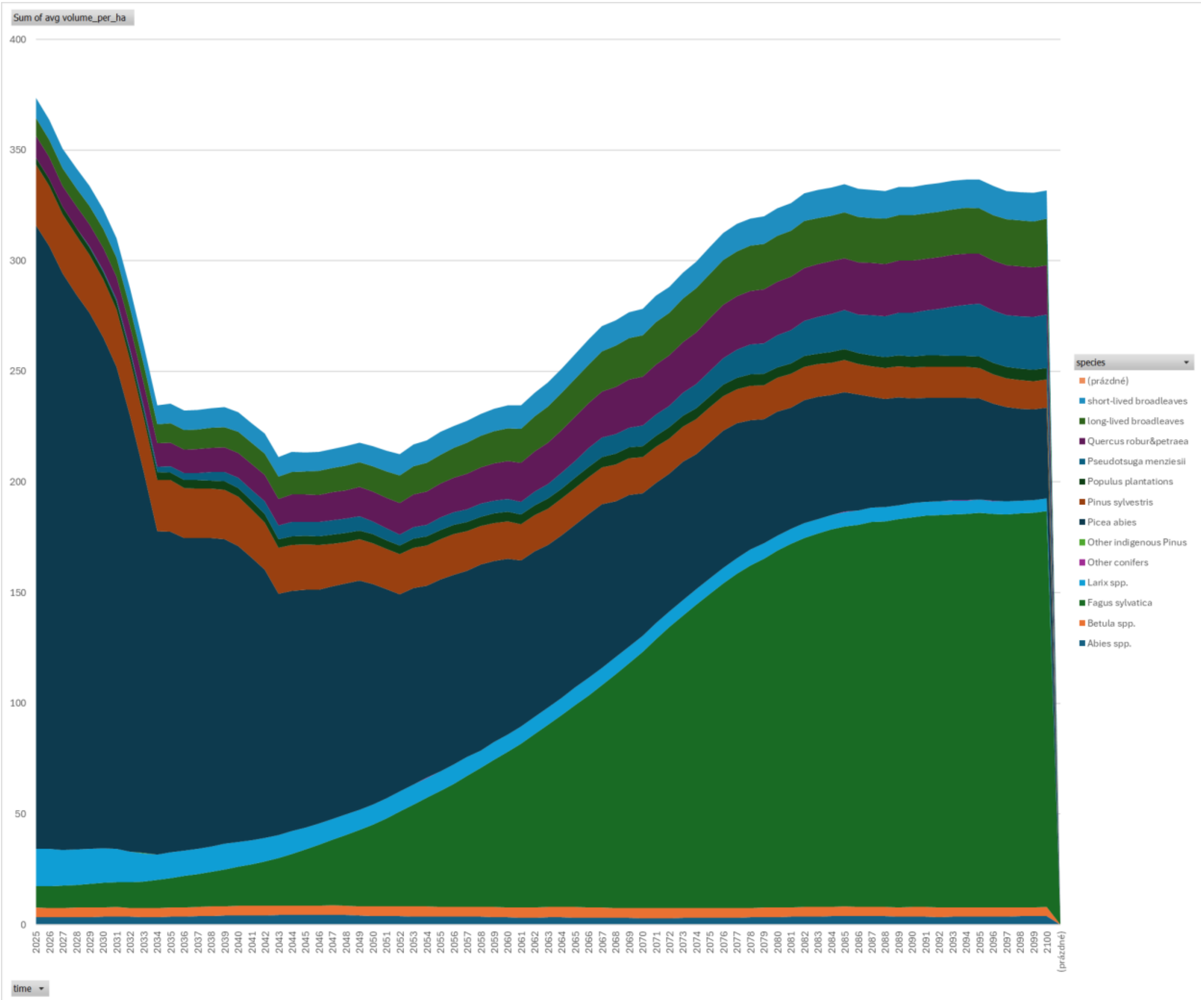

Figure 23. Average standing volume per hectare (m³/ha) from 2025 to 2100, broken down by tree species under the #2 moderate Ips scenario.

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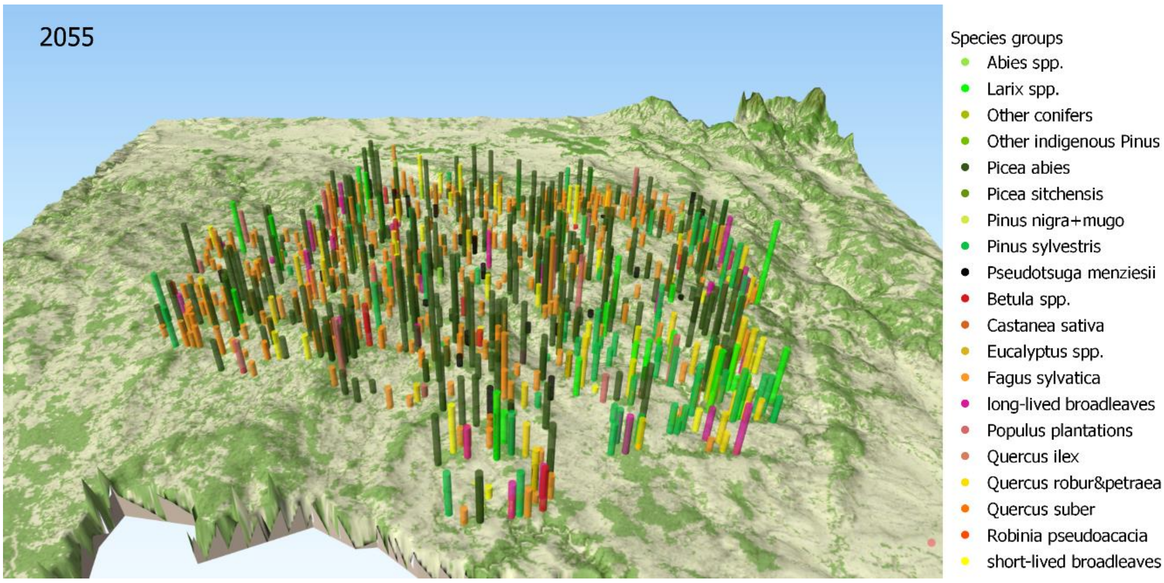


Figure 24. State of forest resources in 20225 under moderate Ips scenario.

Forest structural diversity across three scenarios (Gini; Figure 25) improved from the initial 0.40 (BAU in 2025) to more complex forest structure (0.50) under moderate forest management change of Scenario 2 within the next 30-years. Under intensive management of Scenario 1 and applied drastic planting, the structural diversity indicated strong improvement within first 20-years after which it decreased to similar structure as in BAU scenario. This fluctuation of Gini was a consequence of high harvest levels within first 20-year (Figure 12) after which total standing stock volume was significantly lowered (Figure 26). In addition intensive planting activities resulted in most volume accumulated in diameter class 10 – 20 cm.

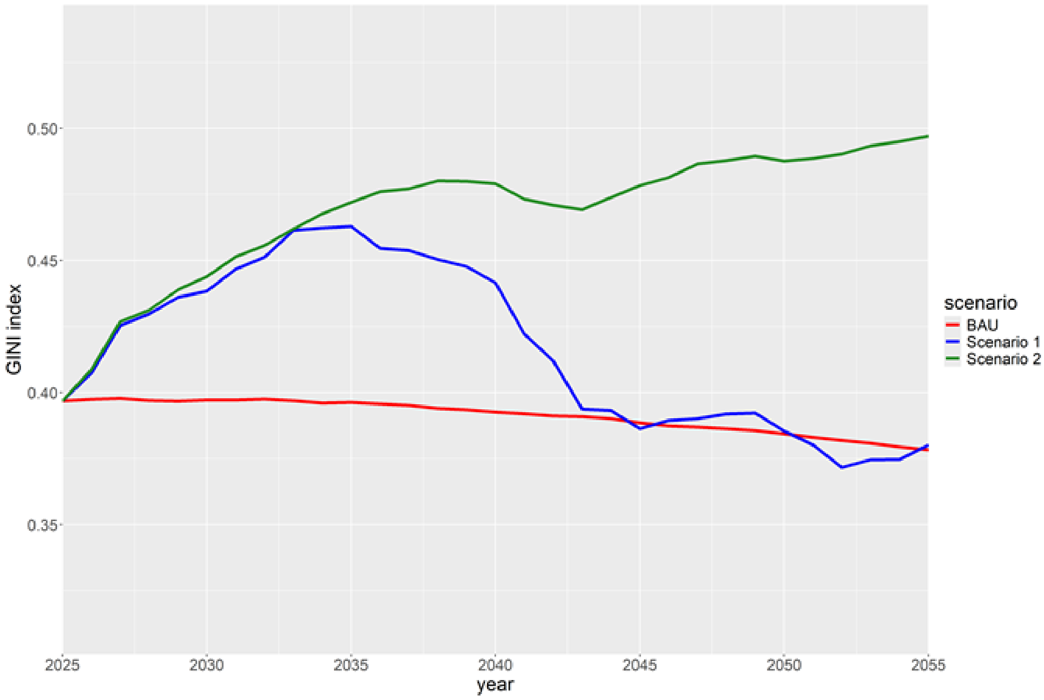


Figure 25. Gini index (inequality index) development for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

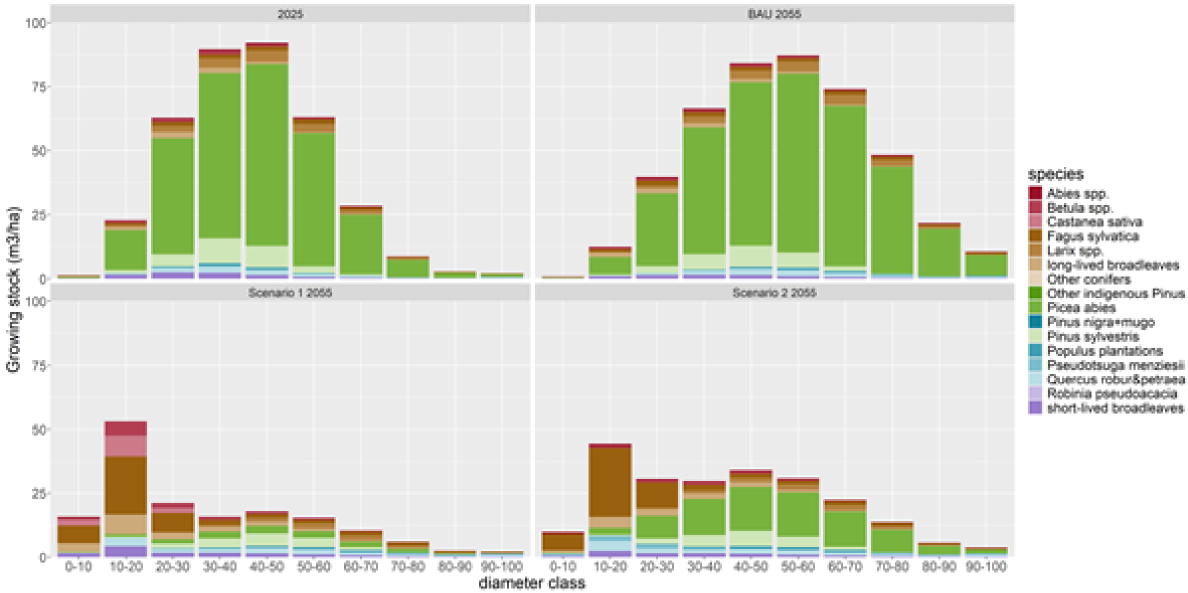


Figure 26. Growing stock (m3/ha) development per species over diameter classes (cm) from 2025 till 2055 for the three different scenarios.

Mean mortality (m3/ha/year) showed high tree mortality in small to medium diameter size classes 0 – 30 cm in both restoration scenarios compared to BAU (Figure 27). This was a consequence of applied planting activities and spontaneous occurrence of natural regeneration.

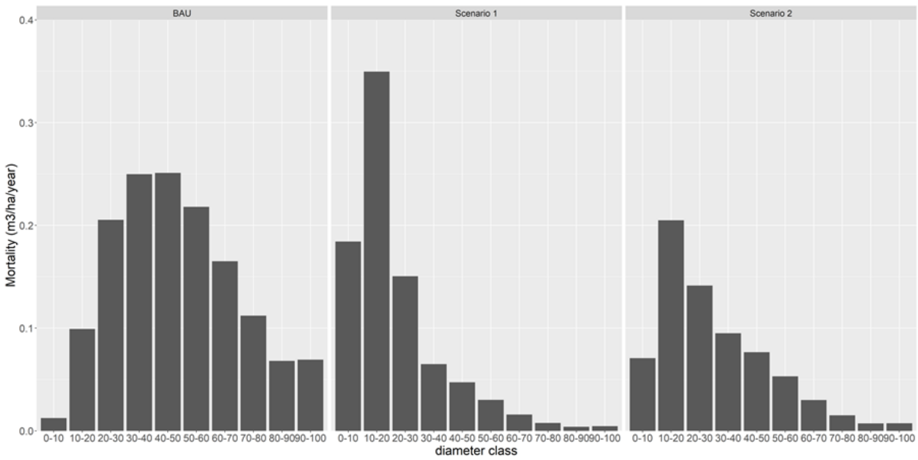


Figure 27. Mean mortality (m3/ha/year) development over diameter classes (cm) for the three different scenarios. Here mortality is estimated as an average of 30-year simulation (from 2025 till 2055).

KEY FINDINGS

Key finding #1

In Vysočina region with 219000 ha of forest (repr by 1097 NFI plots) a calamity regime was applied on 447 plots (95000ha). A rather drastic restoration regime is then the only option.

Disturbance scenarios (#1 intense *Ips* calamity and #2 moderate *Ips* calamity) lead to substantial volume loss in coming decades. While a recovery period occurs in both scenarios, by 2100, standing volumes remain significantly (250 and 330 m^3/ha) lower than in the baseline scenario (450 m^3/ha). In a baseline, assuming very limited influence of bark beetle, the standing volumes increase over time. Diameters of harvested trees increase from currently mostly 40–50 cm to 60+ diameters.

Key finding #2

Forest structure shifts toward smaller trees and more broadleaved species in both *Ips* scenarios. While in #1 intense *Ips* scenario, volume and increment decrease to approximately 50% of the baseline in 2100, in #2 moderate Ips scenario, the reduction of spruce is partially substituted by an increased share of other conifers such as Douglas fir, *Quercus* spp and long lived broadleaved. These drastic restoration scenarios stipulated by large calamities lead to unsustainable developments for several decades, and large volumes of harvestable wood in coming decades. This seems almost unavoidable, although the speed at which it occurs can be influenced and moderated by management. In longer term, less wood will be available and assortments changing drastically.

The more diversified forest planting and restoration leads to an improved structural diversity (Gini) in both Ips scenarios than in the BAU. In #1 (because of drastic planting) the Gini goes down again after 20 years as forest in dominated by smaller diameter size trees.

If the total standing volume decreases as in scenario #1 from 80 million m3 to 30 million m3 in 15 years, this implies a carbon loss of 4 million tonnes CO_2/y.

Key finding #3

Harvest and increment dynamics are severely affected by bark beetle infestations. The *Ips* scenarios show strong peaks in harvested volume during the outbreak years, followed by sustained declines. Gross annual increment also drops, with only partial recovery, highlighting the long-term adverse effect of disturbance on forest productivity and sustainable harvest potential.

RECOMMENDATIONS

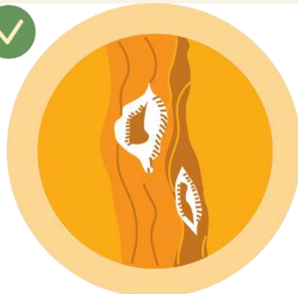
Takeaway #1

Under strong calamities, only a rather drastic restoration option remains. Taking the resources though unsustainable periods.

A comparison of the individual scenarios shows that the #2 moderate *Ips* scenario, with a more balanced share of broadleaved and coniferous species, is likely to result in higher standing volumes, increment and harvest, and lower mortality compared to #1 intense Ips scenario — while simultaneously supporting greater forest resilience and resistance compared to the baseline scenario.

Early adaptation to future climate seems a very good strategy if current periods of oversupply of wood, followed by under supply wish to be avoided. A gradual transition also in currently healthy spruce stands seems a good strategy

Takeaway #2



A combination of artificial and natural regeneration appears to be the optimal approach for establishing mixed stands with sufficient productive and adaptive potential under current conditions.

At average restoration costs of ~ 5000 Euro/ha (see Vysočina workplan), the total costs of the 95000 ha would amount to 475 million Euro in total for coming decades.

However, creating mixed forests possibly places higher demands and costs on forest managers while also being associated with lower expected revenues from timber sales. Consequently, introducing targeted financial support instruments is crucial to maintaining the long-term economic sustainability of the forestry sector.

Takeaway #3

The fundamental shift in species composition and the increasing share of harvests in lower dbh classes will require substantial adaptation in the wood processing industry and related technologies. Reduced harvest volumes and smaller dimensions will place additional economic pressure on forest owners, driving the need for more efficient and cost-effective forest management approaches and strategies.

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