



# FORWARD PROJECTIONS

## NORTH RHINE WESTPHALIA, GERMANY



**SUPERB**  
Upscaling Forest Restoration



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## Recommended citations

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Photo: Calamity site in Großes Sonnenstück (state for 2024-04-03) by Dietmar



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# EXECUTIVE SUMMARY

## Overall key findings:

- On an area of 87000 ha (out of 854000 in NRW) bark beetle calamity management was employed. Either through a more mixed broadleaved approach, or through a wood production orientation
- In the baseline the NRW forest may lose some 50-70 million tonnes of CO<sub>2</sub> between now and 2050 due to calamity
- Forest composition is changing in all scenarios with only restoration scenario two recovering to former levels in terms of total volume and standing stock.
- Reduction of larger dbh classes in particular of broadleaved trees (due to relatively high harvest pressure) in all scenarios which might have implications for biodiversity while the relative stability of broadleaved species in dbh class 90-100 suggests that the restoration scenarios comparatively provide the best conditions for supporting biodiversity.
- The scenarios differ in their potential for climate change mitigation with restoration scenario 2 having the highest potential. Although in all scenarios, the NRW forests go through long phases of carbon losses.
- The restoration of calamity sites with broadleaved species takes time and will be associated with reduced harvesting volumes (1-2 million m<sup>3</sup>/y) at least for decades. More broadleaved wood will be available, less in coniferous
- The 87000 ha of restoration area may cost (at average ha prize of 11.5kEuro (workplan)) around 1 billion Euro. Or if carried out until 2050, some 40 million/y.



# DEMO INFORMATION

The federal state of North Rhine-Westphalia (NRW) is the most populous state of Germany and contains the largest urban network in Germany, the Rhine-Ruhr metropolitan area. The region grew significantly since the mid-19<sup>th</sup> century due to industrialization and was characterized by heavy industry, especially coal and iron mining. The switch from charcoal to black coal as the main source of energy changed the demands on the forest. The need for pit timber increased. As a result, mainly coniferous stands consisting of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) were established in NRW's forests.

Forest ownership in NRW is fragmented. The majority of forests is privately owned by about 152.000 forest owners (63%). Most forest owners own a relatively small area with about 90% owning less than 5 ha of forest. Municipal forests make up 21%, state forest 13%, and federal forest approximately 3%.

Forests in NRW are increasingly exposed to the consequences of a changing climate. Since 2018, around 133.000 hectares of damaged areas have been created due to the interaction of storms, droughts, and the mass outbreak of European spruce bark beetles (*Ips typographus*). More than half of the calamity areas (around 53%) area still requiring reforestation at this date.

According to the latest national forest inventory, NRW has 950.000 ha of forest, which corresponds to 28% of the state's area. The share of deciduous tree species makes up 65%, while coniferous tree species account for 35%. Currently, after the calamity, the most common tree species are beech (19%) and spruce (17%). Before the calamity, spruce was the most common coniferous tree species with 30%. Due to the bark beetle calamity, more than 53% of the spruce population was lost between 2018 and 2023.

To reduce the risk of such large-scale calamities in the future, the restoration approach in the SUPERB demo region NRW focuses on establishing diversified forest stands. A mix of at least four tree species, selected for their suitability to both current and future site conditions and with consideration for the expected impacts of climate change (RCP 4.5/8.5), is being introduced to the restoration sites. Natural regeneration was utilized where appropriate. Guidance is provided by the forest development types (WET) outlined in the silvicultural concept of NRW, which represent ideal tree species combinations for different site conditions and forest owners' preferences. To protect the sites from high browsing pressure and maintain consistency, plantings and natural regeneration are either fenced or protected

with growth shelters. As such the restoration measures aim at restoring spruce calamity areas to ensure the sustainable provision of ecosystem services and enhance forest resilience to the adverse impacts of climate change.

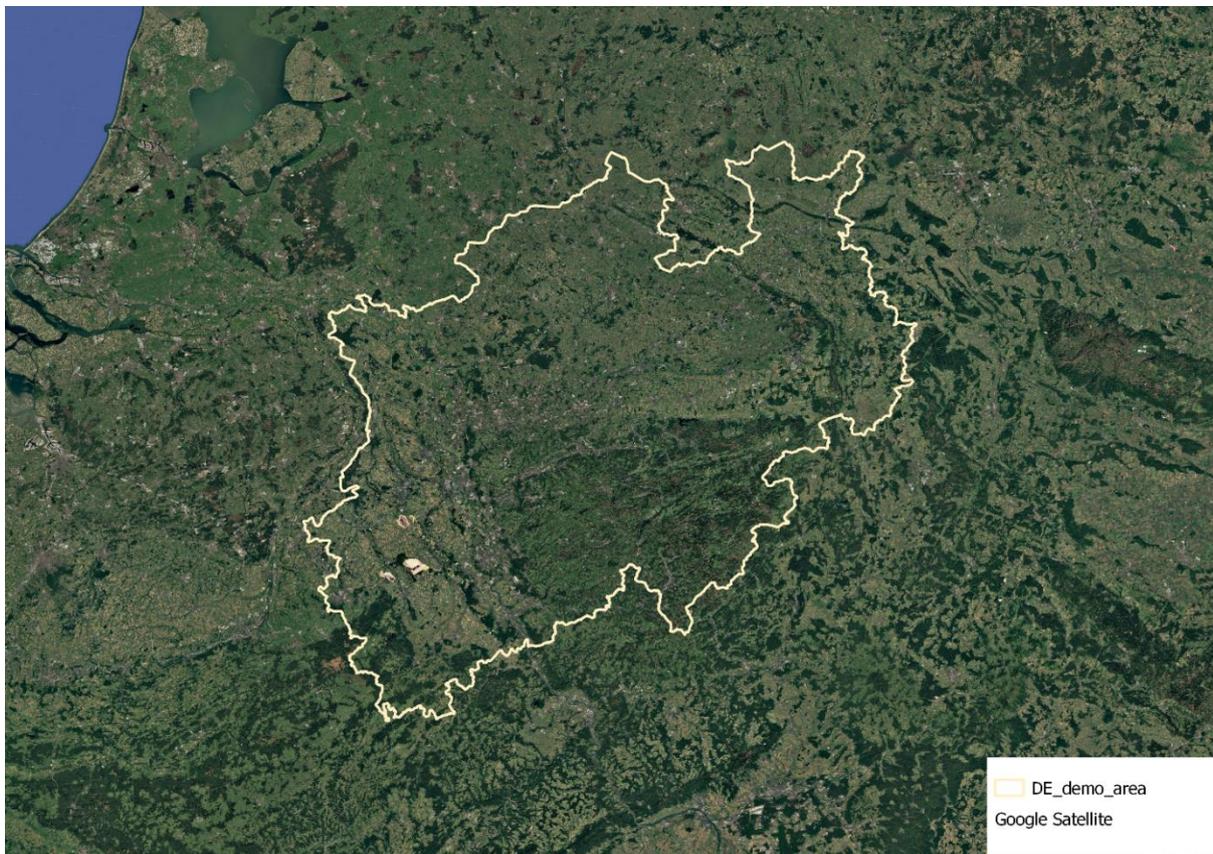


Figure 1. Aerial view on land use in NorthRhine Westphalia

# 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., 2018a). 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; Konig 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 as 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

We cover 854000 ha of forest in North Rhine Westphalia in the data base (officially it is 952000ha). The latest NFI data we had covered the period 2011-2013 in which NRW forests were represented by 2170 plots.

All runs were made from the year 2025 to 2100. As our input NFI cycle was for the years 2011-2013 we first had to bring the forest resource information to the initial year 2025. We implemented the calamity years by applying a higher harvesting intensity from 2012-2025. We did so to arrive at a real growing stock in 2025. We applied this with a intense harvesting prescription and brought the volume down to 268 m<sup>3</sup>/ha o.b. in 2025. This was very close to the real value. Note that we applied it evenly over the region. Only later in calamity runs, plots were overlain on calamity areas and those plots obtained calamity management.

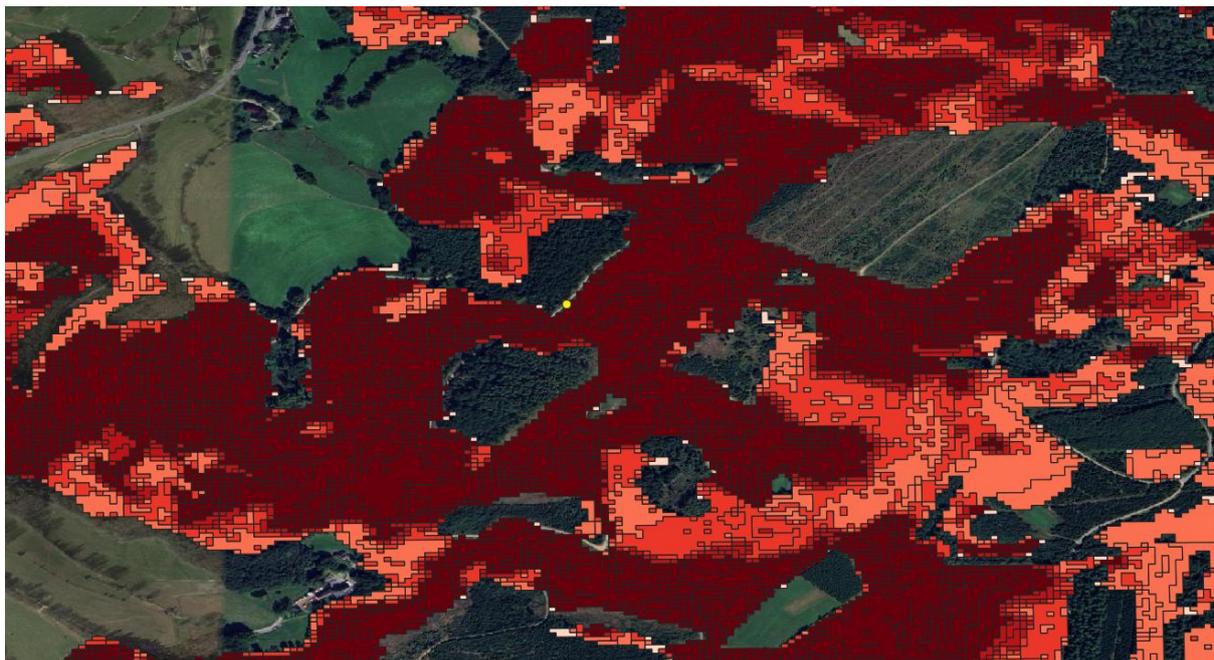


Figure 2: Zoom in to calamity areas (all red areas are forest affected by bark beetle calamity). The yellow dot is one NFI plot that falls inside calamity areas. This one is initialised with calamity management, see scenario 2.

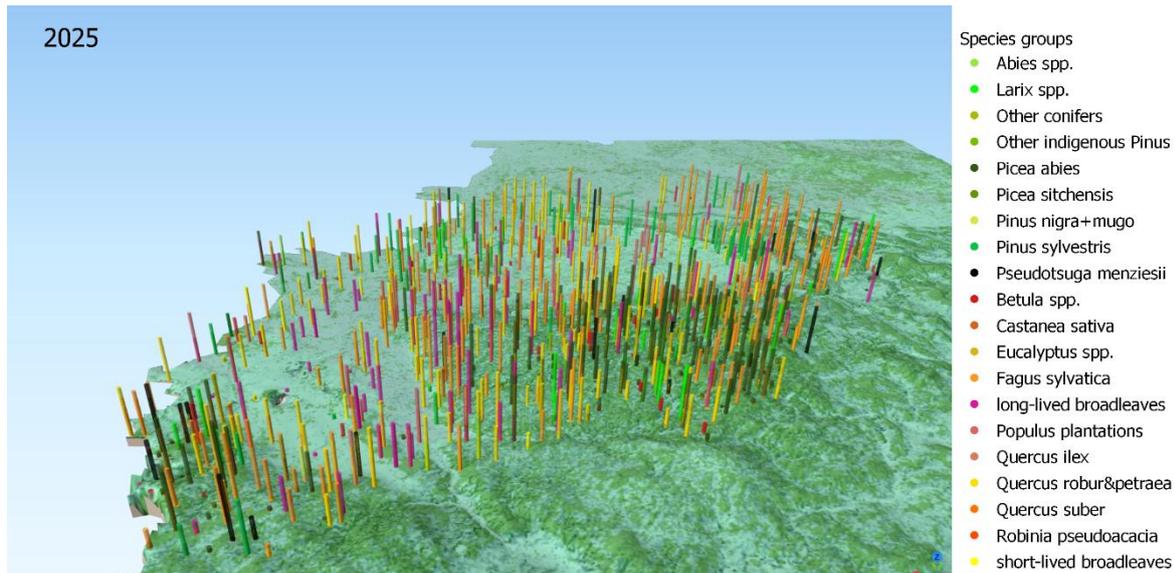


Figure 3. 3D view on North Rhine Westphalia in 2025. Each bar is a NFI plot. The height of the bar is the growing stock, the color is the main tree species. Spruce dominates in Sauerland mountainous area.

## 1. Baseline (BAU)

Much of the natural regeneration in calamity sites includes a significant proportion of spruce, even though spruce is not well-suited to the site conditions in most of these areas. Some spruce monocultures especially in earlier stages also remain standing. This scenario examines the potential outcomes if we were to overlook the calamity and the risks associated with spruce monocultures in planar, colline, sub-montane, and montane forest stands. This with proceeding with a business-as-usual approach to forest management without considering the potential impacts of climate change. Management intensities are applied as derived from the repeated NFIs we had from Germany. This is a relatively high intensity.

## 2. Restoration scenario – Increasing forest resilience (Demo area scenario)

We overlaid all plots on calamity areas. In this way 222 plots were identified out of 2170 total. The idea of this scenario is to create a more resilient diverse (more broadleaved) forest under assumptions of continued pressure on spruce forests. For this a high clearcut pressure was applied on spruce forests, but on those 222 plots only that were identified as current calamity areas. This does not increase over time.

Table 1. Nr of young trees/ha assumed to be planted in scenario 1 in diameter class 5-7.5 cm when the basal area was below 10 m<sup>2</sup>/ha.

Pinus sylvestris	200
Betula spp.	300
Castanea sativa	200
Fagus sylvatica	800
Quercus robur & petraea	800
long lived broadleaves	400
shortlived broadleaves	400

Each demo site was restored establishing a minimum of four site-adapted tree species and using natural regeneration where possible (Table 1). These mixtures were often dominated by broadleaf tree species, especially oak or beech. The goal is to actively establish resilient mixed-species forest stands which diversify the risk of future large-scale calamities and ensure the provision of essential ecosystem services. Each species mixture consists of a main tree species with one to two secondary and additional tree species.

### 3. Restoration scenario – Sustain wood production

This scenario works with the same overlay of plots of calamity areas as in previous restoration scenario but keeps attention on coniferous production in the future. In normally managed spruce stands, we plant fir and Douglas fir in small amounts (300 plants) when those stands are thinned. In calamity stands we plant as given in table 2 below. In calamity stands, many forest owners want to generate a profit from their lands. Despite the calamity the most profitable tree species remain to be coniferous. To increase the stand resilience conifers could be planted in site-adapted species mixtures. This scenario assumes that we reforest calamity areas with a focus on sustainable wood production by focusing on plantings of coniferous species mixtures to nevertheless diversify risks of large-scale calamities.

Table. Nr of young trees/ha assumed to be planted in scenario 2 in diameter class 5-7.5 cm when the basal area was below 10 m<sup>2</sup>/ha.

Abies alba	800
Larix spp.	500
Pseudotsuga menziesii	800
Pinus sylvestris	400

# PROJECTION RESULTS

## EFISCEN-Space

### 1. Baseline (BAU)

In the baseline scenario the average volume as well as the total volume per hectare are gradually decreasing. The average volume per hectare decreases from 265.74 m<sup>3</sup>/ha in 2026 to its lowest value in the year 2072 with 199.78 m<sup>3</sup>/ha. After the continued decline the average volume continues in the same range between 200 – 210 m<sup>3</sup>/ha with only minor changes. The average volume per hectare in 2100 is 208.06 m<sup>3</sup>/ha. The total volume follows a similar trend. From 227.16 Mio. m<sup>3</sup> in 2026 the total volume falls to 170.77 Mio. m<sup>3</sup> in 2072 with a following stabilization of total volume with values between 170 – 180 Mio. m<sup>3</sup> until 2100. The total volume in 2100 is 177.86 Mio. m<sup>3</sup>.

On the other hand, gross annual increment per hectare per year as well as total increment are steadily increasing. Gross annual increment is steadily increasing from 8.74 m<sup>3</sup>/ha in 2026, peaking in the year 2099 with 12.35 m<sup>3</sup>/ha. The same development is observed for the total increment which gradually increases from 7.47 m<sup>3</sup> with its peak in year 2099 at 10.55 m<sup>3</sup>.

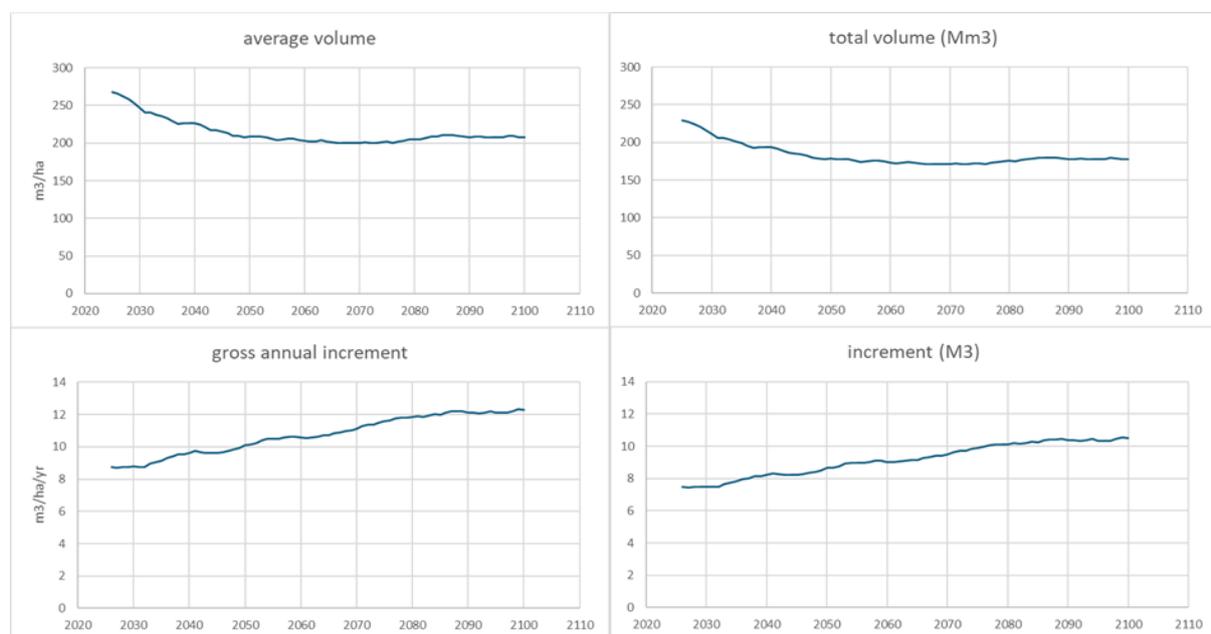


Fig. 4: The graphs show the development of average volume and total volume per hectare as well as the gross annual increment and total increment per hectare per year in the baseline scenario in from 2026 to 2100.

The average harvested volume per hectare varies from year to year. It peaks in 2031 with 14.96 m<sup>3</sup>/ha. In the years following average harvested volume ranges between 8-12 m<sup>3</sup>/ha

with one last peak in 2099 with 13.16 m<sup>3</sup>/ha. The total annual harvest per hectare follows the same trend. Two peaks are observed in year 2031 with 12.8 Mio. m<sup>3</sup> and 2099 with 11.3 Mio. m<sup>3</sup>. Otherwise, the total annual harvest per hectare ranges between 7 – 11 Mio. m<sup>3</sup>.

The average mortality as well as the total annual mortality are reflecting a similar development. Average mortality is initially decreasing from 0.72 m<sup>3</sup>/ha in 2026 to 0.59 m<sup>3</sup>/ha in 2032. Following the decline, a steady incline is observed reaching its peak in 2088 with 0.92 m<sup>3</sup>/ha. Total annual mortality follows the same development.

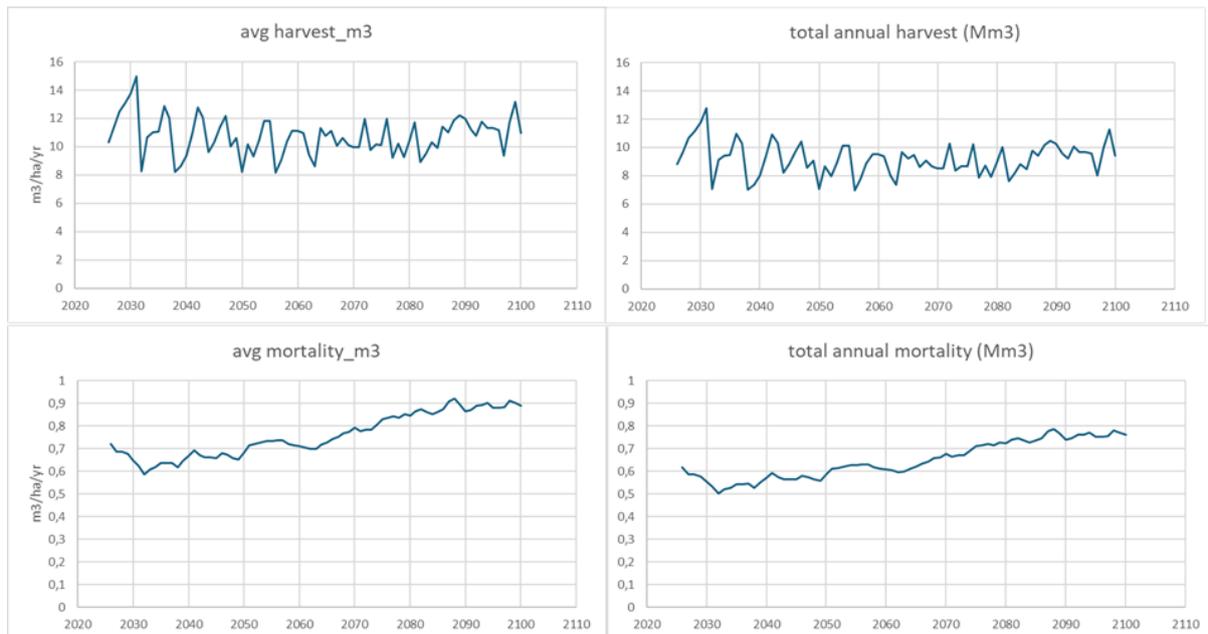


Fig. 5: The graphs show the development of average harvest, total annual harvest, average mortality and total annual mortality per hectare per year from 2026 to 2100.

Fig. 6 summarizes the development described above. Harvested volume generally decreases to a level between 8-12 m<sup>3</sup>/ha/year. The average mortality as well as gross annual increment are increasing over the period of 2025-2100, with the gross annual increment increasing stronger than average mortality.

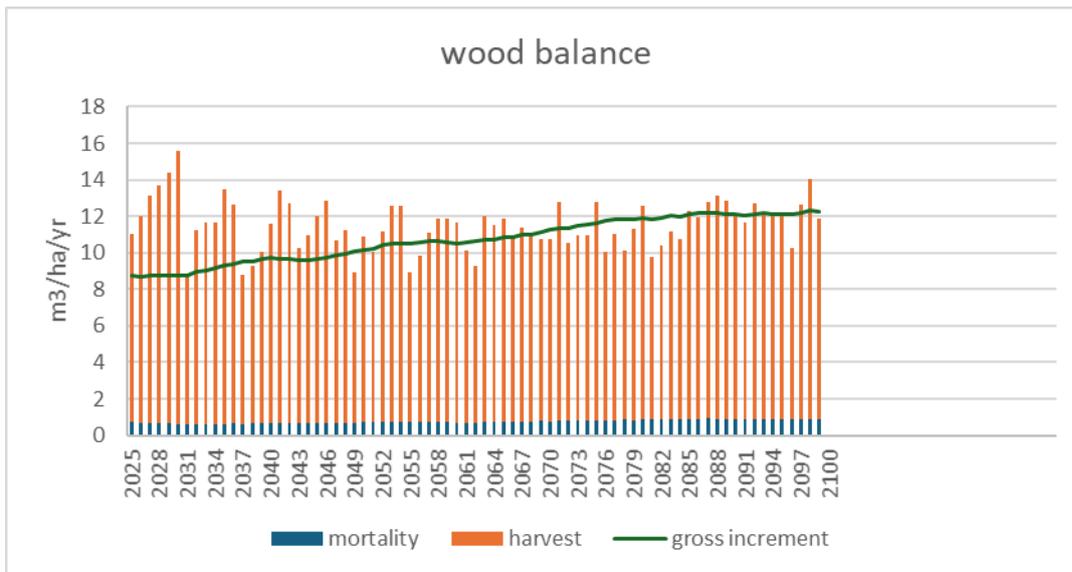


Fig. 6: Development of average harvested volume, average mortality and gross annual increment per hectare per year in the baseline scenario.

The development of the total standing stock overtime shifts from a well distributed dbh spectrum to a dominance of trees in lower dbh classes for both conifers and broadleaves (see figure 7). Volume in larger dbh classes continues to decline between 2026 to 2100. While the total standing stock in 2026 is 227.16 Mio. m<sup>3</sup> it decreases to 173.32 Mio. m<sup>3</sup> in 2060 with a slight increase in 2100 to 177.49 Mio. m<sup>3</sup>. In 2060 as well as 2100 the volume of the total standing stock is found particularly in dbh classes 10-20 cm and 20-30 cm for broadleaf species while the volume of coniferous species mainly spreads between the dbh classes 10-20 cm through to 30-40 cm.

Figure presents the distribution of total harvest of coniferous and broadleaved trees in Mio. m<sup>3</sup> in ten different dbh classes for the years 2026, 2060 and 2100. In 2026 broadleaved trees with higher diameters are predominately harvested. The majority of total harvested volume of broadleaved trees shifts to smaller diameters over the modelled years. The development of harvested volume of trees in lower dbh classes is also observed for coniferous trees. In the year 2100 the majority of the harvested volume comes from the dbh class 20-30 cm followed by harvested volume in dbh class 10-20 cm. The total harvest is increasing between 2026 and 2060 from 8.82 Mio m<sup>3</sup> to 9.51 Mio m<sup>3</sup>. In 2100 the total harvest decreases to 9.38 Mio m<sup>3</sup>.

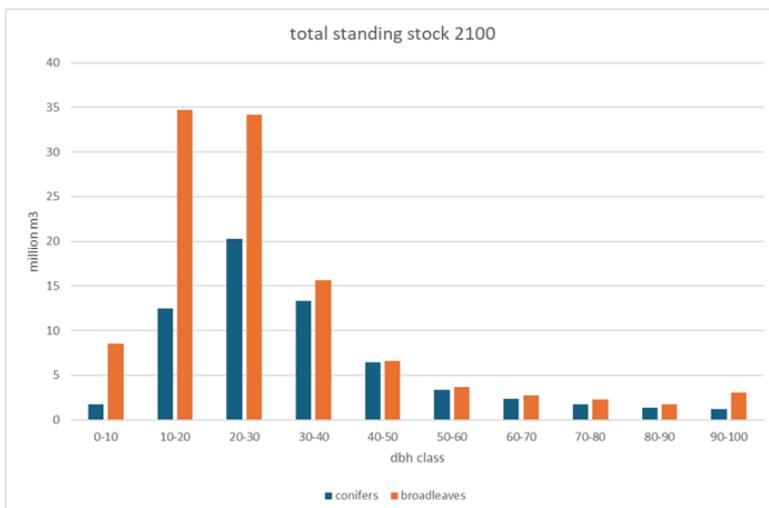
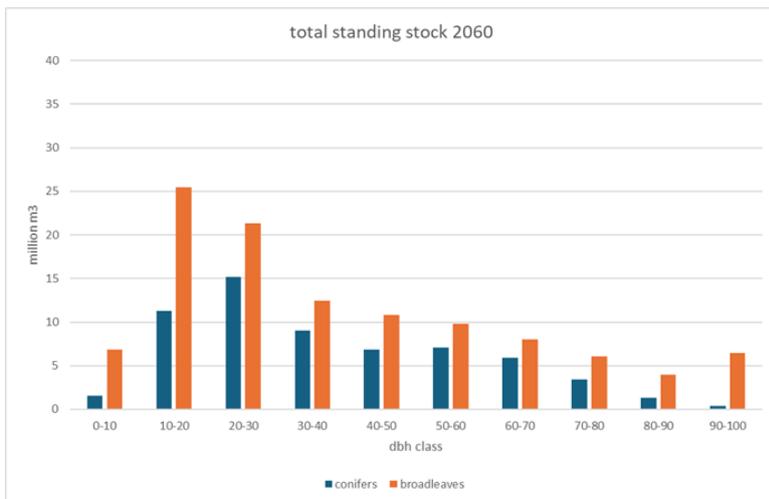
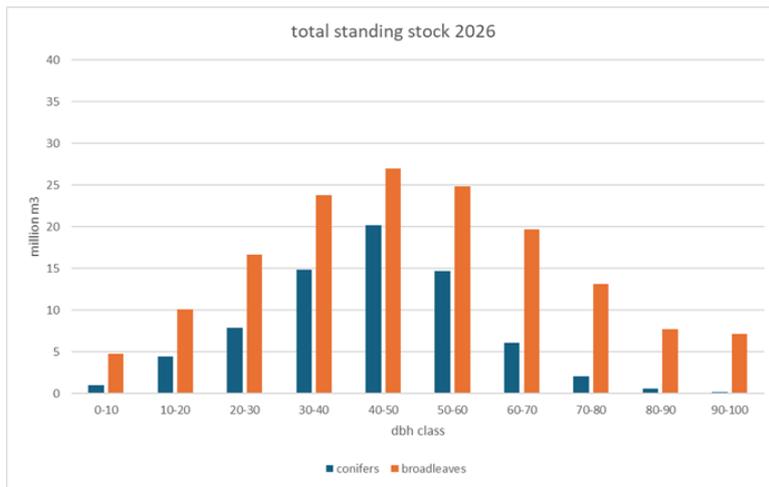


Fig. 7: Distribution of total standing stock in Mio. m<sup>3</sup> across ten dbh classes in the years 2026, 2060 and 2100.

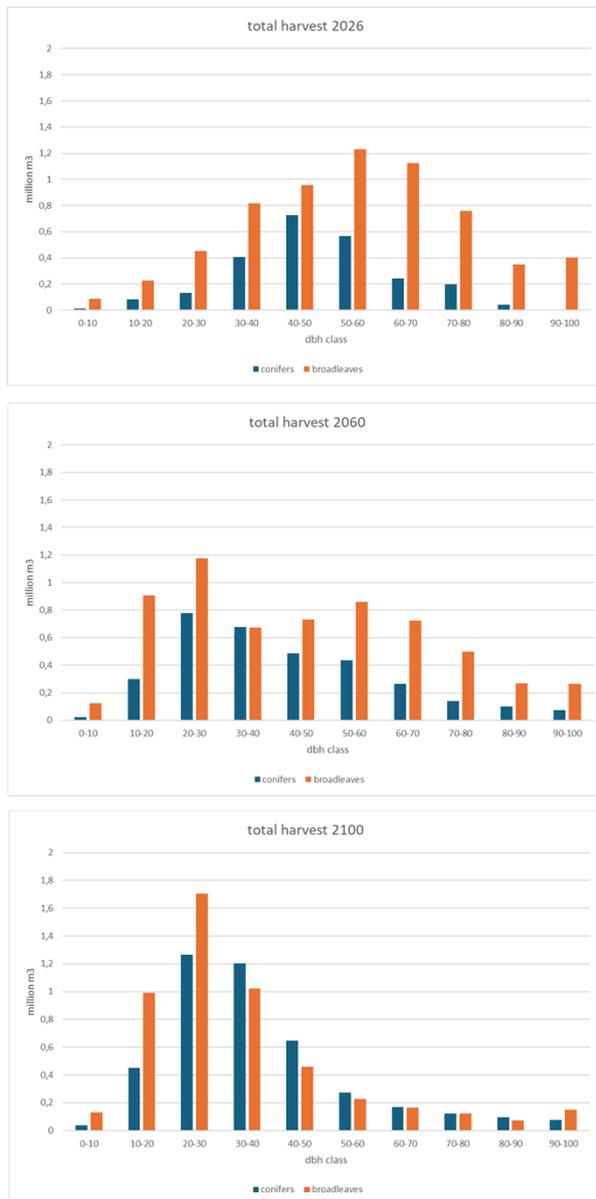


Fig. 8: Distribution of total harvest in Mio. m<sup>3</sup> spread across ten dbh classes for the years 2026, 2060 and 2100.

As already mentioned above, the average volume per hectare is overall declining. In particular, *Fagus sylvatica*, *Quercus robur*, *Q. petraea* and *Pinus spp.* have declining average volumes per hectare over the years (see Fig. 9). Some species however have an increasing average volume per hectare. These are especially *Picea abies*, long-lived and short-lived broadleaves as well as *Betula spp.*

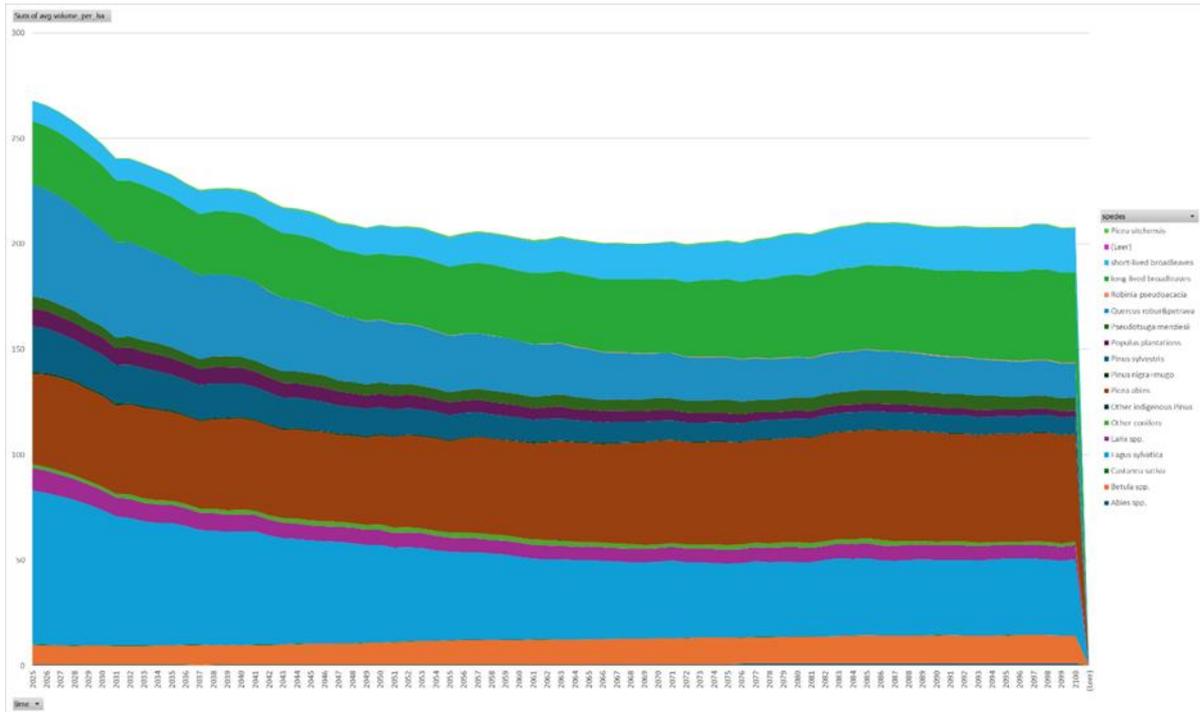


Fig. 9: Development of average volume per ha for different tree species over the years 2026 – 2100.

As outlined above, the total harvest varies between the years. However, it can be observed that an increasing volume is harvested from *P. abies* as well as short-lived and long-lived broadleaves. Although they do not make up a large amount of harvested volume also *Robinia pseudoacacia* and *Picea sitchensis* have increasing harvest volumes. For *F. sylvatica*, the *Pinus spp.*, and the two *Quercus spp.* on the other hand, the harvested volumes are decreasing over time. This development of reduced harvested volume is strongest for the *Quercus spp.* *Betula spp.* have a relatively stable harvested volume over the years.



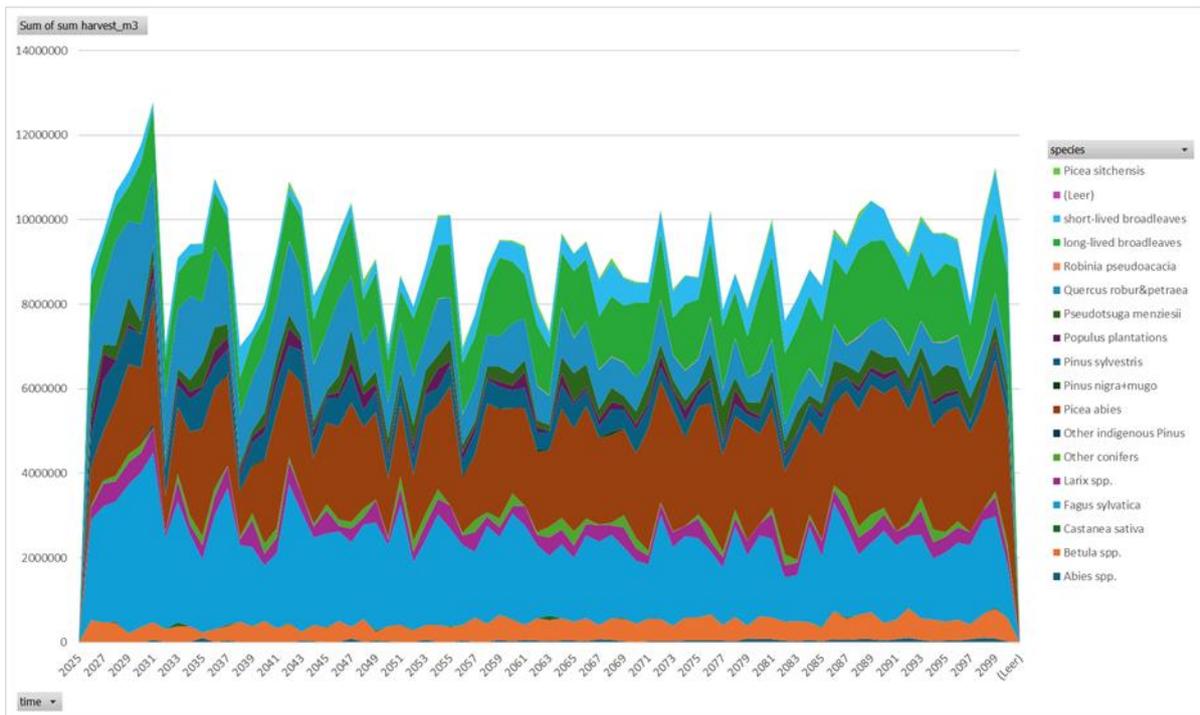


Fig. 10: Development of harvested volume for different tree species over the years 2026 – 2100.

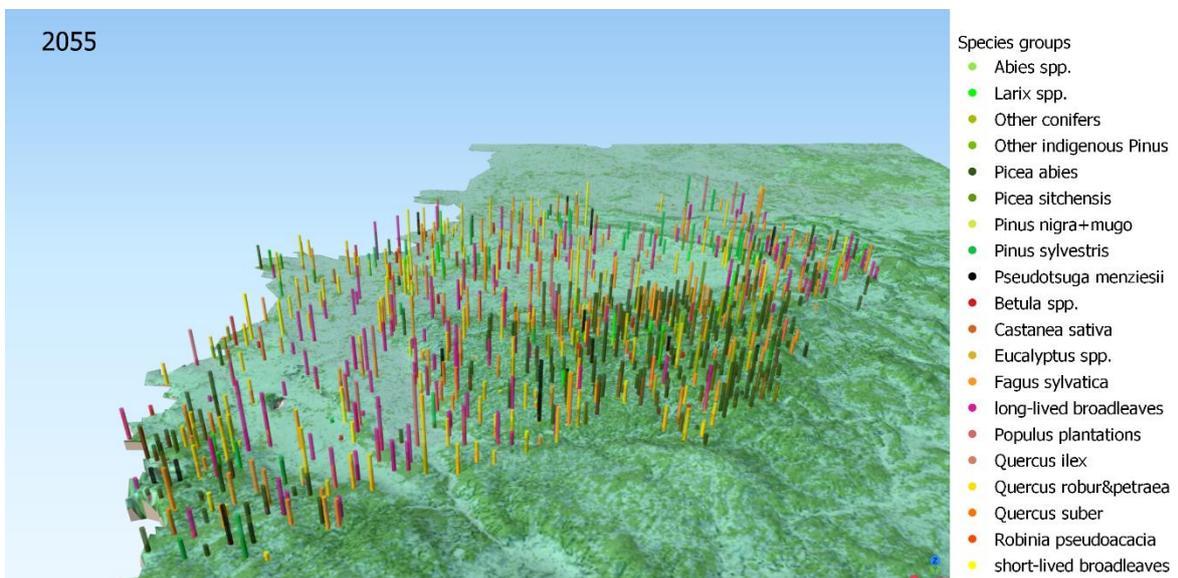


Figure 11. 3D view on NRW in 2055 under the baseline

## 2. Restoration scenario

In the first restoration scenario, the focus was on increasing resilience through the establishment of at least four different tree species on calamity sites as reforestation measure. As seen in figure 12, the average volume per hectare as well as the total volume initially experience a gradual decrease from an average volume of 264.04 m<sup>3</sup>/ha in 2026 until the year 2056 with the lowest average volume of 210.61 m<sup>3</sup>/ha. The same trend holds true for total volume which is 225.92 Mio. m<sup>3</sup> in 2026 and declines to 180.04 Mio. m<sup>3</sup> in 2056. After 2056 average volume per hectare and total volume are gradually increasing again. In 2100 average volume per hectare is at 245,95 m<sup>3</sup>/ha while total volume is at 210.24 Mio. m<sup>3</sup>.

Similar to the volume, gross annual increment and total increment reflect the same pattern (Fig. 12?). A short dip in 2031 with a gross annual increment of 8.67 m<sup>3</sup>/ha and a total increment of 7.41 Mio. m<sup>3</sup> is followed by a consistent increase of both gross annual increment per hectare and total increment. In 2100 gross annual increment has risen from 8.89 m<sup>3</sup>/ha/year in 2026 to 11.45 m<sup>3</sup>/ha/year. Total increment followed the same trend from 7.60 Mio. m<sup>3</sup> to 9.79 Mio. M<sup>3</sup>.

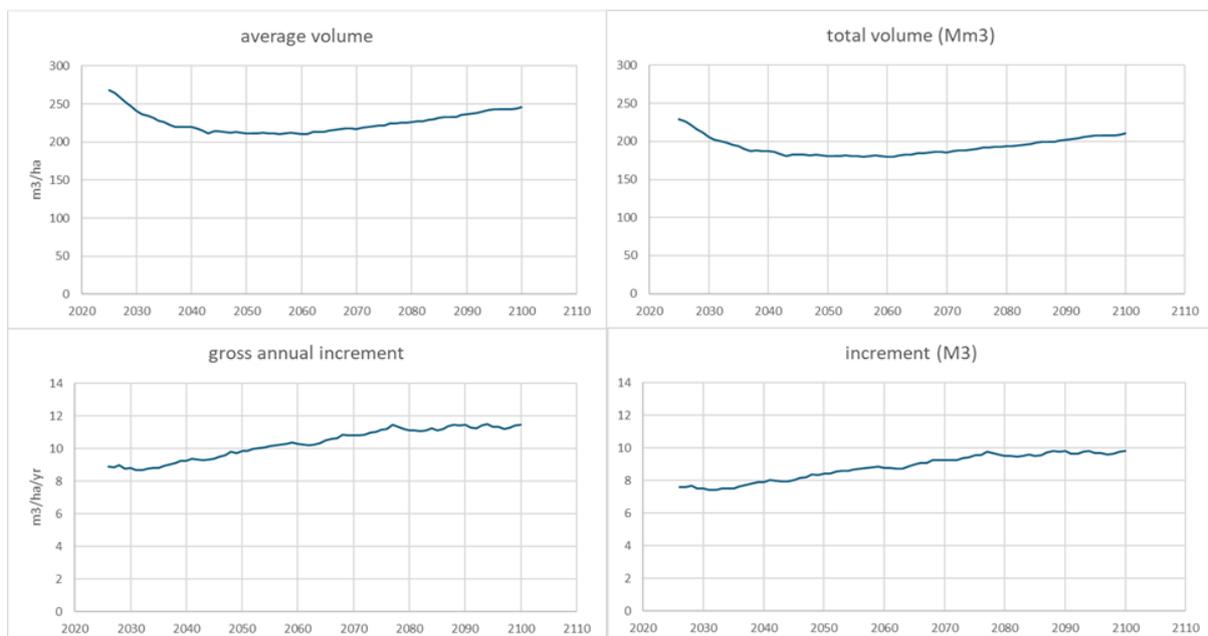


Fig. 12: Development of the average volume per hectare and total volume as well as gross annual increment per hectare and total increment from 2026 to 2100 in the restoration scenario 1 "increasing forest resilience".

Both the average harvest per hectare and the total annual harvest show a relatively rapid initial decline, followed by a period of stabilization at a fairly steady level. Both peak in the year 2028 with an average harvest of 14.87 m<sup>3</sup>/ha and a total harvest of 12.7 Mio. m<sup>3</sup>. The lowest dip occurs in the year 2044 with an average harvest of 6.51 m<sup>3</sup>/ha and a total harvest of 5.6 Mio. m<sup>3</sup>. The relatively steady level after this dip remains between 7-10 m<sup>3</sup>/ha for the average annual harvest and 6-9 Mio m<sup>3</sup> for total harvest.

Average mortality per hectare per year and total annual mortality also show a small decline before increasing quite steadily over time. Average mortality per hectare decreases from 0.72 m<sup>3</sup>/ha in 2026 to 0.59 m<sup>3</sup>/ha after which it gradually increases to 1.10 m<sup>3</sup>/ha in 2100.

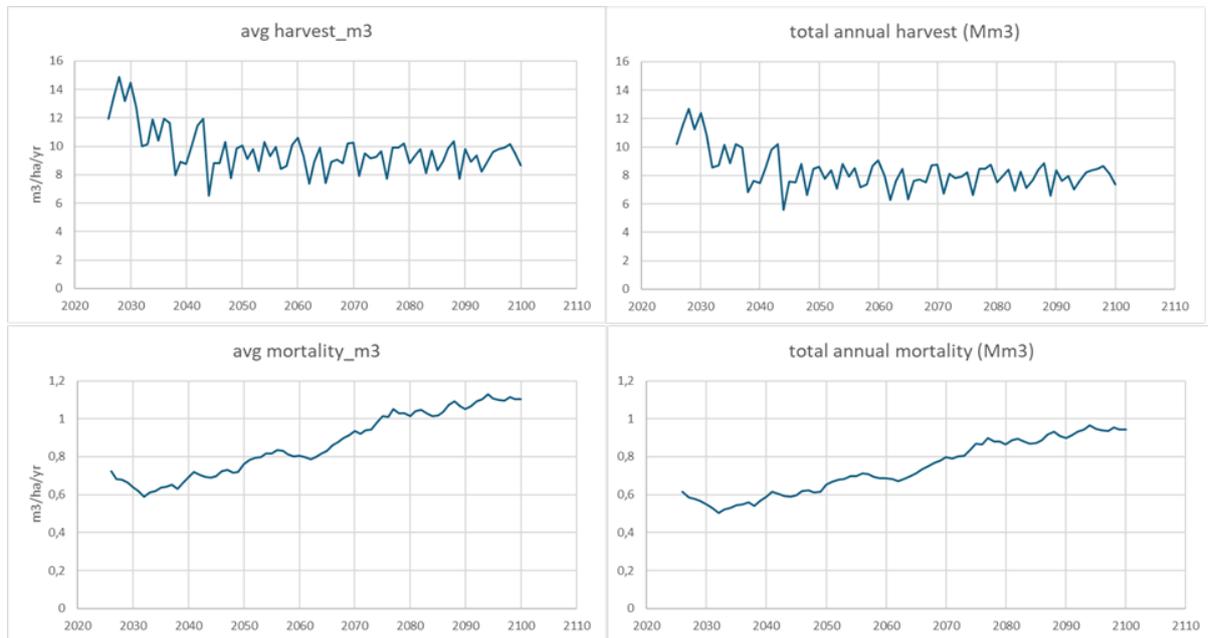


Fig. 13: Development of average harvest per hectare, total annual harvest, average mortality per hectare, and total annual mortality from 2026 to 2100.

Figure 13 illustrates the relationship between average harvest, mortality, and the gross annual increment. While average harvest is experiencing a slight decline and mortality is showing a slight increase, the gross annual increment continues to rise steadily.

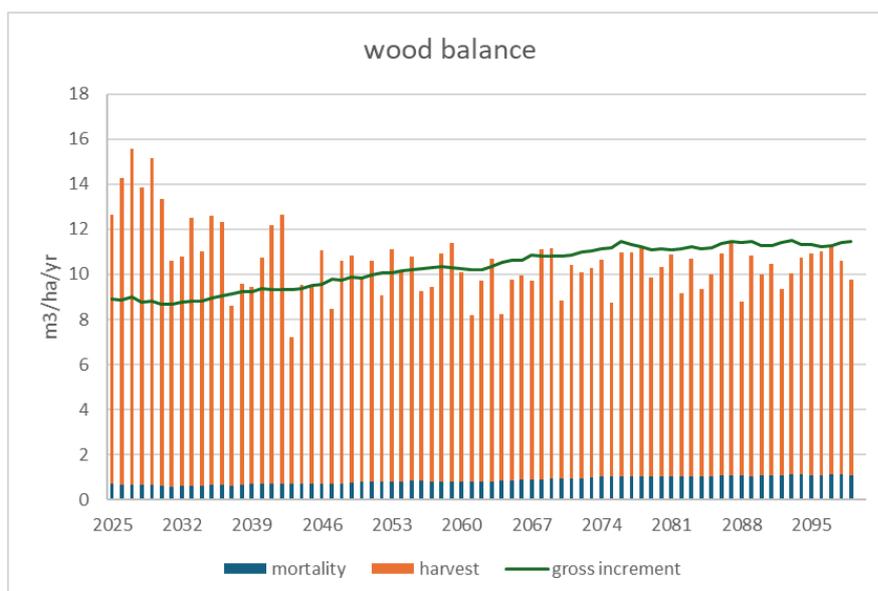


Fig.13: Development of average harvested volume per hectare (m<sup>3</sup>/ha/yr), average mortality (m<sup>3</sup>/ha/yr) and gross annual increment (m<sup>3</sup>/ha/yr) in the first restoration scenario.

Figure 14 shows the changes in total standing stock (m<sup>3</sup>/ha) over time, grouped by diameter classes, for coniferous and broadleaved species. In 2026, broadleaves dominate the total volume across all diameter classes, with both conifers and broadleaves following a bell curve (normal distribution) in terms of volume across the dbh range. By 2035, the overall standing stock has decreased in all diameter classes. In 2100, coniferous species experience a further decline in standing stock, with the majority of the conifer volume now concentrated in the lower dbh classes. Similarly, the standing stock of broadleaves shifts to smaller dbh classes, particularly in the 10-20 cm and 20-30 cm ranges.

While coniferous volume declines consistently from 71.93 million m<sup>3</sup> in 2026 to 37.72 million m<sup>3</sup> in 2100, broadleaved volume increases from 157.93 million m<sup>3</sup> in 2026 to 172.15 million m<sup>3</sup>, after an initial drop to 140.03 million m<sup>3</sup> in 2035. As such broadleaves surpass their 2026 volume value by 2100 while the overall standing stock decreases by 20 Mio. m<sup>3</sup>. The standing stock of broadleaves in dbh class 90-100 cm is relatively stable over the years.

Similar to the standing stock, broadleaves dominate the total harvest in 2026, 2035, and 2100 (Fig. 15). However, unlike standing stock, the total harvest gradually declines from 10.19 million m<sup>3</sup> in 2026 to 7.55 million m<sup>3</sup> in 2100. In 2026, the harvest primarily comes from broadleaves in higher dbh classes, while conifers are mainly harvested from the middle dbh classes. Over time, the harvested volume becomes more evenly distributed across all diameter classes, with broadleaves continuing to make up the majority of the harvested volume.

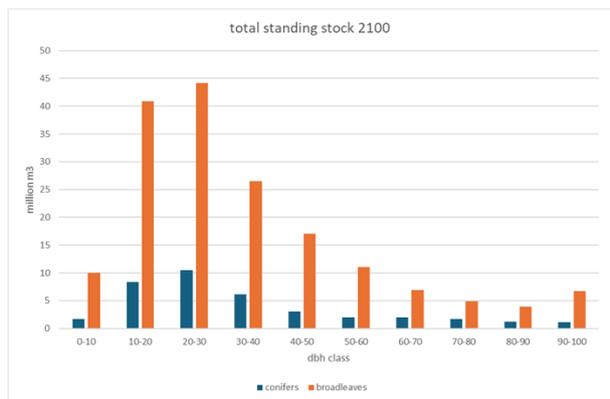
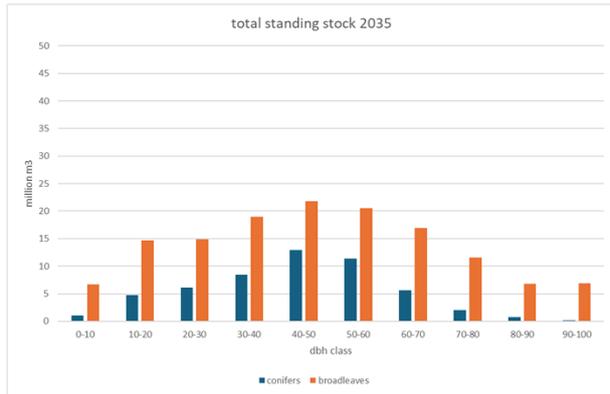
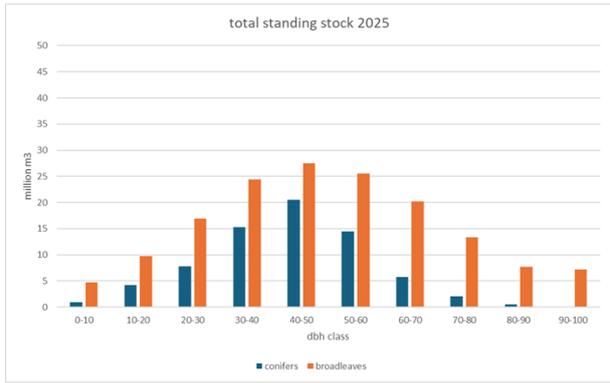


Fig. 15. Total standing stock (Mio. m<sup>3</sup>) in 2026, 2035, and 2100, categorized by diameter classes, comparing coniferous and broadleaved species.

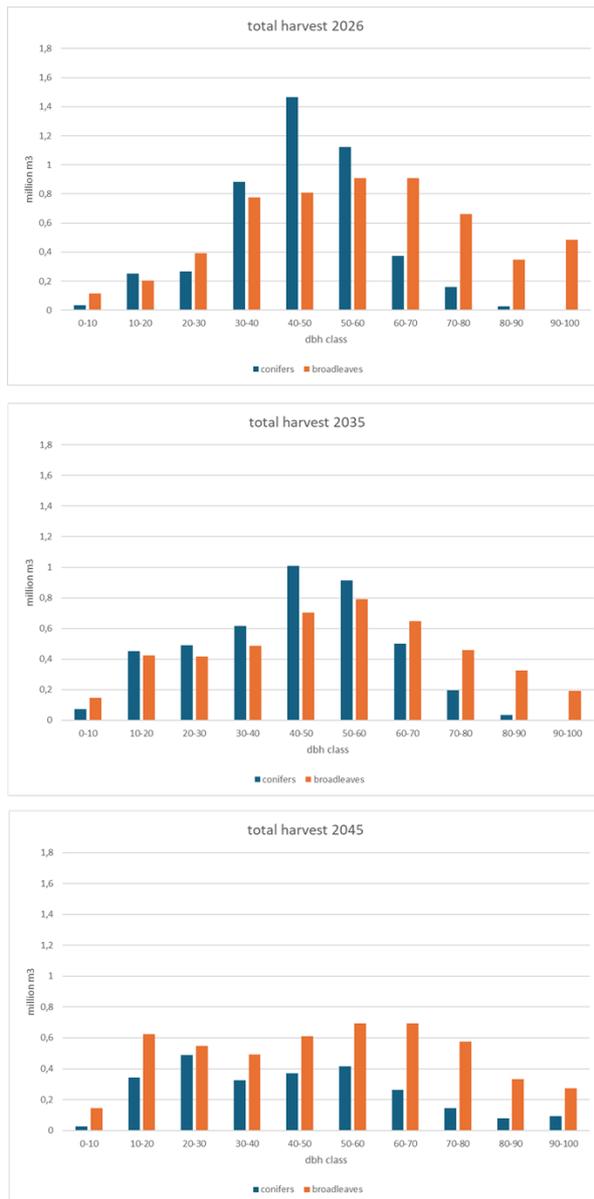


Fig. 16. Total harvest (Mio m<sup>3</sup>) in 2026, 2035, and 2100, categorized by diameter classes, comparing coniferous and broadleaved species.

As described above, the average volume per hectare is initially decreasing followed by a gradual increase over time. Yet, different species show a different development in average volume per hectare (Fig. 17). As such, the decreasing average volumes per hectare of some species are gradually counterbalanced by the increasing average volumes per hectare of other tree species. Conifer species such as *P. Abies*, *Larix spp.* and *Pinus spp.* are consistently declining. Long-lived and short-lived broadleaves as well as *Castanea sativa* on the other hand show a steady incline in average volume per hectare along with *Pseudotsuga menziesii*, *Abies spp.*, and *P. sitchensis*. *F. sylvatica* slowly recovers from an initial decrease in average volume while *Quercus spp.* have a consistently decreasing volume.

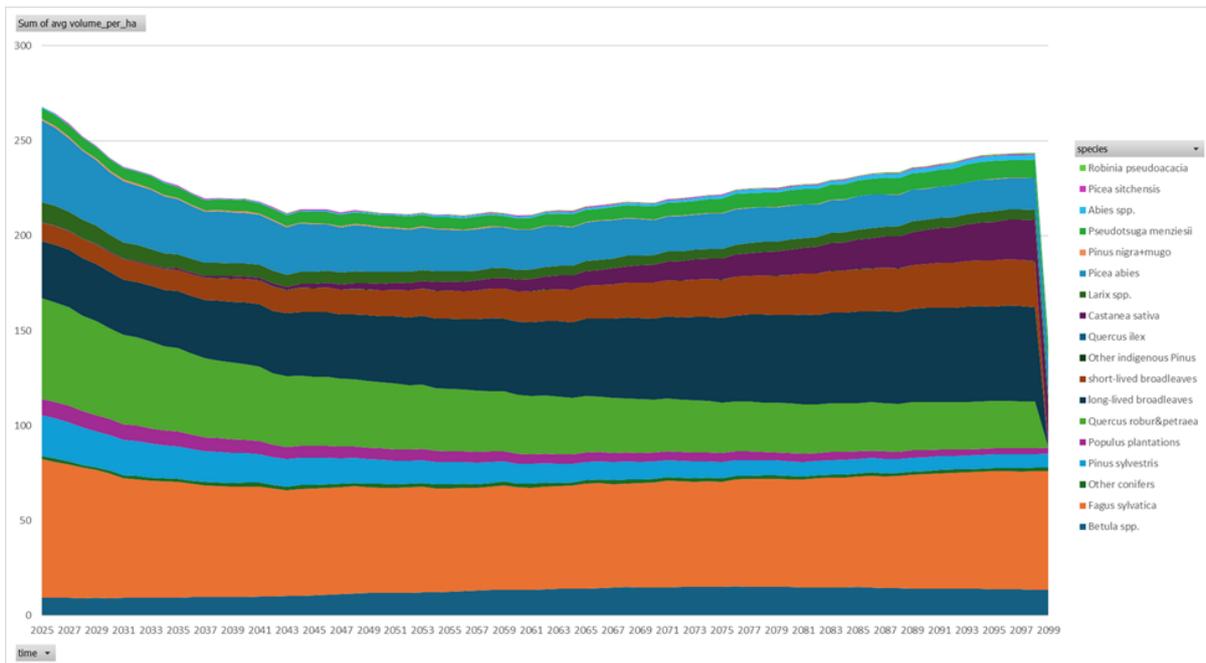


Fig. 17. Average standing volume per hectare ( $\text{m}^3/\text{ha}$ ) from 2025 to 2100 of different tree species.

Looking at the average number of stems per hectare by species (Fig. 18), the development differs from the trends in average volume per hectare by species (Fig. 17). *F. sylvatica* and *Quercus spp.* show a gradual increase in average stem numbers per hectare over time. Similarly, *Larix spp.*, *Abies spp.*, and *Pinus sylvestris* also experience an increase in average stem numbers per hectare over time. In contrast, *Picea abies* and *P. sitchensis* exhibit a decline in stem numbers per hectare over time. Short-lived and long-lived broadleaves have an increasing average stem number per hectare over time with long-lived broadleaves having the highest average stem density per hectare. Overall, tree density per hectare increases over time.

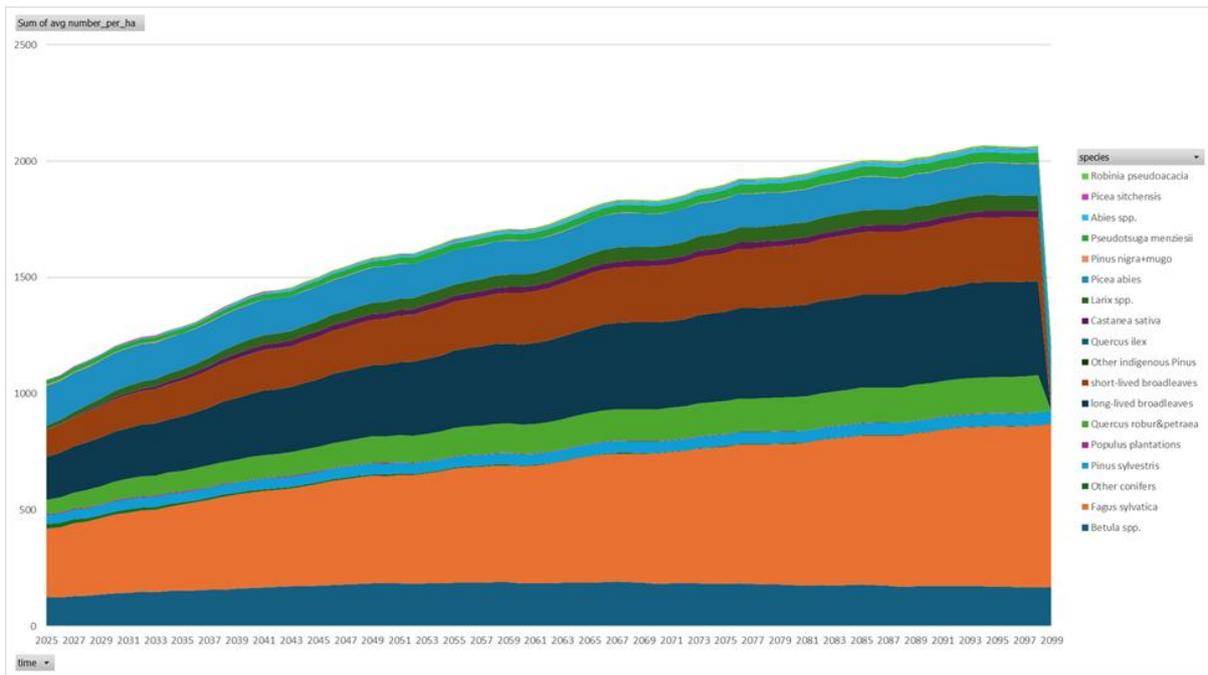


Fig. 18: Development of average stem number per hectare of different species over time.

As mentioned above, in restoration scenario 1 total harvest varies over the years but is generally declining over time for all species.

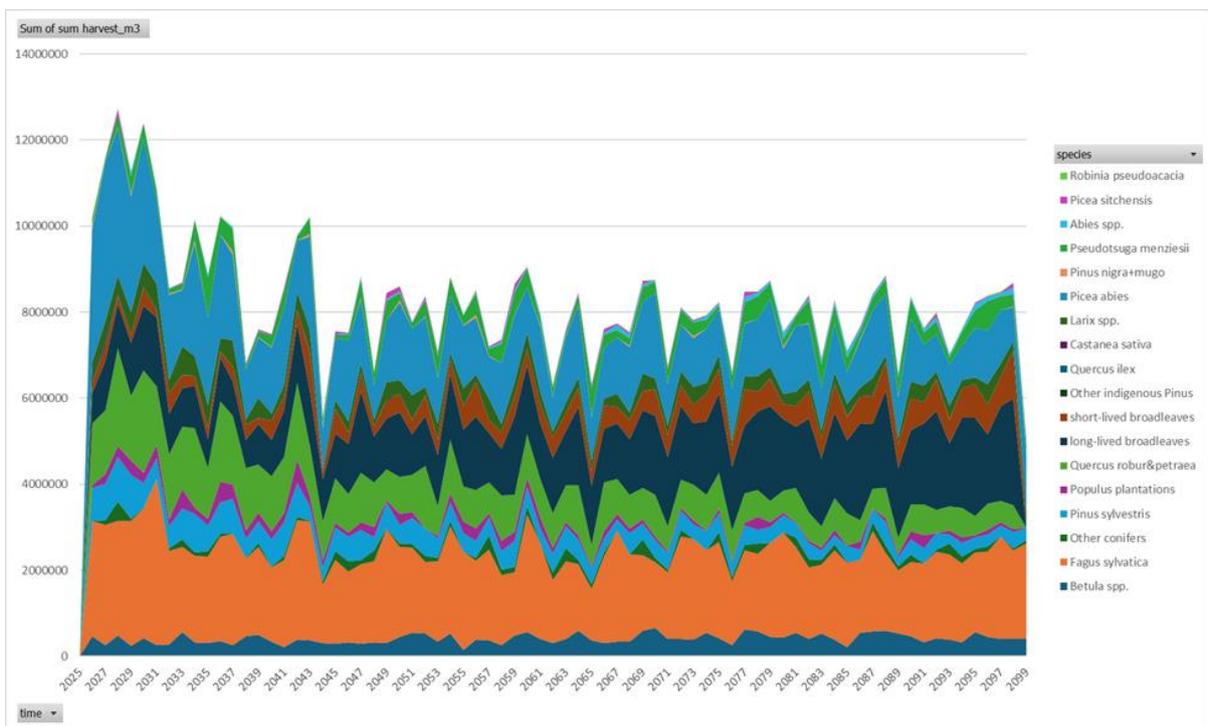


Fig. 19: Development of total harvested volume (m³) of different species over time.

### 3. Restoration scenario; wood

Like in restoration scenario 1, average volume per hectare and total volume are initially decreasing from an average volume per hectare of 265.77 m<sup>3</sup>/ha and 227.19 Mio. m<sup>3</sup> in total volume in 2026. Following the lowest average volume per hectare in 2043 at 227.37 m<sup>3</sup>/ha average volume per hectare is steadily increasing until 285.10 m<sup>3</sup>/ha in 2100. The same development holds true for total volume which dips to 194.36 Mio. m<sup>3</sup> and increases in consequent years to 243.71 Mio. m<sup>3</sup> in 2100.

Gross annual increment per hectare (m<sup>3</sup>/ha) and total increment (Mio. m<sup>3</sup>) are increasing over the years from 9.02 m<sup>3</sup>/ha and 7.71 Mio m<sup>3</sup> until reaching relatively stable levels after 2054 between 12 – 13 m<sup>3</sup>/ha and 10 – 11 Mio m<sup>3</sup>.

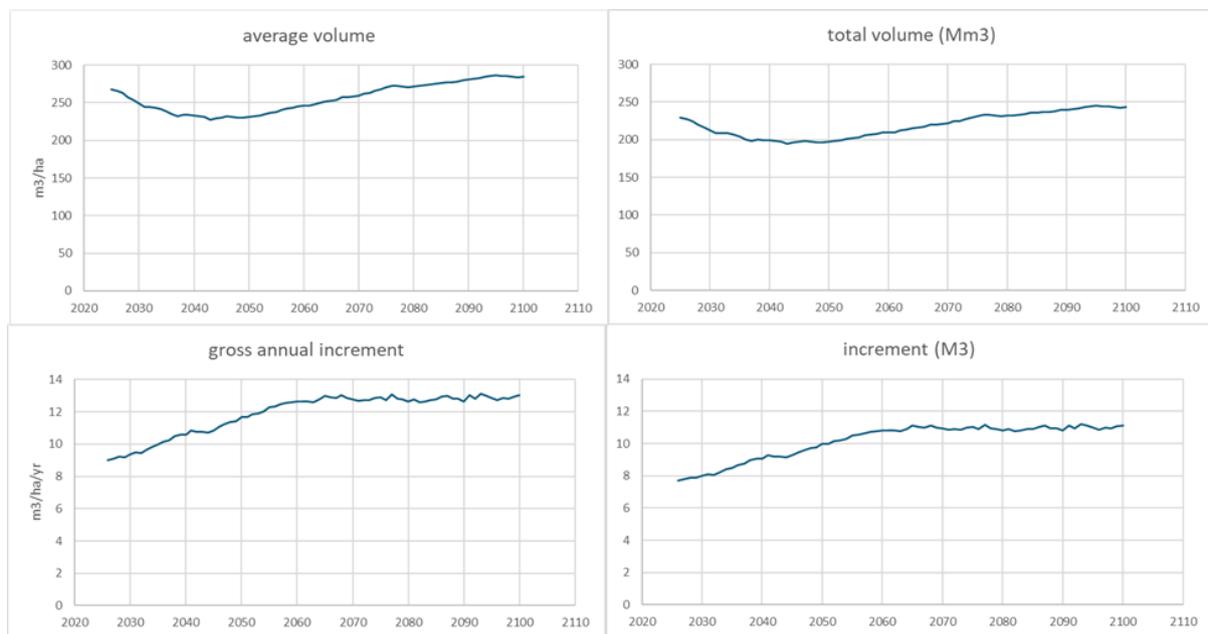


Fig. 20: Development of average total volume per hectare (m<sup>3</sup>/ha), total volume (Mio. m<sup>3</sup>), gross annual increment (m<sup>3</sup>/ha/yr) and total increment (Mio. m<sup>3</sup>) from 2026 to 2100.

Average harvest gradually decreases between 2026 to 2044 (Fig. 21). After the dip in 2044, average harvest is relatively stable between 8 – 11 m<sup>3</sup>/ha until the level increases slightly after a peak in 2079 to values between 9 – 12 m<sup>3</sup>/ha with less strong fluctuations in average harvested volume. The same dynamic can be observed for total harvest.

Average mortality decreases until 2032 from 0.72 m<sup>3</sup>/ha in 2026 to 0.61 m<sup>3</sup>/ha. Afterwards average mortality increases steadily peaking in 2096 at 1.30 m<sup>3</sup>/ha. The same development can be observed for total annual mortality.

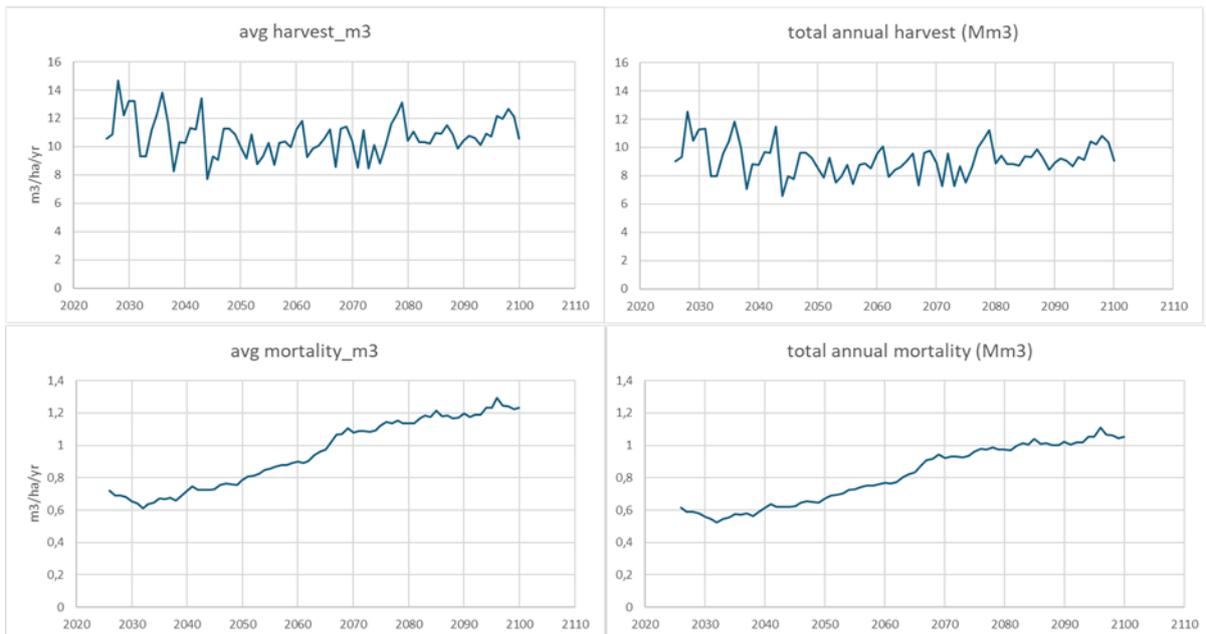


Fig. 21. Development of average harvested volume per hectare (m<sup>3</sup>/ha/yr), total annual harvest (Mio. m<sup>3</sup>), average mortality (m<sup>3</sup>/ha/yr) and annual total mortality (Mio. m<sup>3</sup>) from 2026 to 2100.

The wood balance (Fig. 22) illustrates the described development of gross annual increment alongside average harvest and mortality. It appears that while harvesting levels are stabilizing over the years average mortality is gradually increasing, as also outlined above. Gross annual increment increases initially after which it reaches a relatively stable level alongside stabilizing harvesting volumes.

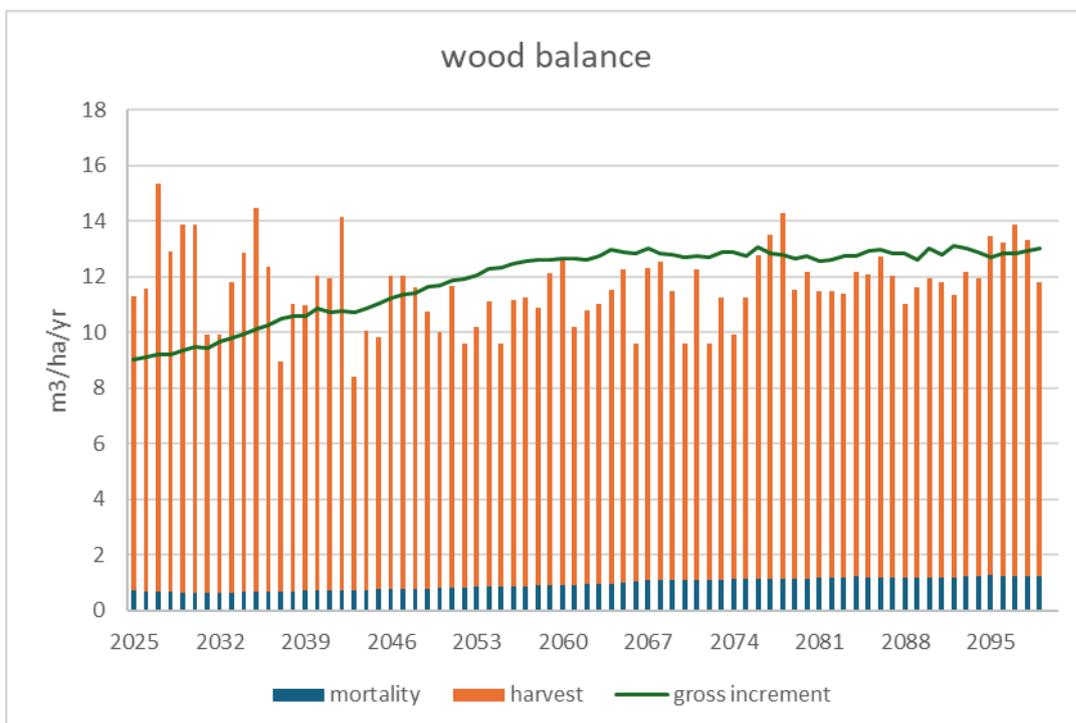


Fig. 22: Development of average harvested volume per hectare (m<sup>3</sup>/ha/yr), average mortality (m<sup>3</sup>/ha/yr) and gross annual increment (m<sup>3</sup>/ha/yr) in the second restoration scenario.

Figure 23 shows the changes in total standing stock (m<sup>3</sup>/ha) over time, grouped by diameter classes, for coniferous and broadleaved species. In 2026, broadleaves dominate the total volume across all diameter classes, with both conifers and broadleaves following a bell curve (normal distribution) in terms of volume across the dbh range. By 2035, the overall standing stock has decreased in all diameter classes.

In 2100, both coniferous and broadleaved species have an incline in standing stock, conifers stronger than broadleaves. This increase in standing stock occurs particularly in lower dbh classes. Broadleaves have an accumulation of volume particularly in dbh classes 10-20 cm and 20-30 cm while conifers are more evenly distributed over the different dbh classes with the majority in dbh class 20-30 cm. Furthermore, in 2100 conifers are more dominant than broadleaves in dbh classes 40-50 cm through to 60-70 cm. The standing stock of broadleaves in dbh class 90-100 cm is relatively stable over the years.

The standing stock of coniferous and broadleaved species initially declines in 2035 from 229.13 Mio. m<sup>3</sup> in 2026 to 204.17 Mio. m<sup>3</sup> in 2035. In 2100 the total standing stock is larger than in 2026 with 243.35 Mio. m<sup>3</sup>. While conifers surpass their standing volume from 2026 after the decrease in 2035, broadleaved species do not reach their initial level of volume in the standing stock.

Unlike standing stock, the total harvest increases from 2026 to 2035 and then decreases back to a similar level as in 2026. In 2026 and 2035, the harvested volume primarily comes from broadleaves in middle to higher dbh classes, while conifers are mainly harvested from lower to middle dbh classes (Fig. 24). In 2100 also broadleaved species are mainly harvested in lower dbh classes. For all years, the majority of the harvested volume comes from broadleaved species.

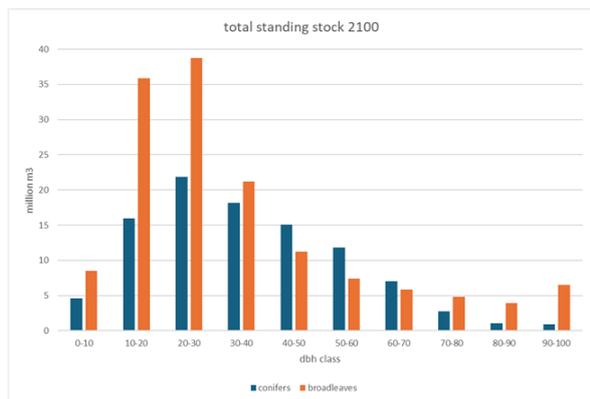
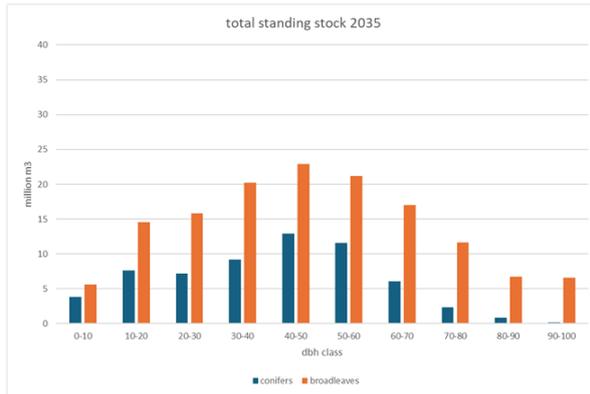
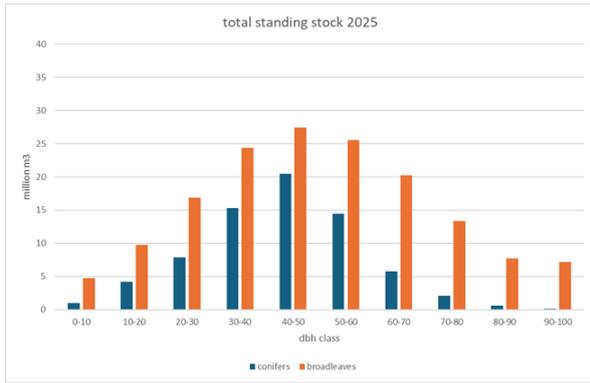


Fig. 23: Total standing stock (Mio. m³) in 2026, 2035, and 2100, categorized by diameter classes, comparing coniferous and broadleaved species.

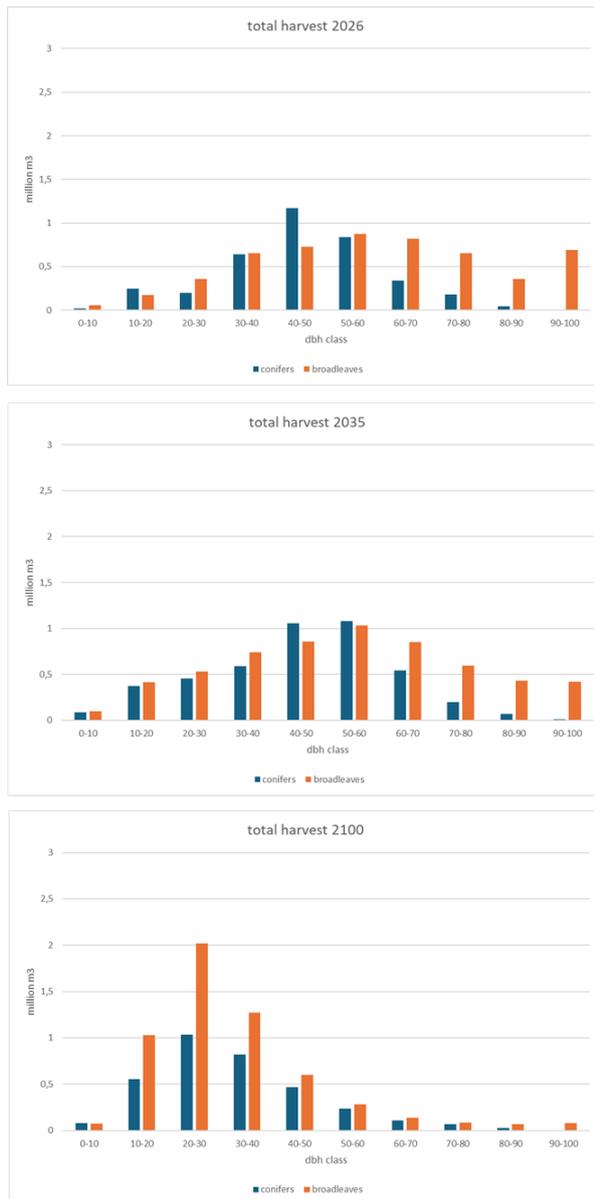


Fig. 24. Total harvest (Mio m<sup>3</sup>) in 2026, 2035, and 2100, categorized by diameter classes, comparing coniferous and broadleaved species.

The development of average volume per hectare by species reveals distinct trends (Fig. 25). *F. sylvatica*, *Pinus spp.*, *Quercus spp.*, *Larix spp.*, and *P. abies* exhibit a gradual decline in volume over time. In contrast, *Pseudotsuga menziesii*, *Abies spp.*, both long-lived and short-lived broadleaves, and *Betula spp.* show a steady increase in volume per hectare. Notably, this shift in species-specific volumes suggests a transition in the tree species that dominate the volume in the standing stock. As previously outlined, while the volume of some species decreases, the volume of others increases. This indicates that the overall average volume per hectare does not recover in its initial composition but rather reflects a change in species that have the biggest volume shares. While initially, particularly *F. sylvatica* and *Quercus spp.* comprised a large share of average volume per hectare *P. menziesii* and long- as well as short-lived broadleaved species gain volume leading to an increase in average volume per hectare over time. In contrast, Figure 26 indicates that the average stem number per hectare

increases for the majority of species also those with decreasing average volumes per hectare. A notable exemption of this is *P. abies* which has a decreasing average volume and decreasing average stem numbers.

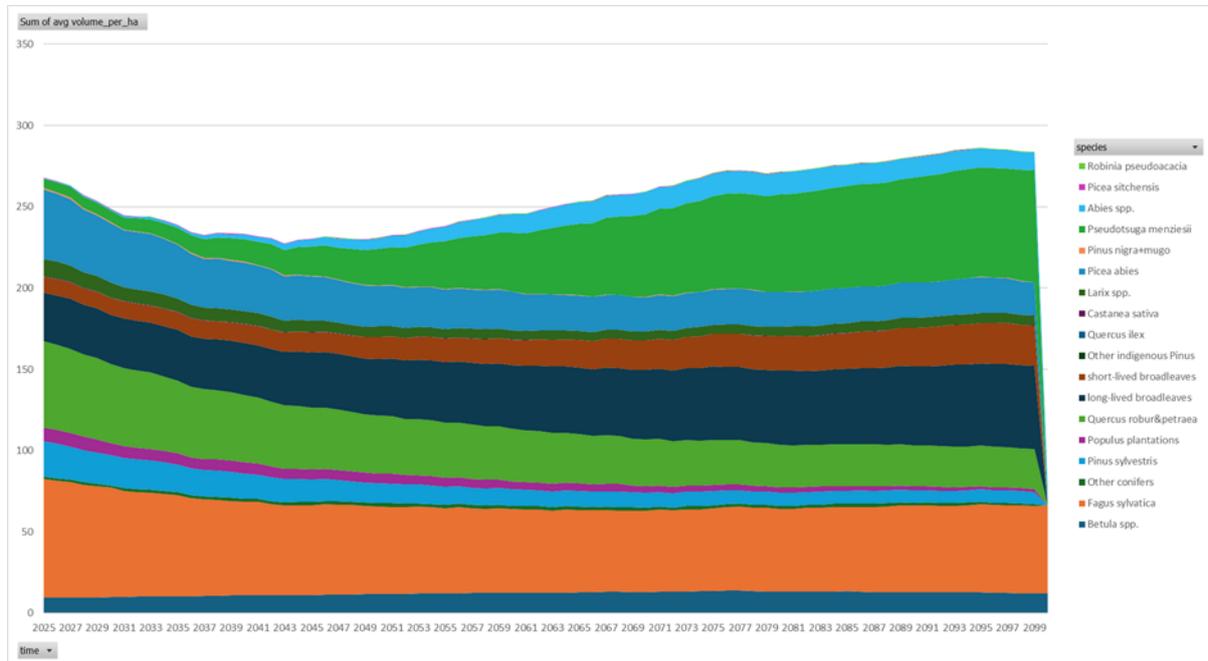


Fig. 25. Average standing volume per hectare (m<sup>3</sup>/ha) from 2025 to 2100 of different tree species.

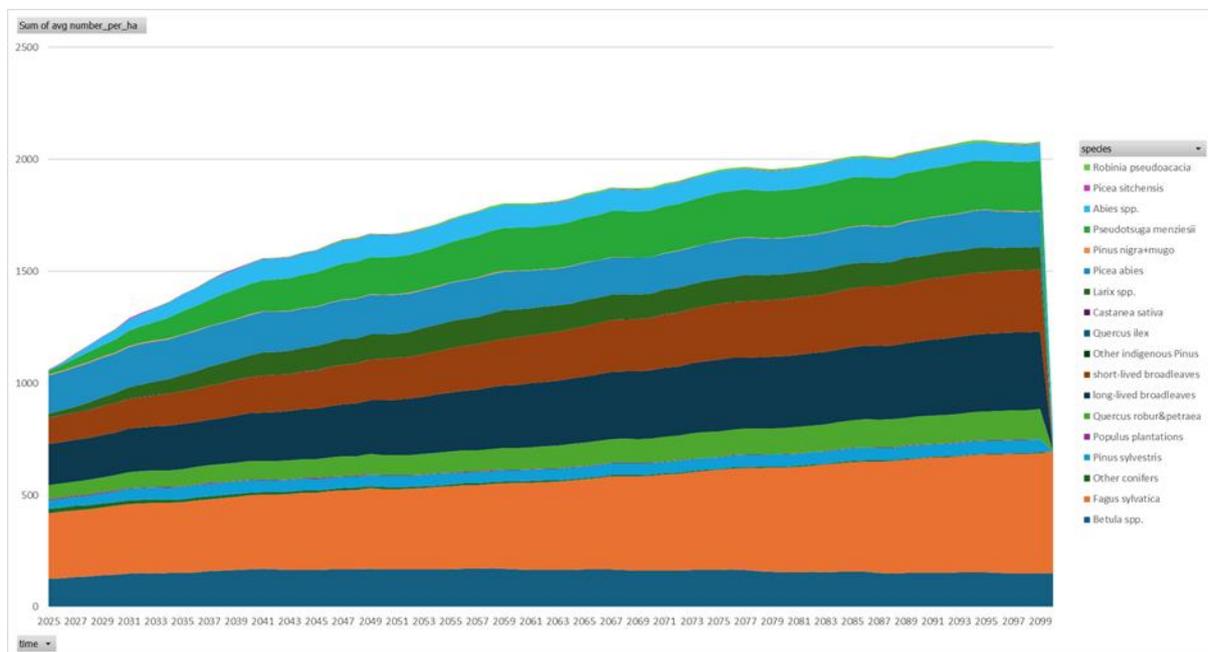


Fig. 26: Development of average stem number per hectare of different species over time.

Despite a shift in dominant tree species, the majority of the total harvest still comes from *F. sylvatica* and *P. abies*, although their volumes decline over time (Fig. 27). Meanwhile, *P.*

*menziesii* and *Abies spp.* account for an increasingly larger share of the harvested volume over time.

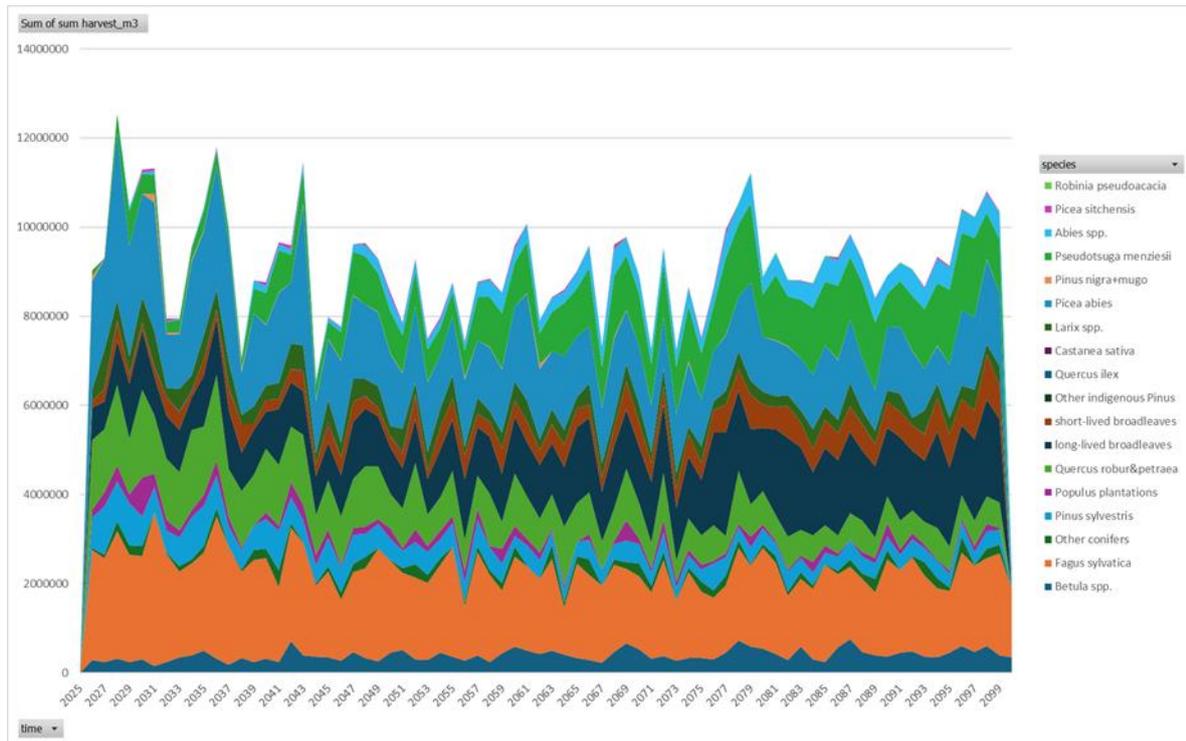


Fig. 27: Development of total harvested volume (m<sup>3</sup>) of different species over time.

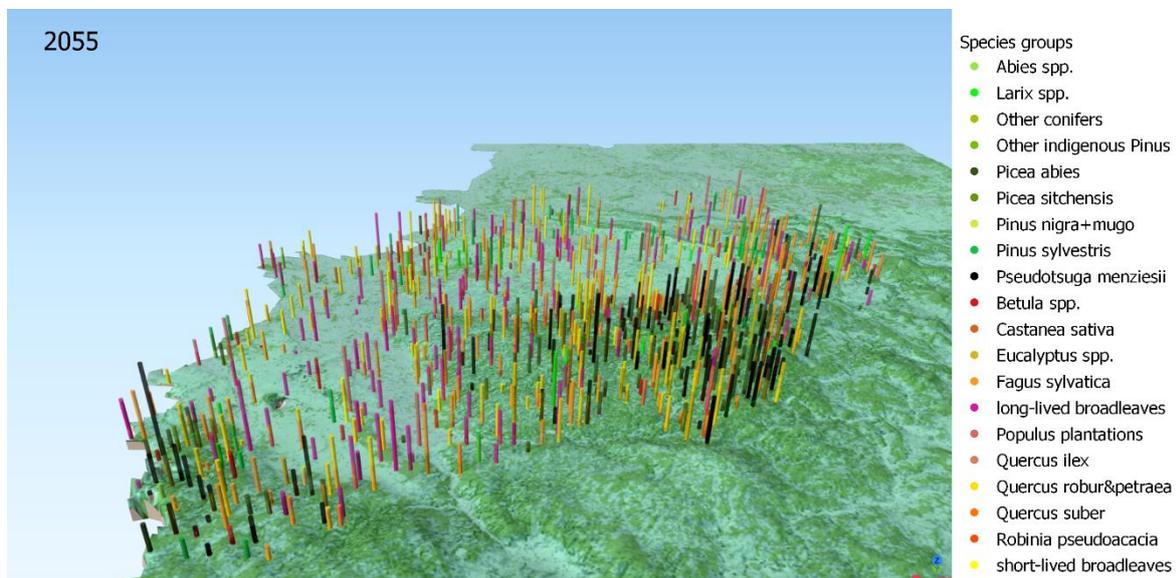


Figure. 28. 3D view on NRW in 2055 under restoration with attention to wood production scenario. In Sauerland, the Douglas fir stands out more now

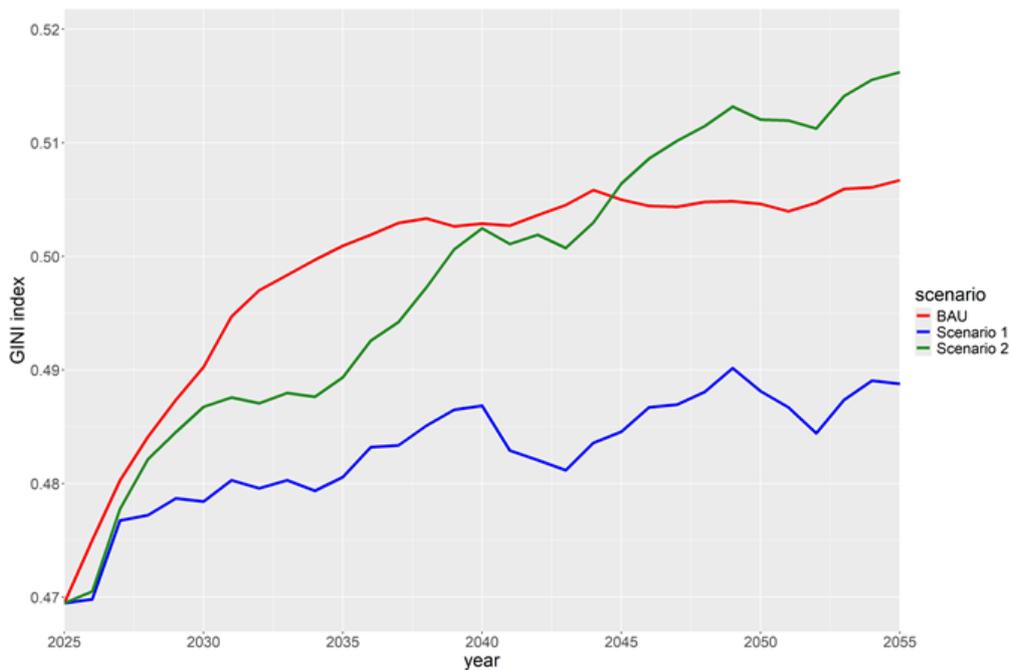


Figure. 29. Comparison of structural development under three scenarios in NRW forest. The strong conversion scenario (1) leads to a more moderate Gini index. The moderate conversion and some planting of production oriented species leads to a higher Gini after 2045.

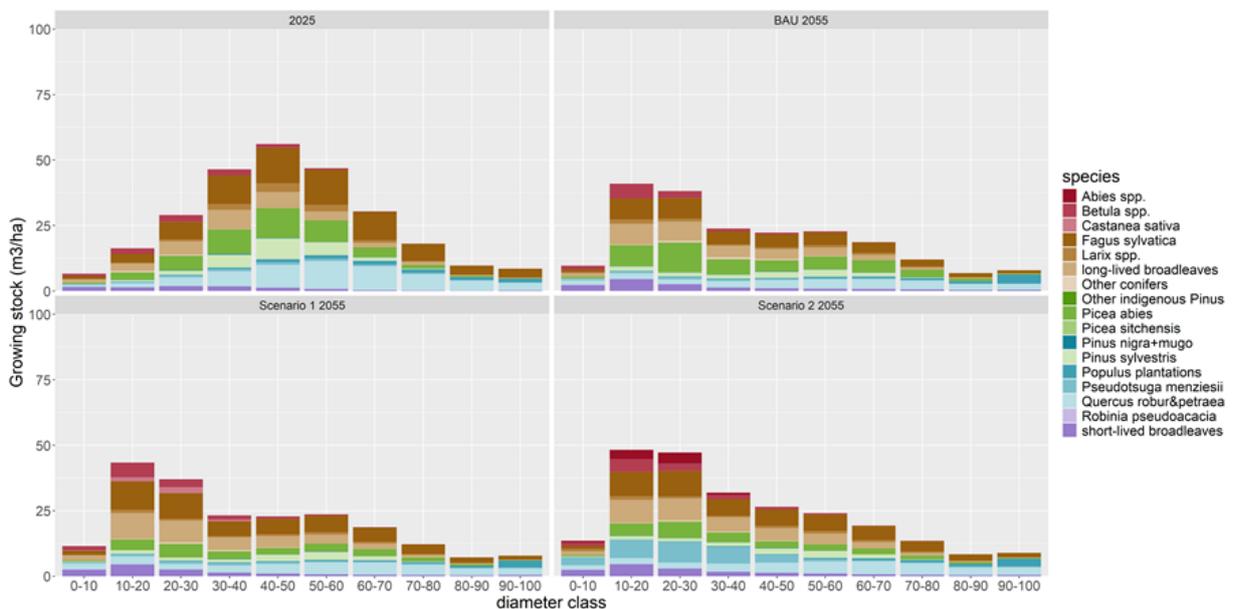


Figure 30. Diameter distributions by species class and volume for the BAU and the two alternative scenarios. The restoration scenarios lead to a drastically changed composition already in 2055.

# KEY FINDINGS

## Key finding #1

In the baseline scenario, the forest experiences a gradual decline in average volume per hectare, stabilizing in the longer term albeit at a lower volume level. The loss of volume is accompanied by a steadily increasing increment, indicating a substantial regrowth of trees. Despite the intensity of the calamity, forest composition maintains a fair share of *P. abies* and long-lived broadleaved species, with a younger forest structure characterized by trees in smaller dbh classes. Beech, in particular, is pushed back to smaller diameters.



The stabilization of volume around the year 2060 is related to the reduced harvest of *P. abies*, as the younger spruce are less likely to be harvested since the regenerated *P. abies* remain in smaller dbh classes for several years. It is uncertain whether the new volume level could be maintained if another bark beetle calamity occurs once the *P. abies* regeneration reaches harvestable sizes.

Key findings from baseline scenario:

- **A Business-as-usual approach is not sustainable in a prolonged calamity scenario:** Assuming that the bark beetle calamity continues with a high intensity, it appears that such an approach leads to a sustained reduction in total volume and standing stock with most of the wood volume found in smaller dbh classes. In a sustainably managed forest, the amount of wood harvested should equate the amount that can permanently regenerate.
- **Shift in species composition and age structure:** The volume of the standing stock maintains a fair share of *P. abies* as well as long-lived broadleaved species (other than *F. sylvatica* and *Quercus spp.*), while the age structure of the standing stock is dominated by trees in lower dbh classes. This constitutes a shift from a formerly more evenly distributed age structure, which was dominated by *Quercus spp.* and *F. sylvatica*. The slower growth of most broadleaved species, compared to coniferous species, will likely mean that it takes a longer time for **them** to develop a more even spread of volume across dbh classes again.



- **Harvest peaks at 12.8 Mio m<sup>3</sup>.** Harvested volumes decline, stabilizing over time at an overall lower level than at the start of the projections. Harvested volumes tend to be higher than in scenario 2 but lower than in scenario 3.
- **Impact on carbon:** The reduced standing stock over time (from 229 million m<sup>3</sup> in 2025 to 178 million m<sup>3</sup> in 2050) leads to a reduction in the forest's carbon stock, equivalent to the loss of approximately 2.4 million tonnes CO<sub>2</sub>/y.
- While the age class distribution indicates a high potential for future carbon sequestration, it is unlikely to offset the lost carbon stock for many years. Furthermore, the development of harvested volumes suggests a reduced capacity for carbon storage in the product stock.

## Key finding #2

In Restoration Scenario 1, there is an initial reduction in average volume per hectare, particularly for *P. Abies*, *F. sylvatica* and *Quercus spp.*, which do not recover their previous volume levels over the projected years. However, over time, oak and beech species show a notable increase in density.



Following the initial decline in volume, both the average volume per hectare and total volume recover, with much of this volume being comprised of short-lived and long-lived broadleaves species. These species exhibit a significant increase in both volume and density. In contrast, *Picea spp.* experience a decrease in density, despite a growing volume. Overall, the total standing stock shifts toward smaller dbh classes along with a consistent reduction in harvested volumes.

Key findings from restoration scenario 1:

- **Shift in forest composition and structure:** The reduction in volumes of *P. Abies*, *F. sylvatica* and *Quercus spp.* is counter-balanced over time by increasing volumes of other broadleaved species. Additionally, the forest is becoming younger, with an increasing number of smaller trees replacing larger ones. The overall reduction in growing stock levels off around 2050 but it recovers only partially.
- **Relatively slow recovery of broadleaved species:** In particular, *F. sylvatica* and *Quercus spp.* grow slowly in volume, meaning the recovery of harvested volumes and restoration of calamity areas with these species is gradual and requires time for full establishment. Harvesting patterns should be adapted consequently to maintain a balanced standing stock.
- **Harvest peaks at 12 million m<sup>3</sup>/y during intense restoration phase,** then declines to 8 million m<sup>3</sup>/y.



- **Impact on carbon storage:** The forest loses carbon until about 2050. The reduction in harvested volumes suggests that less carbon will be stored in the product stock.
- The 87 000 ha of restoration area may cost around 1 billion Euro based on the average ha costs of €11 500 described in the workplan. If the restoration is carried out until 2050, the costs will be €40 million per year.

### Key finding #3

Restoration scenario 2 reflects a similar dynamic to Restoration scenario 1, with the exception that the total volume is recovering faster and reaches higher values compared to the other alternative scenarios. This is due to more intense planting of alternative coniferous species, which are predominately supported in this scenario. These species (such as Douglas fir) have higher growth rates than most broadleaved species. The stabilization of the gross annual increment suggests that the standing stock possibly reaches maturity faster than in scenario 1. Additionally, unlike restoration scenario 1, the amount of harvested volume can be maintained with an increasing share of volume harvested from coniferous trees while the share of volume from broadleaved trees is maintained at similar volumes over the years. Again, this is likely due to the faster growth and therefore shorter rotations of coniferous tree species. In contrast to the baseline scenario, the increase in harvested volumes does not lead to a reduction in total volume, indicating that the harvest matches the rate of regrowth.



Key findings from restoration scenario 3:

- **Faster growth rate of coniferous species:** Coniferous trees grow faster than broadleaved species, leading to a faster recovery of volume and total standing stock, along with a gradual increase in harvested volume. Growing stock is back at the level of 2025 in 2100. Gross annual increment is higher with more than 12 m<sup>3</sup>/ha.y.
- **Shift in species composition and age structure of the standing stock:** There is an increasing share of volume from coniferous species (especially Douglas) and a large share of broadleaved species in lower dbh classes due to their comparatively slower growth rates.
- **Harvest levels: Harvest does not peak so much as in scenario 1 and remains higher overall, ranging between 9-12 million m<sup>3</sup>/y.**
- **Impact on carbon stock:** The development of harvested volumes suggests that this scenario has a higher potential for carbon storage in the product stock than both alternative scenarios.

Overall key findings:



- On an area of 87000 ha (out of 854000), bark beetle calamity management was employed, either through a more mixed broadleaved approach or with a wood production orientation
- In the baseline scenario, the NRW forest may lose around 50-70 million tonnes of CO<sub>2</sub> between now and 2050 due to the calamity
- Forest composition is changing in all scenarios, with only Restoration scenario two recovering to former levels in terms of total volume and standing stock.
- There is a reduction of larger dbh classes, particularly of broadleaved trees (due to relatively high harvest pressure) across all scenarios. This may have implications for biodiversity. However, the relative stability of broadleaved species in dbh class 90-100 suggests that the restoration scenarios, by comparison, provide the best conditions for supporting biodiversity.
- The scenarios differ in their potential for climate change mitigation with Restoration scenario 2 having the highest potential. However, in all scenarios, the NRW forests go through long phases of carbon losses.
- Restoring calamity sites with broadleaved species takes time and will be associated with reduced harvesting volumes (1-2 million m<sup>3</sup>/y less) at least for decades. More broadleaved wood will become available, and less coniferous
- The 87 000 ha of restoration area may cost (based on the average costs of €11 500 per ha described in the workplan) around 1 billion Euro, or about €40 million per year if carried out until 2050.



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