Effects of the 2018 – 2020 disturbances on the projected Carbon balance of German forests and LULUCF climate protection targets

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Summary

Drought, heat and bark-beetle infestations in the years 2018 till 2022 have had severe impacts on German forests. With the results of the National Forest Inventory 2022 being available since late 2023, new projections of possible future development of carbon stocks in forests and the Harvested Wood Products pool have been estimated. Such projections are required by the German Federal Climate Protection Law (CPL) on an annual basis, for policy evaluation and information. Three scenarios have been constructed and implemented in the Matrix-Model, using data from the National Forest Inventories 2012 and 2022, and the Carbon Inventory 2017:

- Changes and developments as in the period 2013 – 2017 (“optimal conditions”),
- as in the period 2018 – 2022 (including disturbances, “pessimistic”), and
- as in the period 2013 – 2022 (”medium”).

The results show that, under “optimal” conditions, -40 to -30 Mt CO2 may be removed from the atmosphere and stored in “living biomass” annually, the “medium” scenario will result in appr. -10 Mt CO2 a-1, and the “pessimistic” scenario in net emissions of 20 – 10 Mt CO2. In the two “extreme” scenarios, sequestration will drop by appr. 10 Mt CO2 per year until 2050. As a result, the targets set by the CPL will be missed significantly even under “optimal” conditions and by up to 60 Mt CO2 per year in 2030 in the “medium” scenario. Measures already implemented in LULUCF will alleviate this by just 3.7 Mt CO2-eq. per year.

Keywords: LULUCF, carbon dioxide emissions and removals, disturbance, forest management, projection report

Zusammenfassung

Die deutschen Wälder wurden 2018 bis 2022 durch Dürren, Hitze und Borkenkäferkalamitäten deutlich geschädigt. Seit Ende 2023 sind die Ergebnisse der Bundeswaldinventur 2022 verfügbar, die neue Projektion zukünftiger Entwicklungen der Kohlenstoffvorräte in Wald und Holzprodukten ermöglichten. Diese Projektionen werden zur Information und Evaluation von Politiken vom Bundes-Klimaschutzgesetz (KSG) jährlich verlangt. Unter Nutzung des Matrix-Models wurden drei Szenarien, die auf den Daten der Bundeswaldinventuren 2012 und 2022 sowie der Kohlenstoffinventur 2017 beruhen, erstellt:

- Veränderungen wie in der Periode 2013 – 2017 („optimale“ Bedingungen),
- Veränderungen wie in der Periode 2018 – 2022 (mit Störungen, „pessimistisch“) und
- Veränderungen und Entwicklungen wie in der Periode 2013 – 2022 („mittlere“ Veränderungen).

Unter „optimalen“ Bedingungen können 30 bis 40 Mt CO2-Äq. pro Jahr aus der Atmosphäre in die lebende Biomasse aufgenommen werden. Das „mittlere“ Szenario resultiert in ca. -10 Mt CO2-Äq. pro Jahr und das „pessimistische“ in Emissionen von 10 – 20 Mt jährlich. In den beiden „extremen“ Szenarien sinkt die Einbindung bis 2050 um ca. 10 Mt CO2 pro Jahr. Die Ergebnisse zeigen, dass selbst bei „optimalen“ Bedingungen die Ziele des KSG deutlich verfehlt werden, beim „mittleren“ Szenario z.B. um ca. 60 Mt CO2-Äq. in 2030. Bereits implementierte Maßnahmen im Landnutzungssektor schwächen dies nur um ca. 3,7 Mt CO2-Äq. pro Jahr ab.

Keywords: LULUCF, Kohlenstoffdioxidemissionen und -aufnahme, Störungen, Waldbewirtschaftung, Projektionsbericht

Inhalt

1 Introduction

Following windthrow in late 2017, drought in 2018 and subsequent years, increased by bark beetle infestations, German forests lost considerable stocked area, and corresponding timber volume (BMEL 2024). Especially Norway spruce stands in a region from mid-western Germany (Northrhine-Westphalia, Rhineland-Palatinate) through Hesse, northern Bavaria, Saxony-Anhalt, and Thuringia to Saxony in the East were affected and lost 220 Mm^3 of timber (18.2% of the stock in 2017). In addition, Scots pine stands in various regions also suffered from bark beetles, fungi, or drought and heat. Even European beech stands in the very core area of its natural distribution died off due to high temperatures and / or water shortages. These effects affected appr. 2 Mha of forest land, where single trees, groups of trees, or complete stands were killed, leading to a cleared area of 5% of the total forest area (BMEL 2024). These disturbances had a significant impact on the Greenhouse Gas (GHG) Balance for the period 2018 – 2022 with significant changes compared to the Carbon Inventory 2017 (CI 2017).

The official results of the German National Forest Inventory (NFI) and the Carbon Inventory (CI) indicate that growing stocks in the forest have declined since 2017 by 41.5 Mt CO_2, turning the pool “living biomass” in forest from a GHG sink into a source (data available at bwi.info). In addition, the current annual increment of -16% compared to findings from the 3rd NFI in 2012. This apparent loss in carbon sequestration capability raised concerns about the future course of forest development and the associated net greenhouse gas emissions, especially with regard to climate protection goals, measures, and policies. For example, the EU LULUCF-Regulation (European_Parliament 2018) and the German Federal Climate Protection Law (Bundesregierung 2019) both set sectoral targets for climate mitigation in the sector Land use, Land-use change, and Forestry (LULUCF) and require annual reports containing, among other information, projections of future net emissions in this sector. The projections shall be accompanied by the evaluation of agreed and planned climate protection measures. For this task, the influences of these measures have to be projected individually, so that their impact can be determined. The results hereof are presented in the Projection Reports (e.g., Harthan et al. 2024). Here, we present the first basic projections (without any measures) considering the findings of the National Forest Inventory 2022 (BMEL 2024), especially the changes in forest structure and composition due to the disturbances since the CI 2017. The main questions are: How does the changed structure (age classes, tree species composition) influence

1) annual increment (as a measure for, e.g., the maximum sink potential of the forest),
2) annual harvest (and, subsequently, the Harvested Wood Products pool, HWP), and
3) net emissions and removals of GHG

related to the baseline currently included in the Projection Report. To reflect different growth conditions and disturbance levels, we analyzed three different scenarios. First, we assumed forest development as in the rather favorable years between the NFI 2012 and the CI 2017 (2013 – 2017), second, as in the calamity years 2018 – 2022 (CI 2017 to NFI 2022), and third, as in the entire period between the two NFIs (2013 – 2022).

2 Applied models and scenario assumptions

For calculating the scenarios and the associated development of biogenic CO_2 emissions and removals arising from the forest-based sector, we used the Matrix Model for the living biomass carbon pool development and WoodCarbonMonitor for the contribution of Harvested Wood Products (HWP) to the sectors’ CO2 emissions and removals. Both models were also employed to model the Forest Reference Level (FRL) according to Reg. EU 2018/841 (European_Parliament 2018) and the projections of future GHG net emissions according to Reg. EU 2018/1999 (European_Commission 2019) and the Federal Climate Protection Law (Bundes-Klimaschutzgesetz, KSG (Bundesregierung 2019)), and are shortly described below.

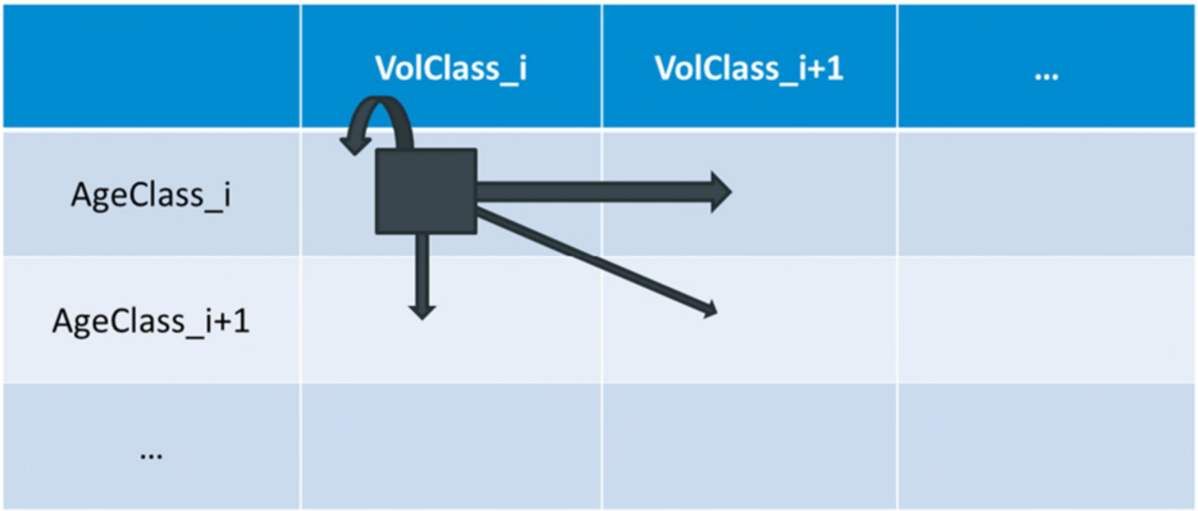
We did not model soil organic carbon or dead wood stocks separately for each scenario. For soil carbon, there is a projection using YASSO 15 (Viskari et al. 2020), based on data from the National Forest Soil Inventory and a specific climate scenario (see (Harthan et al. 2024)) available. At the moment, it was not possible to determine all input factors needed by YASSO distinguished by the three living biomass scenarios applied here, so soil carbon could not be modelled. However, the differences in total carbon are expected to be dominated by differences in the living biomass pools, so a differentiated representation of the soil carbon pool would not alter the general findings. The development of the dead wood pool was also not differentiated, as it is modelled based on NFI data, too, and differences between scenarios were assumed to be very small when compared to living biomass.

2.1 Matrix model to estimate GHG emissions and removals arising from forests

The structure and functioning of the model have previously been described in Rock et al. (2019) and Rock et al. (2021). It is based on data from two subsequent forest inventories

The same forest plots were measured in both inventories and were allocated in age classes and volume classes (for the FRL) in both years (for the FRL 2002 and 2008, resp.). This forms an age class / volume class cross-table for each of these years. In the European Forestry Dynamics Model (EFDM) (Packalen et al. 2014, Vauhkonen et al. 2019), which was used as a blueprint to develop the German model, this is called a state-space. The development of the carbon content in each forest stratum (i.e. tree age, volume class) in the reference period is used as a proxy for the management practices. These vectors (see Figure 1) are then applied to the state of the forest ahead of the commitment period (in case of the FRL), thereby taking into account the shifting age-class structure of the forest. In the construction of the FRL, the development of forest areas in the strata in the base period has been extrapolated until 2022 in order to take into account the age-related forest characteristics. From 2008 onwards, the same area transitions are repeated in five-year time steps to model future inventory intervals. The model applies the vectors at each step to the "new" distribution achieved by the previous modelling step. The areas in each cell of the state-space are split according to the transition vectors and the area in each „target cell“ is aggregated to derive the distribution of area at the subsequent simulated inventory date. The resulting distribution of forest area in the state-space thus describes the state of the forest after each time step. The resulting area distributions for the time steps 2012 (for transparency reasons only) is shown in Table 2. The 2017 matrix (as basis for 2018-2022) is shown in Table I-5 of Annex 1 of the NFAP and as same format (digits) as other tables here in Table 3, the one for 2022 (as basis for 2023-2027) is given in the following Table 2: Area [kha] distribution of age and volume classes at the end of step 2 (2012). The standing timber volume and carbon mass per hectare is estimated for each cell at both points in time. The difference between the two inventories represents the net change (net emissions) of the respective period and can, for C mass, be given as emission factor [tCO_2 ha^{-1} a^{-1}] for this specific cell. This emission factor times the area of the cell at the start of the simulation step (5 years interval) gives the overall emissions from this cell. For increment, the increment of the individual trees found in the plots allocated to a specific cell is taken from the NFI and scaled up to all trees in this cell. Harvest / wood removals are estimated accordingly. The model assumes that the transition vectors and probabilities remain constant over time, i.e. that a hectare of forest allocated to cell X will have the same probability to “move” to cell Y in 2030 than in 2050. This also implies that management will remain constant over time, as it has been in the reference periods.

Figure 1: Visualisation of transition vectors in the age class – volume class matrix



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The age class / volume class matrix used for the FRL is not suitable for projections with a focus on management and climate protection measures, as these are usually connected to tree species and (stand) age. Therefore, for the assessments included in the projection reports, the model was set up with a tree species / age class matrix. For the tree species, the plots were grouped by the main tree species inventoried at the sample plots in nine species groups (oak, beech, other broadleaved trees with high life expectancy (OBH), other broadleaved trees with a short life expectancy (OBL) , spruce, fir, douglas fir, pine, larch). For the estimation of increment and losses (harvest, mortality), all trees captured by the inventory in a given plot were used, irrespective of species. The estimated volumes and masses were subsumed under the main tree species, too. The nine age classes span 20 years each, with the exception of the last class, which covers all trees older than 160 years. The transitions between age classes (figure 2, 4) and tree species classes (figure 3, 5) in the period 2013 – 2022, and the shifts from beech stands older than 140 years (figure 6) is shown here as example. It should be kept in mind that shifts in tree species affiliation of plots can be caused by changes in the percentage of basal area of tree species in mixed stands, and that shifts in age classes can result from e.g. shifts in basal area changes of trees of different age at the same location, if this leads to a change in the respective dominant affiliation. For example, the loss of (some) 180 years old beech trees can shift a plot to the age class of 141 – 160, if the remaining trees are 130 years old (figure 6). The loss of 125 years old spruce at a site that has been underplanted with European beech 25 years ago can move this plot from the age class of 121 – 140 to the class of 21 – 40 years, and from the tree species group *spruce* to *beech.* The German NFI is a plot-based inventory and uses trees with a minimum size of 7cm dbh (diameter at breast height) for attribution of plots to tree species groups. Plots that have no trees that exceed these thresholds are included in the tree species group “not specified”.

Figure 2: Transition of area from the age class distribution in 2017 to the state 2022.

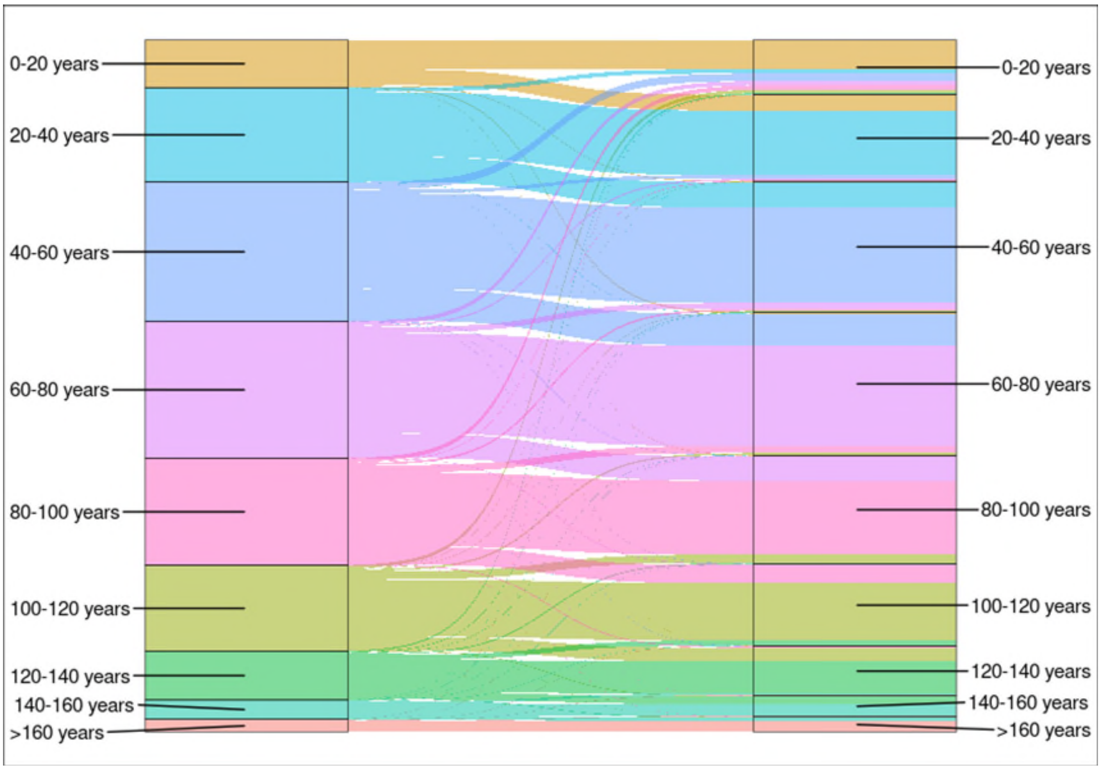

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Figure 3: Transition of area from the tree species group classes in 2017 to the state 2022.

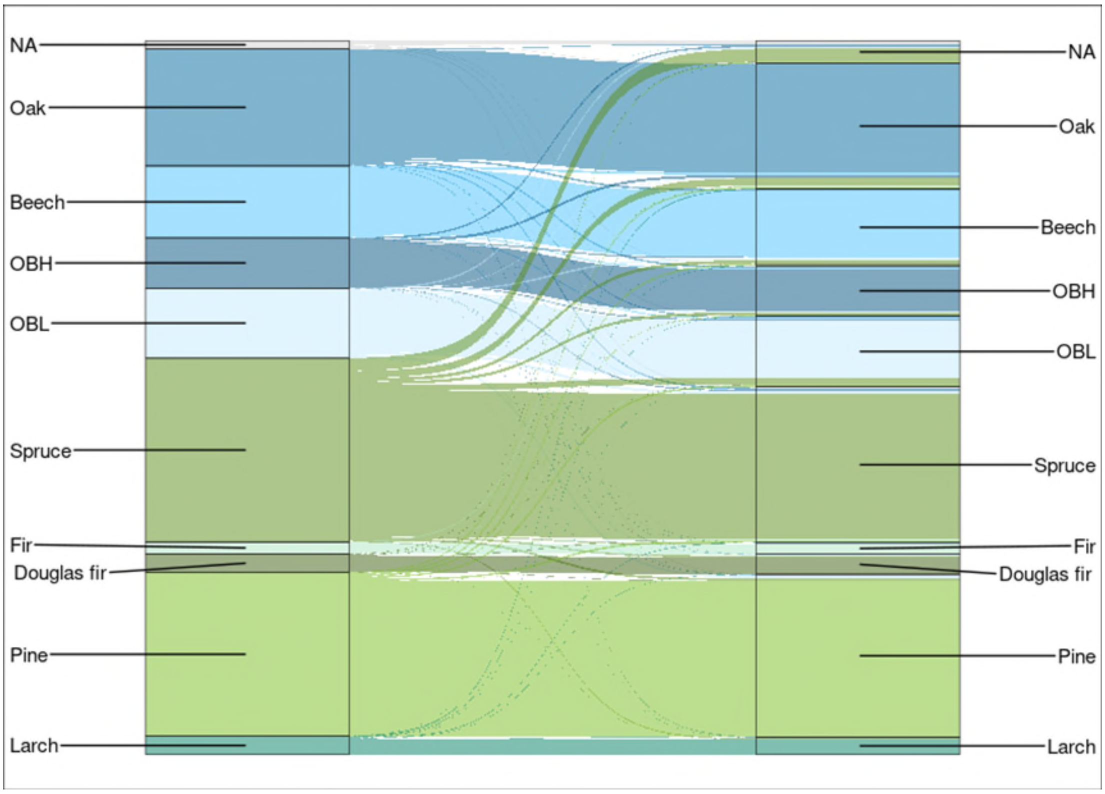

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Figure 4: Transition of area from the age classes in 2017 to other age classes in 2022

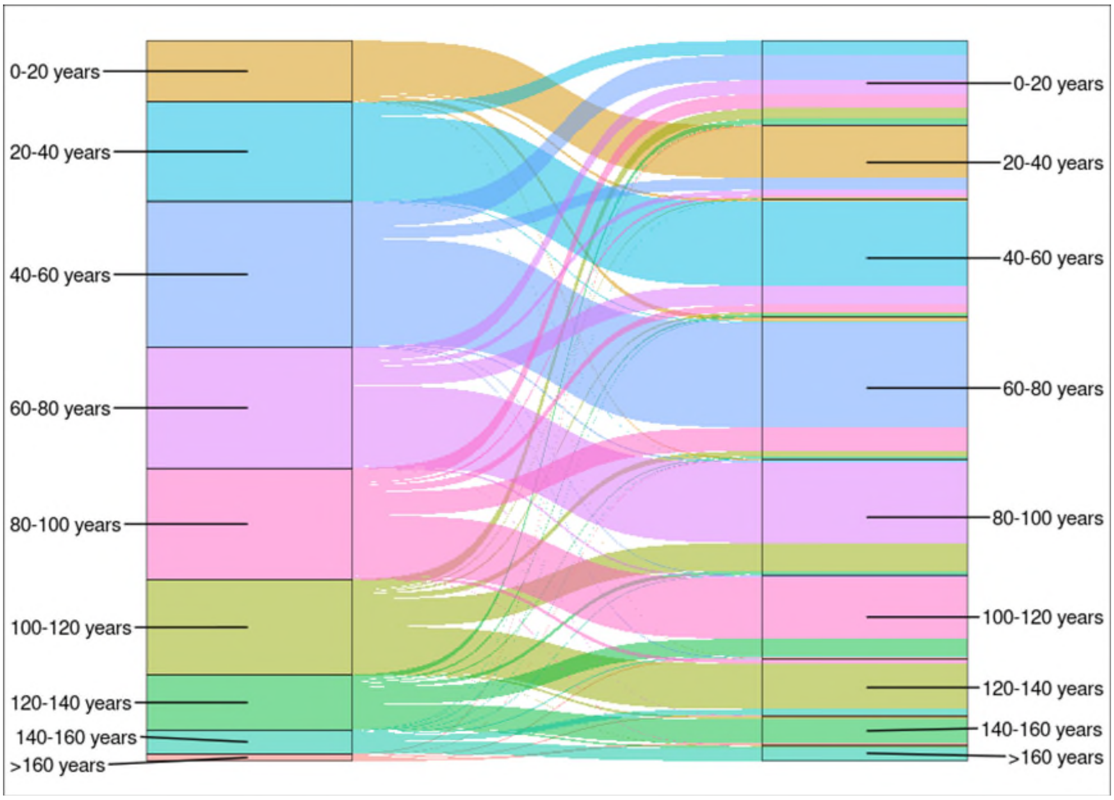

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Figure 5: Transition of area from the tree species group classes in 2017 to other tree species groups in 2022.

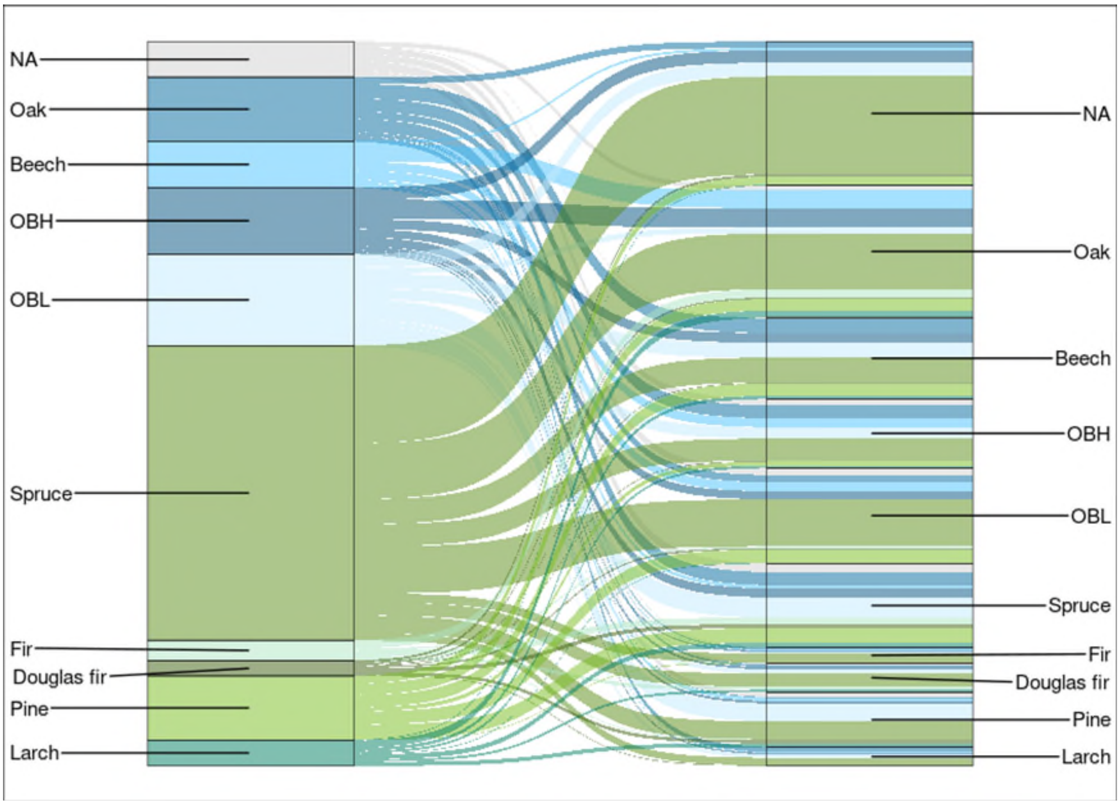

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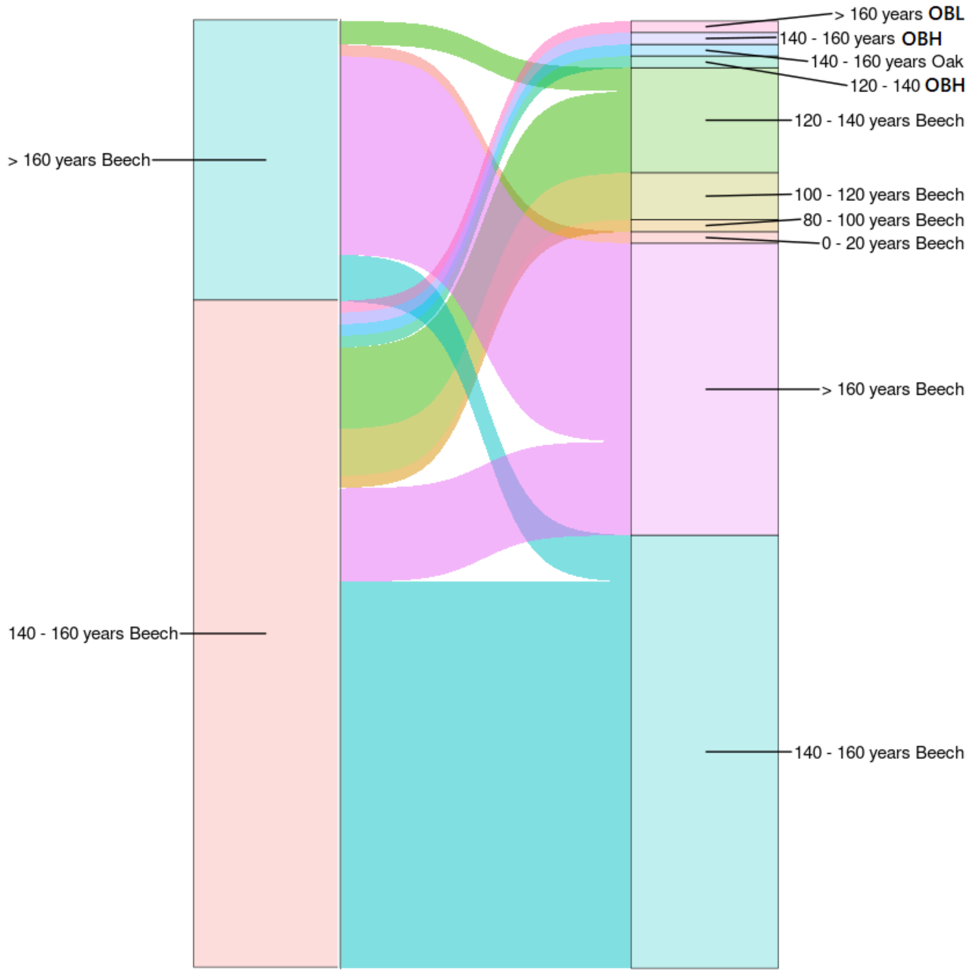
Figure 6: Shift of area from the matrix cells "Beech, age 141 – 160 years" and "Beech, older than 160 years" in 2017 to 2022



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Three scenarios were used to explore possible future development of the forest. Data from the new NFI 2022 and the two most recent inventories, the NFI 2012 and the CI 2017, were used to estimate the transition vectors

1. as in the rather favorable years between the NFI 2012 and the CI 2017 (2013 – 2017) as an "optimistic" scenario,
2. as in the years 2018 – 2022 (CI 2017 to NFI 2022), where three out of five years were exceptionally dry in some parts of Germany, leading to a significant loss of spruce stands through drought and bar-beetles, as a "pessimistic" scenario, and
3. over the entire NFI period (2013 – 2022), as "medium" scenario.

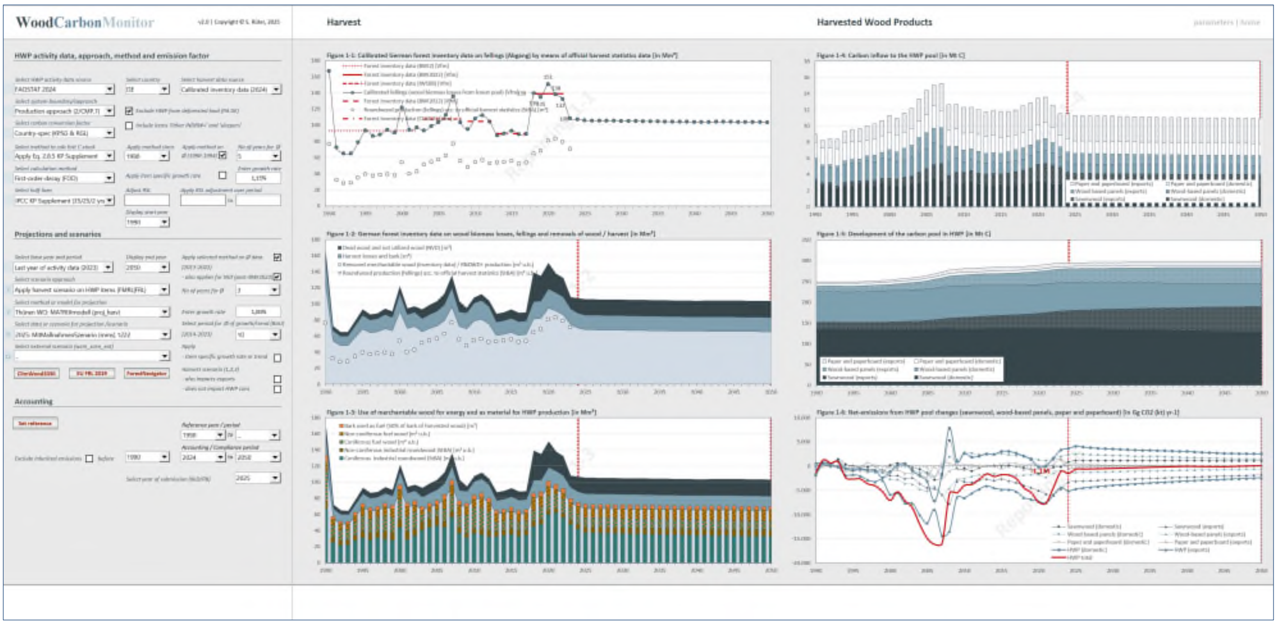
All three scenarios are equally "likely" to occur. The model is not mechanistic, the transition vectors incorporate all drivers, such as natural influences, management impacts, and interactions between them. By applying the same transition matrix each step continuity of, e.g., management, disturbances, and reactions to disturbances is ensured. Changes in site conditions or tree growth due to climate change can not be modelled. The aim of this study is to show possible near-term developments in accordance with the requirements of the EU-LULUCF regulation. Different climatic conditions are inherent in the three sets of change vectors, so an introduction of climate change scenarios in the analysis would complicate the work without generating additional insight, binding resources unnecessarily. Thus, it was decided to keep the approach simple, data-based and robust.

Timber removals are used as input to the model Wood Carbon Monitor (Rüter 2017) in all three scenarios, and treated in the same way harvested wood is treated in the GHG Inventory. This ensures methodological consistency with and comparability to the GHG reporting. Data from forest crown condition surveys was not considered, as natural mortality and management reactions to it are included in the transition data already. Separating natural mortality would only have resulted in a more complex modelling approach, without providing much additional information.

2.2 WoodCarbonMonitor to estimate CO_2 emission and removals arising from HWP

The projection of CO_2 emissions and removals arising from the HWP pool is implemented with the computer model WoodCarbonMonitor used for the German GHG inventory reporting. It has been developed by Rüter (2017) and constitutes an advancement of the IPCC HWP model as suggested by Pingoud et al. (2006). The WoodCarbonMonitor is an integral part of the German national GHG reporting framework for LULUCF that has already been applied for estimating the HWP contribution to the Forest Management Reference Levels (FMRL) of several European countries during the second commitment period of the Kyoto Protocol (Rüter 2011, UNFCCC 2012) and enables estimating historical as well as projected GHG emissions and removals associated with harvested wood. The model implements different reporting approaches presented by the IPCC (i.e. stock-change, production and atmospheric-flow approach) and further methodological elements provided in the latest IPCC guidelines on HWP (Rüter et al. 2014, Rüter et al. 2019), which can be combined with each other via a user interface (figure 7).

Figure 7: WoodCarbonMonitor user interface



Source: Rüter (2017)

Via the woody raw materials contained in the respective products (i.e. industrial roundwood, pulp and recovered paper) and the forestry activities associated with their production, the HWP can be allocated to the respective land-use categories. The historical timber harvest time series, which is annually calculated with the WoodCarbonMonitor for further use in the forest and HWP GHG reporting, is based on the relevant national statistical time series as well as detailed national data from the national forest inventories on the losses and use of wood biomass discriminating between the main tree species.

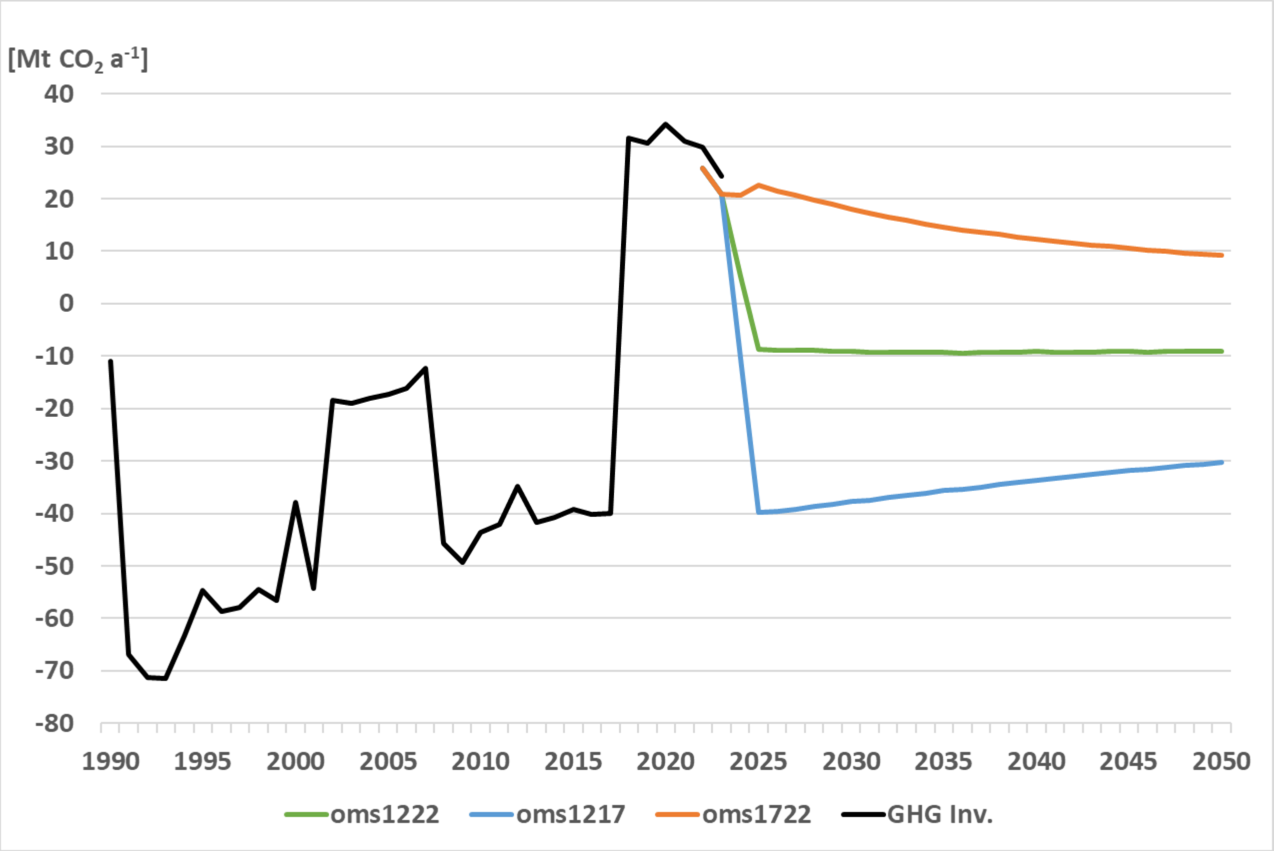
Besides the data on the historic time series, the model contains an integrated data interface to models providing projections and scenarios on harvest quantities and traded HWP raw materials (e.g. Matrix-Modell, GLOBIOM) in order to allow for estimating the HWP contribution in line with Forsell et al. (2018) (see also Rüter et al. 2016, Rock et al. 2021).

3 Results

3.1 Aboveground living biomass

Applying the three sets of change vectors results in three different levels of annual net emissions of carbon dioxide (figure 8). The projected development shows that even under optimistic circumstances and with a continuation of current management, living biomass will hardly be a sink in the years to come.

Figure 8: Annual net CO2 emissions from living biomass GHG-Inv.: reported in NID 2025, "oms1217" represents conditions as from 2013 to 2017 ('optimistic scenario'), "oms1722" conditions as from 2018 – 2022 ('pessimistic'), and "oms1222" conditions as from 2013 – 2022 ('medium'), resp.



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3.2 Increment

The current annual increment measures the carbon absorbed by the forest and available for allocation in aboveground biomass and harvest (and, subsequently, into the HWP pool). It should be kept in mind that the model does not calculate values for single tree species, but attributes values to tree species that dominate the respective inventory plot. For example, a value reported here for the tree species group "beech" will contain also increment from spruces, pines, oaks or other broadleaves growing on the respective plot. Combining all tree species, the three scenarios show distinct levels of annual increment of appr. 125 Mm^3 a^{-1} ('optimistic'), 110 Mm^3 a^{-1} ('medium') and 97 Mm^3 a^{-1} ('pessimistic'), respectively (figure 9). In the "optimistic" 1217 scenario, increment slightly increases and then drops as in the other two scenarios. This is due to a continuous increase in overall increment on plots dominated by oak, beech, fir and Douglas fir, and a decrease of increment of pine, larch, other broad leaved tree species with short as also with high life expectancy. In this scenario, spruce shows a minor increase in increment in the initial periods, followed by a decline. This is not sufficient to explain the overall course of increment (figure 10a). In the other scenarios the drop in increment of spruce and pine is much more pronounced (figures 10b, c).

Figure 9: annual increment, roundwood, over bark. Designation of scenarios is given in the text.

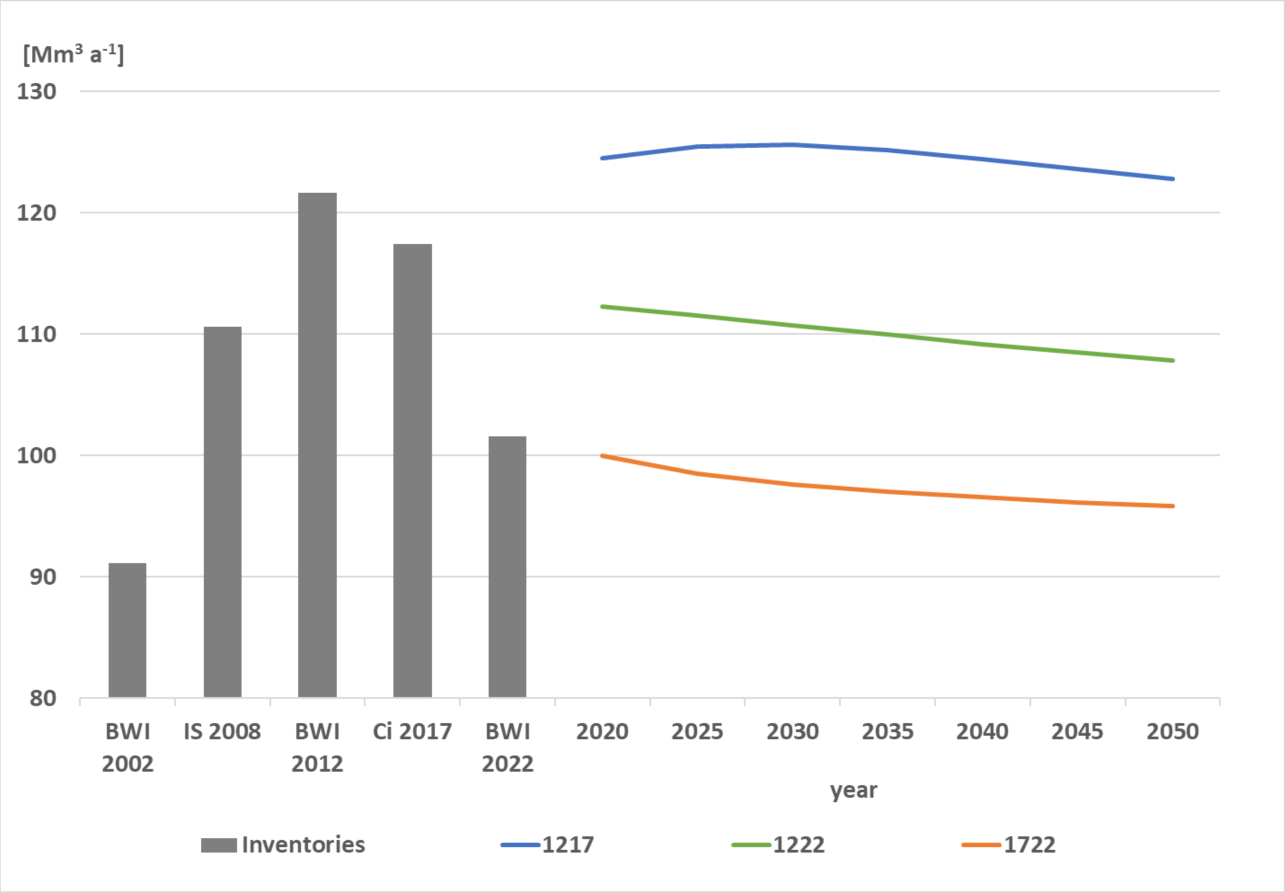

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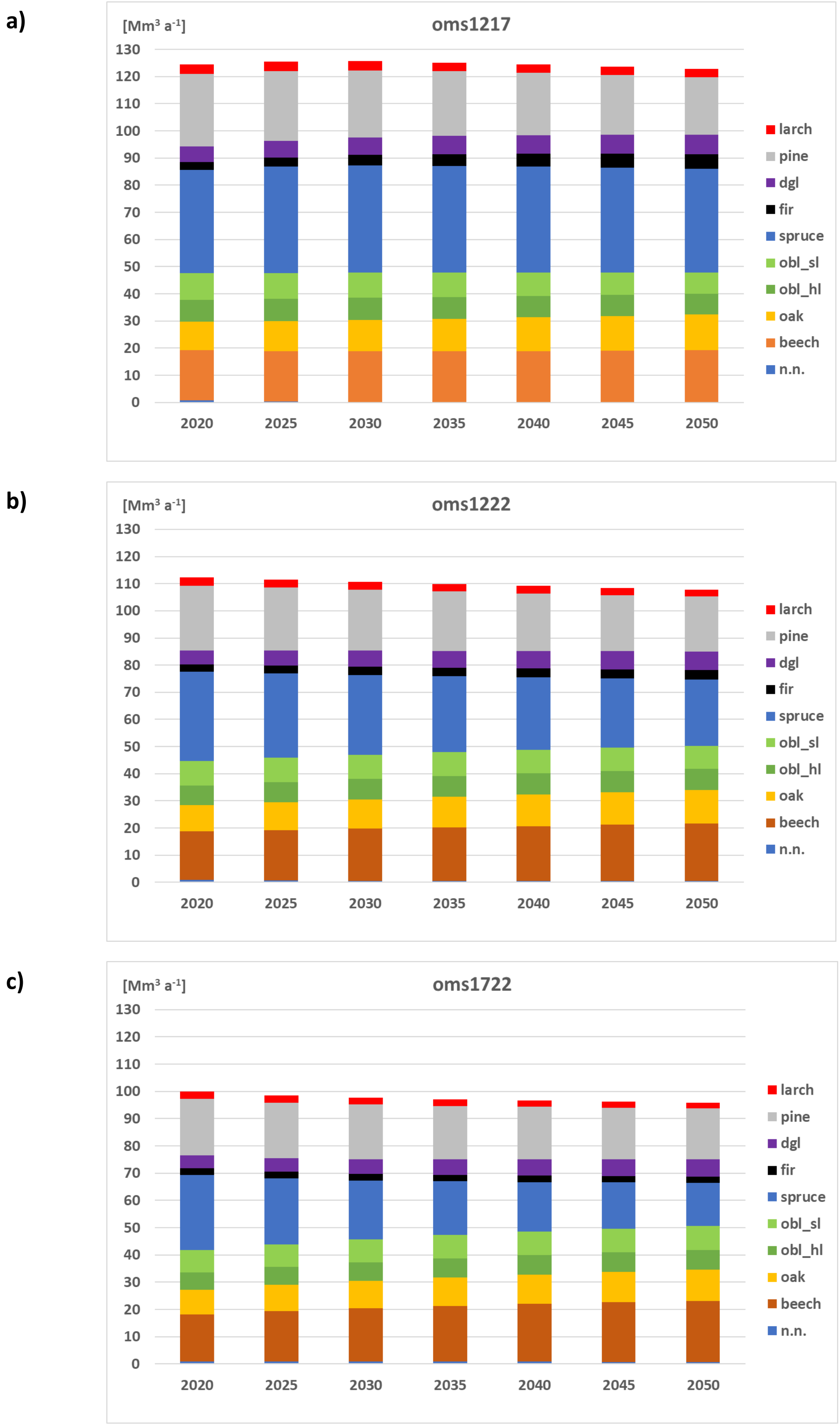
Figure 10: annual increment by tree species or species groups, resp. Scenarios are indicated in the panels. 'obl_sl': other broadleaved tree species with short life expectancy, 'obl_hl': other broadleaved tree species with high life expectancy, 'n.n.': forest area without trees larger than 7cm d.b.h.



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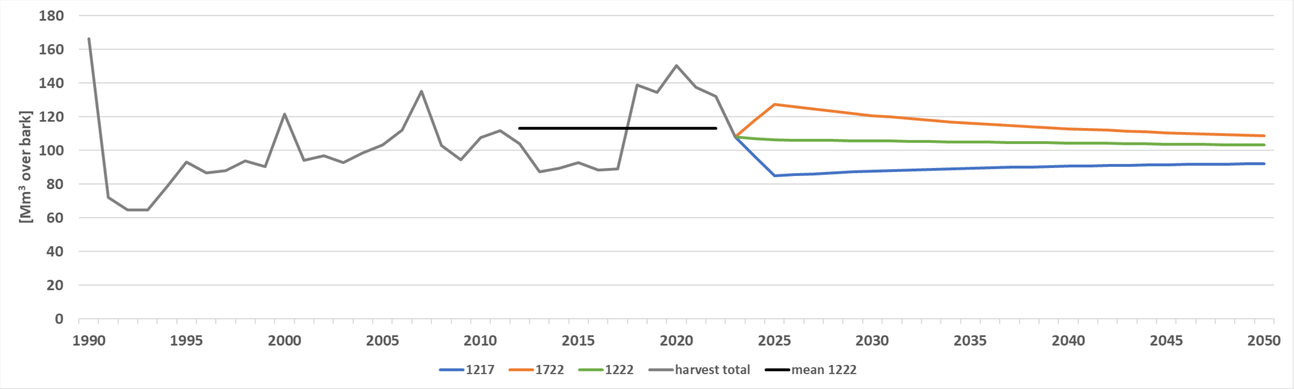
3.3 Annual harvest

Harvest levels are clearly distinctive between scenarios, due to the different amount of salvage logging included in the change vectors. The calamities (wind throw) in 1990, 1999 and 2007 are apparent in the recorded harvest (figure 11). All three scenarios converge in the future, as the structure of the forest changes over time. Because of the changes in forest structure caused by the drought years 2018 ff, scenario 1217 does start below the harvest recorded during the respective period. The same holds true for scenario 1722, as the stock (and area) of conifers deceased and thus only a smaller absolute amount of timber will be harvested given identical change vectors (i.e., harvest probabilities).

Figure 11: Annual harvest projected in the three scenarios, in Mm^2 o.b. (please note: the “forking” of the reported harvest into the three scenario projections is due to graphical reasons, the trajectories start in the period denominated “2025”)**.**



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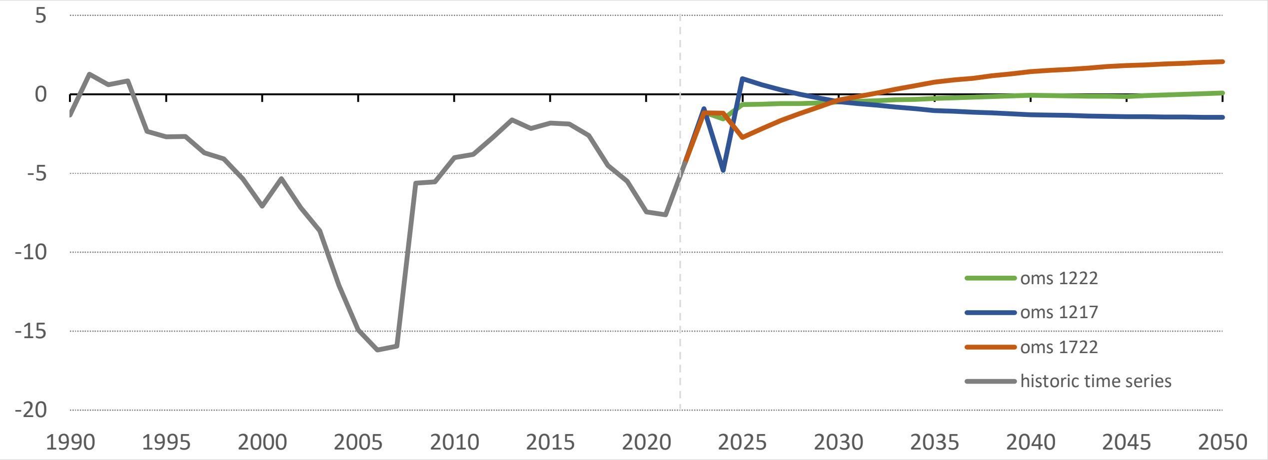
3.4 Harvested wood products

In order to derive the contribution of the HWP pool to emissions and removals, the applied approach follows the steps described in Sections 2.3.5 and 2.5.6 of Forsell et al. (2018). The time series of harvest amounts (i.e. harvest as loss of timber) projected by the Matrix model are thus used as input parameter for the HWP calculation (figure 12).

Figure 12: Annual CO2 emissions and removals arising from HWP, in Mt CO_2



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3.5 Aggregated view

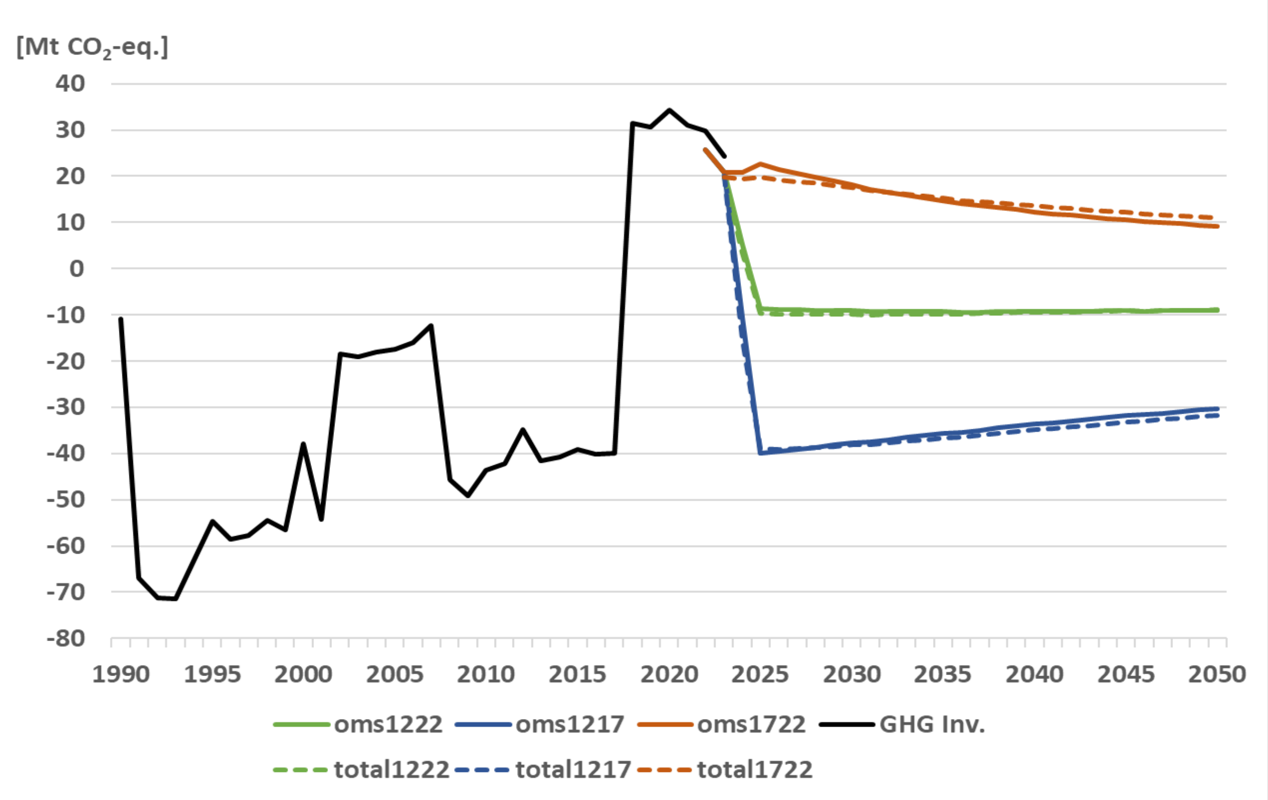
The development of the forest is the main driver of the course of the net emissions in the GHG reporting sector Land Use, Land-Use Change, and Forestry (LULUCF), as the other sub-sectors show rather small changes over time, even in years where forest biomass reacts strongly to, e.g., effects of disturbances and subsequent salvage logging, like 1990 or 2018.

The dead wood pool comprises dead trees or parts of trees and originates from the living biomass through mortality or harvesting. There is a correlation between the amount of damaged wood and the amount that is added to the deadwood pool. High levels of damaged wood from disturbances for example, lead to larger amounts of biomass being added to the deadwood pool. Deadwood is also left in the forest to increase biodiversity.

Newly added deadwood begins to decompose immediately through biochemical processes and the stored carbon is subsequently released to the atmosphere. A minor proportion is leached into the soil (e.g., as dissolved organic matter). This dynamic process of dead wood decomposition is not represented in the matrix model. Thus, the development of the dead wood pool is not incorporated in this analysis.

As shown here, the development in living biomass can vary considerably due to weather and climatic impacts. If the disturbance regime continued as it was in the five years 2018 to 2022, living biomass would act as a source of CO_2, with emissions ranging from 20 to 10 Mt CO2 per year. Conditions as in the more favourable period 2013 – 2017 could lead to a significant sink, but this would decrease till 2050 by appr. 10 Mt CO2 per year. Under "mixed" conditions, there could be a quite stable sink of 10 Mt CO2 per year (figure 13).

Figure 13: Annual net CO_2 emissions from living biomass and HWP (1990 – 2022: measured, 2023 – 2050: modelled). "oms1217" represents conditions as from 2013 to 2017 ('optimistic scenario'), "oms1722" conditions as from 2018 – 2022 ('pessimistic'), and "oms1222" conditions as from 2013 – 2022 ('medium'), resp. The hatched lines represent net emissions including HWP.



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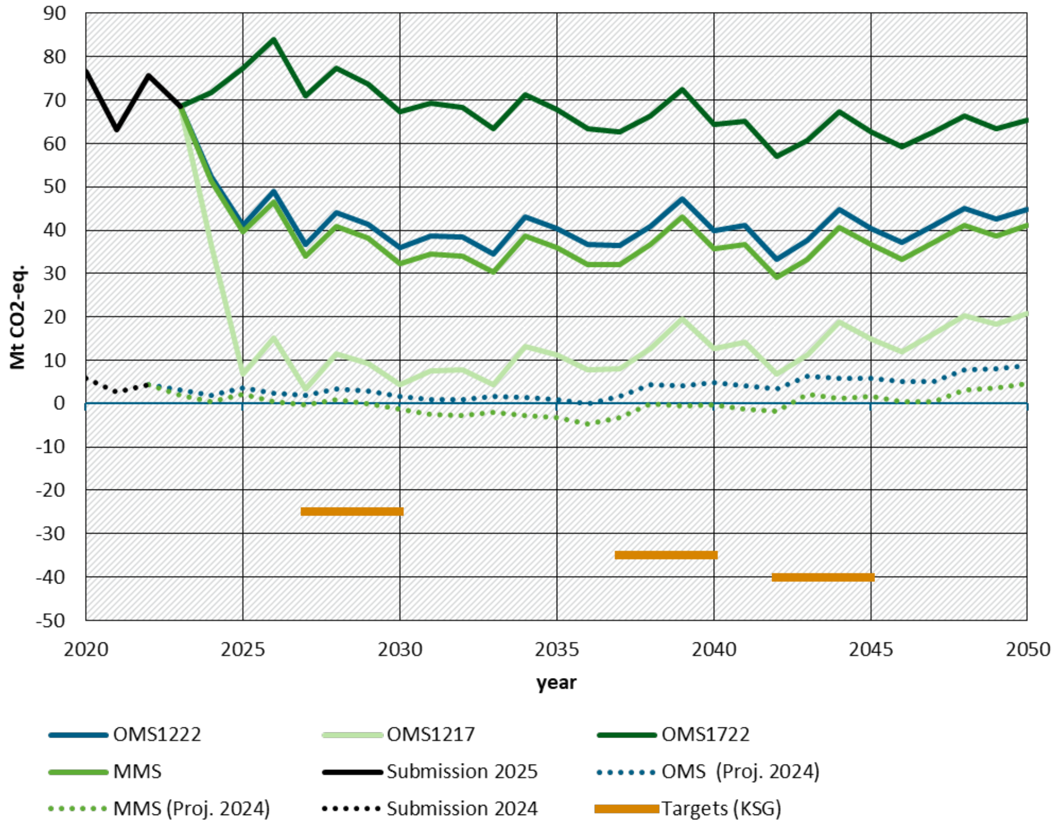
The future climatic and weather conditions are uncertain. Given current trends, the development will likely commence similar to the “optimal” scenario, but may drift towards the “mean” or, by the end of the period of interest in 2050, even the “worst” case’s path The German Climate Protection Law sets targets for a LULUCF sink at -25 Mt CO_2 in 2030, -35 Mt CO_2 in 2040, and -45 Mt CO_2 in 2045 (to be estimated as the mean of the target year’s emissions and the emissions of the three previous years).

The projections used in the PB 2024, which was based on the forest structure found in the CI 2017, change vectors from the NFI 2012 to the CI 2017, reported losses due to drought and bark beetles, and expert assessments, were approximately at the same level as the “optimistic” scenario. This shows that the expert assessments were quite correct. The 2024 projections missed the 2030 climate targets by appr. 25 Mt CO_2, the 2025 projections (Wehnemann 2025) that include the scenarios described above show deviations to the targets of appr. 35 to 95 Mt CO2-eq. in 2030 (figure 14). Our findings show that forests most likely will not provide enough net carbon removals to cancel out the emissions from the other land-use categories, even if they recovered from the disturbances and no disturbances like 2018ff took place in the (near) future. This also shows that it is highly unlikely to reach the targets set by the Climate Protection Law even under “optimistic” conditions.

In conclusion, the high variability in net emissions from LULUCF pools, the inherent risks associated with these pools, and the slow and weak controllability of these pools advocates for a shift in paradigm, to concentrate on forest resilience, adaptability and vitality, instead of concentration on existing carbon stocks, or even aiming at their increase.

Figure 14: Projected net emissions of the German LULUCF sector, taken from the 2025 projections’ report and adapted. MMS: projected emissions “with measures” (already implemented), Submission 2025, 2024: reported emissions from the 2024 and 2025 NID, resp., Targets: additional sequestration aimed for by the German Climate Protection Law. Other abbreviations as above.



Source: Wehnemann et al. (2025), supplemented

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