Forest Vision Germany

Description of methodology, assumptions and results

Berlin, 26 February, 2018

Commissioned by Greenpeace

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Scenario development, characterisation of different options for forest management and the analysis of BWI data for the selection of areas excluded from wood production was carried out in cooperation with the Naturwald Akademie. Chapter 3 (Scenario development) includes content by:

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Summary

Introduction

The goals of the present study included the development, characterisation and evaluation of a scenario for alternative ecological forest management in Germany, the so-called ‘Forest Vision’. This vision is intended to serve as a foundation to spark a debate on the development of future-proof, sustainable and ecological forestry in Germany. Based on the results of the most recent German National Forest Inventory (*Bundeswaldinventur*, BWI-3), the development of forests was modelled for the period between 2012 and 2102 using the Forestry and Agriculture Biomass Model (FABio) developed at Oeko-Institut. Three alternative scenarios for forest management were defined and implemented in the model. The differences between scenarios were assessed for a number of select indicators, including increment and growing stock, distribution of tree species and diameters, deadwood stock, carbon sequestration and wood supply.

Methods

Oeko-Institut has been continuously developing the *Forestry and Agriculture Biomass Model* (FABio) since 2015. FABio is a simulation model based on systems dynamics and agent-based modelling methodology for describing biomass growth and use in agriculture and forestry systems.

The forest model in FABio is based on data collected for the **German National Forest Inventory** (BWI) in 2002 and 2012 (BWI-2 and BWI-3, respectively). It characterises the growth of individual trees recorded in the inventory as a distance-independent individual tree growth model. For this purpose, individual trees are modelled as agents associated with a number of different specific traits, e.g. species, age, diameter, height etc. Data for individual trees at designated inventory sites are scaled to one hectare by multiplying trees depending on their frequency in the respective stand. The growth of trees is estimated using growth functions to get increment and changes in growing stock. In addition, FABio includes modules for the calculation of carbon stored in living and dead forest biomass, wood products, litter and soil.

A number of different indicators characterise forest development and allow the evaluation and comparison of model results for different scenarios. In addition to **growing stock** and woody biomass volumes of stems, branches, foliage and roots, the model also calculates annual **increment** and **carbon sequestration** of a given stand. The application of the single tree model allows projections of changes in **stand structure** (tree species composition, diameter distribution, percentage of large-dimensioned trees etc.). **Deadwood stock** and quality are key criteria and proxies for the assessment of forest biodiversity. A mortality model allows projections of deadwood production and decay.

In addition, the model projects future growing stock available for **wood supply**, i.e. the volume of harvestable woody biomass and its potential use as different products. The model distinguishes stem wood, industry wood and x-wood depending on tree species and diameter. The sorted wood is allocated to four different groups of **wood products**: sawn timber, wood-based panels, pulp wood and wood fuel. Carbon storage in wood products is considered in three different compartments with varying residence times: saw timber, wood-based panels and paper. Carbon stored in wood used for energy production is assumed to be emitted at the time of harvest.

The use of wood instead of other, more energy-intensive materials or the displacement of fossil fuels by wood biomass results in potential **substitution effects**. Due to the lack of data for a well-

founded description of such effects, these were excluded from the overall carbon footprint. The impacts of climate change and natural disruptions on forests were also not taken into account. Depending on the region, soil conditions, tree species composition and crop composition, these can have a negative or positive effect on forest growth.

Various **management options** can be included in the model. Forest management measures are adapted to eight different groups of tree species (spruce, pine, larch, fir, Douglas fir, beech, oak and other broadleaf tree species) and correspond to certain stages of succession and stand development:

- **Forest restructuring**: shift in tree species composition through targeted harvesting and **regeneration**. Tree species can be introduced, supported or pushed back and thus tree species distribution be influenced.
- **Intensity of management**: measure for the intensity of activities for wood extraction. In this context, the minimum tree **diameter** allowing thinning or **target diameter harvesting** is a key control variable. The **intensity** and **frequency** of interference determine the amount of biomass available for wood supply to be harvested. As a result the growing stock may increase or decrease, also age class and diameter distribution of the forest are affected.
- **Areas excluded from wood extraction**: Stands can be left to **natural development** when they are no longer used for forestry purposes. The selection of areas can follow a range of different criteria, e.g. **naturalness** of the forest by comparing the current tree species composition with the potential natural forest community, stand age or certain technical or economic **restrictions**, e.g. steep slopes etc.

Scenarios

Three scenarios for the implementation of alternative forest management strategies across all German forests were developed based on the options introduced above.

The **Base Scenario** is a projection of existing conditions. Parameter selection followed the rationale to assume and reflect current management intensity. The settings for target diameter and management intensity are based on the WEHAM base scenario (BMEL 2016c). A targeted forest restructuring is explicitly excluded. Restructuring measures carried out between the two German National Forest Inventories in 2002 and 2012 is not extended. The Base Scenario assumes natural forest development on 4.1 % of the forest area. In addition to areas that have already been designated as protected areas without wood extraction (e. g. national parks or nature reserves), this figure includes also currently unused areas without a legal protection status.

The **Timber Scenario** describes forests under the assumption that management is intensified. The intensity of management is increased compared to the baseline scenario by roughly doubling the intensity of thinning and extraction rates while maintaining similar target diameters. In addition, coniferous trees are promoted during the regeneration of the stands. Areas excluded from wood extraction do not change in comparison to the baseline scenario.

The scenario **Forest Vision** reflects the implementation of ecological forest management across all of Germany. For this purpose, target diameters are increased by 17-22 %, whereas intensity and frequency of interventions is reduced by 10-65 %. In contrast to the Base Scenario, broadleaf trees are given preference in their native habitat and conifers are suppressed. Furthermore, the percentage of areas excluded from wood extraction is increased to 16.6 % in the Forest Vision Scenario and thus effectively tripled in comparison to the Base Scenario (4.1 %). The selection of new areas excluded from wood extraction is based on natural forest communities worth protecting (e.g. ravine and riparian forests), areas with high naturalness (i.e. natural compared to actual tree species distribution of a forest), and age structure.

Results and discussion

Table 0-1 summarises the most relevant results for the key indicators.

Table 0-1: Overview of the most relevant results

Indicator	Unit and reference	Base	Wood	Compared to base	Forest Vision	Compared to base
Growing stock	Billion m^3 in 2102	5.0	3.8	76%	7.1	142%
	m^3/ha in 2102	484	368	76%	686	142%
Increment	m^3/a/ha 2012-2102	9,3	8,6	93%	9,9	107%
CO_2 storage in woody biomass	Million t CO_2/a 2012-2102	17.2	1.4	8%	48.2	280%
Total CO_2 storage*	Million t CO_2/a 2012-2102	31.9	17.2	54%	56.3	177%
Growing stock in diameter classes >60 cm	Billion m^3 in 2102	0.62	0.41	66%	1.67	269%
Deadwood stock	m^3/ha in 2102	22.5	16.2	73%	26.2	118%
Growing stock available for wood supply	m^3/a/ha 2012-2102	6.8	7.8	115%	5.1	75%
	Million m^3/a in 2102	71.8	78.0	109%	61.8	86%

Source: own calculation
* includes living forest biomass, deadwood, litter, soil and harvested wood products

A key indicator for the evaluation of impacts of alternative forest management scenarios is the development of the **growing stock in forests**. According to BWI-3, the growing stock increased by 9 % between 2002 (3.4 billion m³) and 2012 (3.7 billion m³). In the Base Scenario, the total growing stock is expected to increase to approx. 4.1 billion m^3 by 2052 with a further growth to 5.0 billon m^3 by 2102. This equals an increase of 11 % by 2052, and 35 % by 2102 in comparison to 2012. The Timber Scenario on the other hand projects an initial decrease of growing stock across all tree species of 11 % by 2032. In 2052, the scenario arrives at the initial value of 2012 and then continues to grow to 3.8 billion m³, i.e. a 3 % increase in comparison to 2012. In contrast, the Forest Vision Scenario expects a distinct increase of the growing stock from 3.7 billion m^3 in 2012 to 5.2 billion m^3 by 2052 (a 40 % increase). In 2102, the total growing stock cumulates at 7.1 billion m³, which corresponds to a 92 % increase, thus effectively doubling the existing stock of 2012. At the end of the simulation period, the Forest Vision Scenario achieves a growing stock that exceeds the projections for the Base Scenario by 42 %. The comparison between WEHAM results and the FABio model reveals FABio outputs similar to the WEHAM base scenario for the overlapping period 2012-2052 with similar parameter settings. Additional details may be found in Figure 5-1.

The Forest Vision Scenario achieves an average growing stock per ha of 501 m^3/ha in 2052 and 686 m^3/ha in 2102. In the Base Scenario 484 m^3/ha are estimated for in 2102, whereas the Timber Scenario totals at 368 m^3/ha. In addition to considerable differences in the size of the growing stock, the model reveals distinct **shifts in tree species composition of the stock**. According to BWI-3 a share of 39 % of broadleaf species in the growing stock was recorded in 2012. The Forest Vision Scenario predicts an increase to 50 % in 2052, which further increases to a share of 58 % in 2102. Beech alone accounts for 29 % of this figure and thus roughly half of the total growing stock of broadleaf species. Both the Base and the Timber Scenario also predict an increase of the share of broadleaf species of the growing stock. This effect is primarily caused by the reduction of the growing stock of conifer species in the Timber Scenario, which assumes intensified use of conifer species. It has to be noted that in the Forest Vision Scenario, the absolute numbers for growing stock in 2102 exceed those of the Base Scenario by 69 % for beech, by 55 % for oak and by 81 % for other broadleaf tree species. More information may be found in Figure 5-2.

The effect of different forest management options on **increment** are overall less pronounced, although several trends may be identified. The most productive tree species in all scenarios is Douglas fir, which achieves an average increment of 21 m^3/a/ha. Pine turns out to be the least productive species in all three scenarios. With an increment of 5.6-6.2 m^3/a/ha, it distinctly falls behind all other tree species. Forest management changes stipulated in the Forest Vision Scenario result in increased increments for broadleaf trees. The 90-year average (2012-2102) reveals a 15-22 % increase in comparison to the Base Scenario. In contrast, the average increment for broadleaf trees in the Timber Scenario does not change much. The increment of conifers in the Forest Vision Scenario increases only slightly compared to the Base Scenario (fir, Douglas fir) or decreases rather (spruce, pine). The most productive scenario across all tree species is the Forest Vision Scenario. The average growth of trees across the entire simulation period is 10.6 m^3/ha. This average increment exceeds the Base Scenario by 9 % (9.7 m^3/a/ha) and the Timber Scenario by 12 % (9.5 m^3/a/ha). Figure 5-3 illustrates additional information on increment.

The increase in growing stock in the Forest Vision Scenario is also reflected by the rate of **carbon sequestration** of forests. An implementation of the Forest Vision Scenario across all forested areas in Germany between 2012 and 2102 results in the formation of an average carbon sink of living biomass of 48 million t CO_2 per year. Including deadwood, soil and wood products the average carbon sequestration during the simulation period increases to 56 million t CO_2 per year. In consequence, the overall carbon sink potential of 54 million t CO_2 per year calculated for Germany in 2015 can be achieved with the implementation of the Forest Vision Scenario, although any further improvement appears unlikely. In this balance wood products form a source of carbon of 7.4 million t CO_2 per year if wood utilisation patterns remain as they are and imports are not increased. In the Timber Scenario 1.4 million t CO_2 per year are stored by living woody biomass across the 90-year average. Including carbon transferred to wood products of 1.4 million t CO_2 per year and soil carbon sequestration, the average carbon sink of the Timber Scenario amounts 17 million t CO_2 per year. However, forests actually form a source of CO_2 in this scenario until 2032. The Base Scenario achieves an average carbon sequestration of 32 million t CO_2 per year, of which approx. half is attributed to living biomass. Please see Figure 5-5 to Figure 5-7 for additional information.

From the distribution of the growing stock across different diameter classes, it is possible to infer both **stand structure and the proportion of larger trees**. Management practices have a distinct influence here. With a share of 79 %, the growing stock of conifer in the Base Scenario mostly falls into diameters below 50 cm. In the Timber Scenario, conifers up to 50 cm diameter represent 75 % of the conifer growing stock. In contrast, the Forest Vision Scenario assumes a considerable increase of older forest stands and larger trees. Here, only 61 % of the growing stock falls into diameter classes below 50 cm, while the diameter class of 50-60 cm increases. For broadleaf trees, both Base and Timber Scenario assume high shares in the diameter class up to 60 cm, i.e. 81 % and 89 %, respectively. In contrast, in 2102 the Forest Vision Scenario projects 70 % of broadleaf trees in the diameter class up to 60 cm, while the remaining 30 % fall into classes of larger diameters. The growing stock in the diameter class above 60 cm across all tree species amounts to 400 million m^3 in 2102 in the Base Scenario, whereas the Timber Scenario reports half of that value with 200 million m^3. However, the Forest Vision Scenario triples the Base Scenario with expected 1200 million m^3. The diameter class distribution of broadleaf trees above 80 cm is most relevant for nature conservation due to the fact that these trees are functionally most diverse with a range of habitat structures for endangered species. Broadleaf trees above 80 cm form 2.4 % (50 million m^3) in the Timber Scenario, 5.9 % (144 million m^3) in the Base Scenario and total at 6.1 % in the Forest Vision Scenario (262 million m^3). Figure 5-8 illustrates these results in detail.

For conservation purposes, **deadwood** plays a key role as habitat and feed for a range of specialised organisms, yet it is in short supply in German forests. Deadwood stocks of broadleaf trees are particularly low. Deadwood stocks are governed by the mortality in stands, which supplies new deadwood and depends on stand density in the model. Intensified use in the Timber Scenario with an average of 16 m^3/ha results in the lowest amount of deadwood, since both density and mortality decrease with increased harvesting. The Base Scenario achieves a deadwood stock of 22 m^3/ha. However, the reduced management intensity in the Forest Vision Scenario is not immediately leading to an increase of deadwood in forests due to the fact that mortality does not substantially increase until 2052. Nevertheless, a shift in deadwood quality towards broadleaf species can be observed, most notably a higher share of oak. In 2102, they amount almost double the stock of the Timber Scenario (18 m^3/ha). The total deadwood stock in 2102 in the Forest Vision Scenario amounts to 26 m^3/ha. Figure 5-9 provides further information on deadwood.

The increment balance that includes increment, mortality and harvesting reveals that predicted changes in growing stock primarily result from changes in harvest amounts, to a lesser extent from changes in increment and mortality (Figure 5-4). As expected, overall timber available for supply is lower in the Forest Vision Scenario than in the other scenarios. Over the period of 90 years (2012-2102), the average potential wood supply in the Forest Vision Scenario amounts to 5.1 m^3/a/ha, about 25 % lower than the Base Scenario (6.8 m^3/a/ha). With 7.8 m^3/a/ha, potential wood supply in the Timber Scenario increases by 14 % in comparison to the Base Scenario. However, the annual potential wood supply steadily increases in the Forest Vision Scenario over the simulation period. In 2102, potential harvest volumes in the Forest Vision Scenario achieve 86 % of those projected in the Base Scenario. Wood supply of spruce remains at levels similar to the Base Scenario for a long period of time. Moreover, the actual number of larger trees harvested in the Forest Vision Scenario is higher. Additional information may be found in Figure 5-12.

Conclusions

The study illustrates that the implementation of alternative ecological forest management in Germany for considering higher nature conservation goals can be demonstrated robustly and realistically using the forest model FABio and publicly available input data from the German National Forest Inventories. The specific measures considered in the model include:

a) support of broadleaf trees;

b) reduced management intensity and increased target diameters;

c) additional protection of areas of rare natural forest communities and old forests.

Modelling results reveal that implementation of these measures would allow a sustainable increase of growing stock in German forest by 42 % over a period of 90 years in comparison to the Base Scenario. The forest represents a strong sink for CO_2 over the entire period. At the same time, nature conservation aspects and forest growth, especially of broadleaf trees, are increasing. This reveals that ambitious climate and nature conservation goals in the forest do not have to be mutually exclusive.

The Forest Vision scenario assumes to exclude an additional 12.5 % of forest from timber harvest. Thus, in total 83 % of the area is available for wood supply under extensive forest management. Due to these protective measures, potential wood supply decreases 25 % on average, although supply of spruce wood is expected to be similar to the Base Scenario. Reduced yields are expected for broadleaf species in particular and transitory.

For meeting nature conservation and climate protection targets, however, the implementation of the Forest Vision requires that the use of harvested wood will have to be different from today. Building on substitution effects through the use of wood alone, as intensification scenarios often aim for, will not be effective due to decreasing substitution effects. Rather, a significant increase in the efficiency of wood use through more material and less energetic use, especially of wood from broadleaf trees, is required not only from the point of view of climate protection, but also to achieve a more sustainable use of resources.

1. Introduction

Forests in Germany play a wide range of important ecological, economic and social roles. These include their **protective function** (i.e. permanent ecosystem performance and services such as air purification, biodiversity protection, carbon sequestration and climate regulation, soil protection, and water regulation and supply), their **productive function** (e.g. marketing of wood products and other non-wood services) and their **recreational function** (e.g. leisure and recreation). The National Forest Act stipulates the preservation and development of protective, productive and recreational functions and calls for sustainable safeguarding of all three. Depending on the nature of the forest, the forest can perform its functions better or worse. Sustainable use is characterised by the fact that all forest functions are preserved in the long term.

Every decade, the German National Forest Inventory (*Bundeswaldinventur*, BWI) records the state of existing forest stands in Germany. The National Forest Inventories BWI-2 carried out in 2002 and BWI-3 in 2012 provide the first instance of a consistent repeated survey data set. Thus, it is possible to not only assess the state of forests in 2012, but to identify and evaluate changes between 2002 and 2012. For instance, Reise et al. (2017) explore parameters such as tree species distribution, diameter distribution, wood volume, deadwood volume and stem damage including tree hollows to evaluate nature conservation in German forests including future trajectories. In which state do we find the German forest, from a nature conservation perspective?

Areas excluded from wood production are an important aspect of nature conservation. For the implementation of the National Biodiversity Strategy, 5 % of forests shall be given over to **natural development**, i.e. conservation primarily of forests with a key role for native biodiversity (e.g. highly natural forests, old-growth stands, biodiversity hotspots). At present, an overall total slightly exceeding 4 % of forests in Germany are not in use. More than half of the areas are not used due to economic reasons or poor accessibility. These include sites that are valuable in terms of nature conservation. In general, the areas do not form a representative cross-section of natural forest communities. However, only approx. 2 % of forests have permanent conservation status (Engel et al. 2016).

The vegetation of most forested areas in Germany does not match the expected potential natural vegetation (PNV). Forested areas with highly natural to natural tree species compositions, i.e. areas with a considerable match between PNV and actual tree species present, cover 3.9 million ha (32 %) of the total forested area of 11.4 million ha. This percentage of forested area remained essentially unchanged between 2002 and 2012 (BMEL 2016a). Spruce and pine stands in Germany accounted for 26 % and 23 % of the total area, respectively (Table 1-1). These two species frequently occur at sites where beech or oak forests would be expected as natural vegetation. Beech and oak covered 16 % and 11 % of the area in 2012, respectively (Table 1-1). The percentage of broadleaf trees increased by 315,000 ha (2.8 %). However, recommendations exist to rather reduce or even reverse this trend (BMEL 2016b).

Table 1-1: Composition of forested area in Germany

	BWI-2 (2002)		BWI-3 (2012)		Difference
Tree species groups	**Area(ha)**	**Percentage**	**Area(ha)**	**Percentage**	**Area change (ha)**
Oak	1,059,485	10.0%	1,129,706	10.6%	70,221
Beech	1,577,748	14.9%	1,680,072	15.8%	102,324
Other broadleaf species	1,774,659	16.8%	1,917,482	18.0%	142,823
Broadleaf species	**4,411,892**	**41.7%**	**4,727,260**	**44.5%**	**315,368**
Spruce	3,005,706	28.4%	2,763,219	26.0%	-242,487
Fir	164,217	1.6%	182,757	1.7%	1854
Douglas fir	182,399	1.7%	217,604	2.0%	35,205
Pine	2,514,397	23.8%	2,429,623	22.9%	-84,774
Larch	300,754	2.8%	30,705	0.3%	6296
Conifers	**6,167,473**	**58.3%**	**5,900,253**	**55.5%**	**-26,722**
Total	**10,579,365**		**10,627,513**		

Source: www.bwi.info

The total **growing stock** in Germany in 2012 amounted to 3.5 billion m^3 (an average of 356 m^3 per ha). With a total of 2.20 billion m^3, conifers represented two thirds of the grand total (mostly spruce and pine, BMEL 2012). The growing stock of broadleaf trees (mostly beech and oak) was considerably lower and amounted to 1.34 billion m^3 (approx. one third). In the period between 2002 and 2012, the growing stock of broadleaf trees increased by 160 million m^3 (14.1 %) and that of conifers by 52 million m^3 (2.4 %). The only tree species to experience decline was the spruce, in fact a 4 % decline (approx. 49 million m^3). Intensified spruce utilisation is in line with silvicultural practices and forestry politics of recent years. In addition, storms and insect calamities had impacts resulting in increased use of conifers in particular.

The total **increment** of forests in Germany between 2002 and 2012 amounted to an average of 114 million m^3 per year. Depending on tree species distribution, broadleaf trees accounted for approx. one third of the total increment (39 million m^3/a), whereas conifers represented the remaining two thirds (75 million m^3/a; BMEL 2012). According to the National Forest Inventory, a total of 76 million cubic meters under bark of wood were used in Germany annually between 2002 and 2012. Considering harvest loss and bark, this figure results in an average **management intensity** of 79 % of increment. Data of the Federal Statistical Office[1] reveal that 18 % of logging was used for energy purposes. The share of logged beech timber directly used as wood fuel

[1] https://www.destatis.de/DE/ZahlenFakten/Wirtschaftsberoak/LandForstwirtschaftFischerei/WaldundHolz/Aktuell.html

amounted to 40 %. However, the official logging statistics cover only 75 % of the total logging included in the National Forest Inventory (Jochem et al. 2013). In all likelihood, the remaining 16.0 million m³ of logged timber was also used as wood fuel. Thus, the total use for energy purpose could be as high as 35 %.

Old forests are important **carbon stocks** that are often able to absorb yet more carbon and thus still act as sinks for CO_2 (Knohl et al. 2003). There is mounting evidence contradicting the traditional view that old-growth forests cease to absorb carbon (Köhl et al. 2017; Luyssaert et al. 2008; Stephenson et al. 2014). Instead of tree age, forest structure appears to be the key factor governing net uptake and exchange between atmosphere and plants, e.g. via existing leaf area (Schulze et al. 2009).With a balance of -40 million t CO_2 in 2015, living biomass in German forests acted as a considerable carbon sink[2]. However, modelling efforts of the Thünen Institute for their Projection Report 2017[3] with the WEHAM Model revealed that under forest management continuing the forestry practices of recent years, this sink is likely to decrease (to -11 million t CO_2 in 2020; to -21 million t CO_2 in 2035).

The effects of forest management on **soil carbon** are subject to controversial debate. Intensified harvesting that includes tree tops and other harvest residues is associated with distinct negative impacts on soil carbon sequestration (Achat, Deleuze et al. 2015). Long-term data on the effects of more moderate intervention are lacking and thus ambiguous (Achat, Fortin et al. 2015; Jandl et al. 2007). However, soil carbon sequestration in old-growth forests in typically higher than in industrial forests (Gleixner et al. 2009; Pan et al. 2011). Mineral forest soils in Germany in 2015 acted as a sink for 14.6 million t CO_2/a, i.e. carbon uptake took place. In contrast, the 244.000 ha of bog woodland in Germany acted as a carbon source due to the fact that drainage leads to gradual degradation of organic soils and thus, CO_2 emission. For effective climate change mitigation, these areas could be restored, i.e. rehydrated (Osterburg et al. 2013), a measure that would be in line with many conservation goals.

In addition to carbon sequestration, forests provide habitats for an immense range of animal and plants species. Especially **deadwood volumes** of different tree species, thicknesses and states of decay play a key role for the quality of forest habitats (Lassauce et al. 2011). Thus, they represent a crucial indicator for forest assessment as a habitat and refuge for biodiversity. In 2012, deadwood volumes in Germany amounted to a relatively low average of 20.6 m³/ha. Two thirds of existing deadwood volume were derived from conifers, which strongly dominate supply. Habitat quality could be considerably improved with complex standing deadwood of native broadleaf species (Reise et al. 2017).

Forest **age structure** in Germany forests is dominated by tree age categories below 100 years. Trees of that age accounted for 8.0 million ha or 74 % of the total forested area. The percentage of old-growth forest exceeding 160 years of age amounted to a mere 350,000 ha (3.2 %). The share of these old forests increased by 109,000 ha (1 % in reference to the total forested area in Germany) between 2002 and 2012. Old-growth forests are essential not least for **biodiversity conservation**. The low share of old forests in Germany is reflected in the fact that a considerable number of species that depend on old-growth forest habitats are threatened or even extinct in Germany. These endangered species include nesting birds, bats, beetles, mosses, lichens and

[2] Inventory report 2017 for Germany according to (EU) No. 525/2013, http://cdr.eionet.europa.eu/de/eu/mmr/art07_inventory/ghg_inventory/envwhvj6g/

[3] Projection report 2017 for Germany according to (EU) No. 525/2013, http://cdr.eionet.europa.eu/de/eu/mmr/art04-13-14_lcds_pams_projections/projections/envwqc4_g/170426_PB_2017_-_final.pdf

fungi (Reise et al. 2017). Old broadleaf trees are also underrepresented in Germany. In fact, broadleaf trees with a diameter exceeding 60 cm amount to 235 million m³ and thus, only approx. 7 % of the total growing stock in Germany (BMEL 2012). However, in a positive development, the share of such habitat trees has considerable grown with a 66 million m^3 increase over the past decade.

The national trajectory of expected forest development in Germany was modelled with **WEHAM** (*Waldentwicklungs- und Holzaufkommensmodell,* Forest development and wood volume model) (BMEL 2016c). Working with stakeholders, several new scenarios including different perspectives were developed in 2017 (Wood Preference Scenario and Nature Conservation Preference Scenario[4]). These scenarios show that there does not necessarily have to be a conflict between wood use, climate protection and nature conservation in the forest. Thus, the nature conservation measures described in the model hardly lead to a reduction of the potential impact but significantly higher CO_2 storage in the forest. Effects on substitution effects were not quantified. However, only small shares of land have been taken out of use and the reduction management intensity has only been reduced in certain areas.

The goals of the present study included the development, characterisation and evaluation of a scenario for alternative ecological forest management in Germany, the so-called 'Forest Vision'. This vision is intended to serve as a foundation to spark a debate on the development of future-proof, sustainable and ecological forestry in Germany. Based on the results of the most recent German National Forest Inventory (*Bundeswaldinventur*, BWI-3), projected forest development was modelled for the period between 2012 and 2102. Initially, alternative options for forest management were characterised in a forest growth model, which was then applied for scenarios based on these different management regimes. The differences between scenarios were assessed for a number of select indicators, e.g. increment and growing stock development, distribution of tree species, deadwood stock, age structure or diameter distribution, carbon sequestration and supply volumes of wood.

The study assumes the following **hypotheses** that characterise the Forest Vision Scenario:

1) Considerable increase of average growing stock in forests;
2) Constant or increased forest increment;
3) Constant or increased forest net carbon uptake;
4) Increase of high-diameter trees;
5) Increase of forest deadwood volume;
6) Support of broadleaf species promotes forest naturalness and increases the percentage of broadleaf trees;
7) Decrease of wood extraction and shift towards larger trees.

In the Forest Vision Scenario, the goals above are expected to be achieved with the following three key measures:

a) Promotion of broadleaf tree species;

[4] http://www.weham-szenarien.de/

b) Decreased management intensity with increased target diameters;

c) Designated protection for areas of high conservation value, rare and old-growth forests.

This report characterises input data, methodology for forest modelling and scenario development. It further presents key results for all indicators and discusses the outcome in light of potential consequences of an implementation of the Forest Vision.

2. Methods

2.1. Model description

The Öko-Institut has been developing the *Forestry and Agriculture Biomass Model* (FABio) since 2015. FABio is a cluster of simulation models based on system dynamics methodology and agent-based modelling. FABio characterises biomass production and use in both agriculture and forestry, and the effects of such activities on environmental indicators[5].

The forest model in FABio (see Figure 2-1) is based on input data collected in German **National Forest Inventories** (*Bundeswaldinventuren*, BWI) in 2002 and 2012 (BWI-2 and BWI-3, respectively). It characterises the growth of individual trees recorded in the inventory as a distance-independent **individual tree growth model**. For this purpose, individual trees are modelled as agents associated with a number of different specific traits, e.g. species, age, diameter, height etc., and their expected development trajectory is projected with the help of growth functions. In addition, FABio includes modules for the characterisation of carbon content of wood products, forest litter and soil. The model is based on the following components:

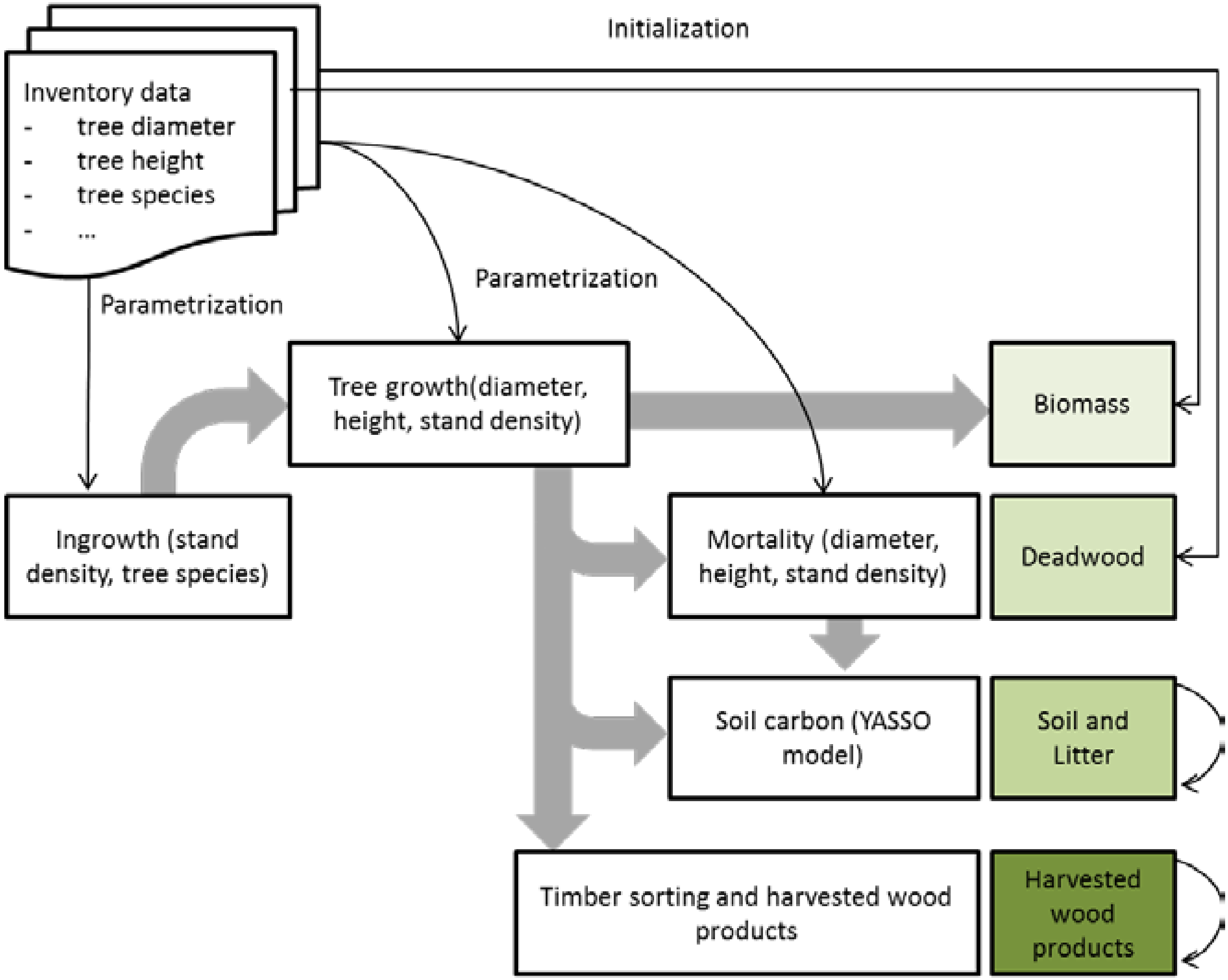
- a model for the characterisation of **tree growth** based on diameter, height, site productivity and forest stand density,
- an **ingrowth model** for the characterisation of new trees based on stand density and tree species,
- a **mortality model** for the characterisation of dieback processes depending on tree species, site productivity, age and stand density,
- a **deadwood model** factoring in decomposition of dead trees,
- a **soil carbon model** simulating the decomposition of biomass in litter and soil over time depending on climate factors, and
- a **model for the sorting and classification of wood products**, i.e. to sort harvested trees into use categories and quantify carbon retention times of wood products.

The model is implemented with the AnyLogic[6] Software. AnyLogic is based on a visual drag-and-drop modelling language, yet is also enables users to extend simulation models with Java code.

[5] A detailed model description in German can be found at https://www.oeko.de/fileadmin/oekodoc/FABio-Wald-Modellbeschreibung.pdf

[6] http://www.anylogic.de/

Figure 2-1: Flow diagram of the model and input data



Source: own illustration

2.2. Input data for modelling

The key input data for the characterisation of the present state of forests (initialisation) and selection of model parameters (parameterisation) of the model were based on the National Forest Inventory (BWI) database of the Thünen-Institute, which compiles results of the analyses of the BWI-2 and BWI-3[7]. The National Forest Inventories BWI-2 carried out in 2002 and BWI-3 in 2012 provide the first instance of a consistent repeated-measure data set that allows the modelling of temporal changes and trajectories for the total forested area in Germany.

The inventory procedure of the National Forest Inventory follows a sampling schedule in a base grid of 4 km by 4 km. This base grid was condensed to a 2.83 km by 2.83 km or a 2 km by 2 km grid in a number of regions. A square of 150 m x 150 m is located at every node of the grid (section point). The four resulting section points form the sampling sites for the inventory (assuming they

[7] Available from the BWI results database at https://bwi.info/

are located in the forest). Thus, a total of more than 47,000 section points with tree cover were recorded in the sampling process.

Monitoring was carried out at the four section points of every grid node. Recorded data included number of trees per sampling site and characterisation of tree traits such as tree species, diameter at breast height, tree height. Moreover, a number of additional features were recorded, e.g. deadwood (type of deadwood, degree of decomposition, diameter class), protected habitats and ecologically relevant trees (veteran trees and tree hollows), and nature conservation areas and use restrictions. The tree species recorded in the BWI were conflated to 24 groups of tree species that were included in the model. The present study further aggregates these into eight supersets: spruce, pine, fir, Douglas fir, larch, beech, oak, and other broadleaf trees.

All available input data from the inventory were used for the parameterisation of the model. Due to limited computing capacity, the simulations were carried out with a reduced data set limited to the 6500 plots of the 4 km base grid, of which one section point was selected. Preliminary modelling revealed that such a sub-selection was sufficiently robust and representative for the entire forested area in Germany.

It is not possible to simply infer the total forested area from the sampling sites due to the fact that these were not of a standardised area, but applied angle-count sampling instead. Area estimates were derived from the estimated stand space of recorded trees above the merchantable timer volume and thus established. The total forested area derived from this approximation amounts to 10.4 million ha. This result falls short of the actual total forested area of 11.4 million ha. The deviation arises from the fact that forest gaps or open spaces are ignored, and that only trees above merchantable timber volume were included for the area calculation. As a result, the model slightly deviates in its per ha results in reference to literature data based on different area data.

2.3. Characterisation of model indicators

During any modelling effort, there is the challenge to develop clear indicators that not only reflect forest development, but also allow the comparison of results in different scenarios and the testing of different project hypotheses. Our initial hypotheses require the model to explore the following indicators:

2.3.1. Growing stock and increment

To model the change of the average growing stock in forests, the volume of merchantable timber, i.e. the aboveground wood volume with a diameter larger than 7 cm including bark, is an essential indicator. The total growing stock and its distribution over diameters and groups of tree species as well as increment are key output variables of the model. State-of-the-art forest modelling requires a step away from the characterisation of stock and increment in differentiated stands in age class models. In contrast, individual tree growth models provide a valid alternative (e.g. FABio or WEHAM). Through these, trees of different heights and diameters can grow and treated individually, which is closer to a realistic description of forest management in Germany than using age class models.

The second hypothesis stipulates constant or increased increment of merchantable timber. Increment is defined as the gross production of wood per year and is derived from the growth model. In consequence, forest growth in FABio is calculated with a tree species-specific diameter model. The model is based on a logarithmic function for the characterisation of basal area and height increment that depends on tree maturity (diameter and height), competition (basal area of larger trees in the neighbourhood) and site productivity. Site productivity is determined for every section point included. For this purpose, the average stock growth depending on existing stock is calculated and normalised across all samples to a value between 0 and 100. The growth model distinguishes 24 tree species (see model description). During parameter development, tree species present in low individual numbers were further aggregated where required to ensure parameterisation results were robust.

2.3.2. CO_2 sequestration

In addition to the growing stock of merchantable timber, the model further quantifies biomass volume of stems, branches, foliage and roots as well as existing carbon stocks in these compartments. These are relevant for carbon sequestration assessment. One of the key hypotheses of the project is the assumption that ecological forest management increases forest carbon sequestration. For a comprehensive balance of forest carbon sequestration in biomass, the wood volume has to be converted into woody biomass. Biomass functions help estimate the shares of branches, needles, foliage and roots in reference to total biomass, depending on diameter and tree height. The average carbon concentration in wood amounts to 0.5 kg carbon per kg dry weight.

Living biomass produces plant litter of dead plant material, e.g. leaves, bark, twigs and branches. This litter layer is included in a soil carbon model and gradually decomposes. The YASSO 05 model (Liski et al. 2005) estimates the change of soil carbon stock based on the chemical composition of dead plant material (percentage of cellulose, hemicellulose and lignin) and average climate parameters. Initialisation of the soil carbon model is carried out with a spin-up run of the model covering 300 years to fill different carbon pools and reach a near steady-state of uptake and degradation. In other words, soil carbon content is assumed constant under similar forest management and a stable age structure.

With a transition into wood products, harvested timber exits the forest carbon stock. Such transitions have to be factored into the calculations of the carbon balance indicator. In consequence, carbon sequestration in wood products with differing retention times (paper, wood-based panels and saw timber) is considered in addition to living biomass. Initialisation of the wood product carbon model is also carried out with a spin-up run of the model covering 300 years.

The use of wood instead of other, more energy-intensive materials or the displacement of fossil fuels can lead to potential substitution effects. These occur when wood products, such as wooden window frames, replace functionally equivalent products made of non-wooden materials (e. g. aluminium window frames), which cause higher emissions during production than the corresponding wood products. However, these effects depend on numerous assumptions that have to be specified, including the production conditions of the respective products, the energy mix used and future demands. In addition, with increasing proportions of renewables in the energy system, a significant reduction in the effects of both energy and product substitution can be expected. Due to these limitations and the lack of data for a well-founded description of the effects, these were explicitly excluded from modelling and are not calculated in the model.

2.3.3. Stand structure and large trees

Hypothesis #4 requires a separation of trees of different diameters in the model. This assumption is satisfied with the single tree model, which computes complex stand structures based on individual tree data instead of simulation of homogenous stands. The individual tree model thus infers changes in stand structure (diameter distribution, stem number distribution, tree age etc.).

2.3.4. Deadwood stock

Deadwood stock and quality are key features for the assessment of biodiversity in forests. Expected deadwood volume may be modelled based on assumptions of the mortality model. Density stress under natural conditions is likely to result in a certain number of dead trees in a stand over time. Modelling of individual tree mortality is based on a comparison of data collected in the BWI-2 and BWI-3 inventories. In stands without management in the decade between the inventories, all dead or dying trees during this period were part of the analysis. The dieback probability is calculated based on data on age, diameter and species of individual dead trees, further including information on tree species composition, density and site productivity of the stand. Dead trees are recorded in three tree species categories of deadwood with differing degradation rates: oak as the slowest, conifers with a medium degradation and other broadleaf wood (including beech), which decomposes very fast.

2.3.5. Growing stock available for wood supply and harvested wood products

Another important hypothesis to be tested with appropriate indicators is that the Forest Vision Scenario will reduce the amount of timber, but with a simultaneous shift towards more high-diameter logs. According to the scenario settings, the model calculates the volume of wood produced, i.e. the harvest volume that can be obtained from the forest and the amount of wood that can be used for various wood products.

The wood use model divides harvested wood into size classes. Data on detailed features characterising wood quality are missing (e.g. branching, trunk form, percentage of rotten wood, etc.). In consequence, the model is based mainly on tree species and the diameter of the tree under examination. Classification can vary depending on the federal state, tree species, diameter class, and top end diameter. A distinction is made between logs, industrial wood and x-wood. Losses during timber harvest (e.g. bark, branches and stumps) account for the difference between the volume of the trees still standing (stock in cubic metre over bark) and harvest volume (cubic metre under bark). Harvested and sorted wood is assigned to four groups of wood products, differentiated according to type of wood (hardwood or broadleaf and coniferous wood): lumber (for the production of lumber), board wood (for the production of particleboard and fibreboards), pulpwood (for the production of paper and cardboard), and energy wood (for the production of electricity and heat).

2.4. Representation of forest management in the model

The model considers different **management strategies** characterised by specific measures. Their implementation may lead to changes in forest stand structure, e.g. diameter distribution, tree species composition, age structure and thus, increment and stock. The measures are adapted to the 24 tree species groups modelled and are based on specific stages of stock development. Three main options are distinguished:

- Forest restructuring;
- Change of management intensity and
- Designation of areas excluded from wood extraction.

The specific measures are described by **control parameters**. These are model parameters that can be adjusted by the user, thus allowing a “steering” of the model. They are the key factors distinguishing different scenarios due to the fact that these control parameters can directly or indirectly influence and change indicators. A set of specific control parameters settings is then combined into a scenario.

2.4.1. Forest restructuring

Forest restructuring involves a change in tree species composition, growing stock of different tree species and the area these species cover, which is governed by different levels of management intensity for certain tree species and by regeneration management. It is possible to selectively introduce individual tree species groups, or to select and promote existing tree species after natural regeneration. In this way, the development of forest stands may seek to support naturalness, i.e. native tree species of the natural forest community are given preference over introduced or invasive species.

2.4.2. Management intensity

A key control variable is the tree diameter threshold that indicates **thinning** is carried out or trees are harvested by **target diameter harvesting**. The strength and frequency of these interventions determines how many mature trees are actually harvested. In this way, forest growing stock can be increased or decreased and the age and diameter structure of stands can be influenced. The intensity of management distinguishes certain stages of stock development and is customised for tree species groups. The following stages are distinguished:

Stand establishment: New trees are modelled with an ingrowth model that allows distinguishing between natural regeneration and deliberate planting. The various available management options are characterised by rules defining the type of regeneration depending on site specifics, tree species, target tree species, etc.

Young tree care: Tending and maintenance of young stands covers the forest development stage from new seedlings to the first thinning, with the goal to improve wood quality or to influence the distribution ratio of different tree species (ForstBW Praxis 2014).

Thinning: Single tree modelling requires age and diameter as well as the height of the individual trees to be known. As a result, targeted interventions focusing on specific target diameters or diameter classes can be made. The growth model of the remaining trees reacts dynamically to an intervention in response to changing competitive conditions, which may be represented as a factor in the model.

Thinning includes both young and old-growth maintenance. In the model, thinning activities commence from a certain species-specific diameter at breast height. Targeted removal of trees of inferior quality (so-called competitors) allows and safeguards the increment of healthy and high-quality trees (so-called “future trees”, ForstBW Praxis 2014).

Stock maintenance: Stock maintenance is the management stage representing the main use of many silvicultural concepts. It aims to promote growth of valuable tree species by removing trees of inferior quality, use of mature trees and preparation of regeneration measures. At this stage the growing stock is increasing or the increment is harvested.

Final harvest: An important feature of alternative management forms is the shift away from rigid business models toward target diameter use in the forest and selection of single trees. The model can capture this type of management as it is an individual tree model. Final harvest can thus be carried out by removal of single trees when they reached the target diameter, groups of trees but also by removing all trees in the stand (clearcutting), e.g. depending on stand age.

2.4.3. Areas excluded from wood extraction

Stands can be left to **natural forest development** and no longer be used for forestry purposes. The selection of protected areas can be made based on a number of criteria, such as the **naturalness** of the forest by comparison of the current tree species composition with the potential natural forest community, or by existing **use restrictions** such as steep slopes, but also the stand age. Input data for this selection are provided by the National Forest Inventory. For instance, all sample sites are assigned to protected areas and other existing use restrictions are on record. In addition, sample sites may be selected according to main tree species, average age, natural forest community, diameter, etc.

3. Scenario development

Three different scenarios were developed based on the management strategies described above. Table 3-1 provides a general overview of the control parameters that were adapted to reflect the specific settings each scenario. In the model, the scenarios were characterised by a combination of different management options for different use intensities or different vegetation covers. The specific parameters for various **use intensities** in the scenarios may be found in Table A-3 and Table A-4. Assumptions for the selection of areas excluded from wood extraction are described in Chapter 3.4.

3.1. Base Scenario

The Base Scenario represents a projection of the present state, and as such provides a reference for the following scenarios. The selected settings reflect the continuation of past development between BWI-2 and BWI-3, but also describe common practices in forestry in Germany. The underlying assumptions correspond to the WEHAM Base Scenario that projects the trajectory of forest development and timber volumes for the period 2012 to 2052 (BMEL 2016c).

3.1.1. Forest restructuring

Forest restructuring is not explicitly expected in the Base Scenario. However, past forest restructuring efforts already implemented, i.e. between the two forest inventories in 2002 and 2012, are expected to continue. In consequence, changes in tree species composition occur dynamically and without targeted measures such as planting or tending of young trees. Tree species composition may further be altered during thinning or general use.

3.1.2. Management intensity

The parameter settings of the Base Scenario are chosen to reflect the current management intensity. The settings for target diameters and use intensities are based on the WEHAM Base Scenario[8]. To harmonise WEHAM thinning types with the management types listed in FABio, several thinning types were combined and simplified assumptions were made. For example, uniform thinning intensities of 20% were assumed due to the fact that the available data did not provide any specific information on actual thinning intensity. For a better compatibility of the parameter sets, the management types were also differentiated by federal state and type of ownership, a step omitted for the other scenarios. On average, the target diameter for conifers and broadleaf tree species is set to 54 cm and 59 cm, respectively. Intensity of target diameter use is 76% for conifer wood and 79% for broadleaf tree species, respectively (Table 3-1).

3.1.3. Areas excluded from wood extraction

The Base Scenario assumes the size of areas excluded from wood extraction to remain constant. Currently existing conservation areas and other areas with use restrictions, such as steep slopes (as identified by the National Forest Inventory), were modelled as excluded from wood extraction. According to the National Forest Inventory, wood use in these areas is either not permitted or not expected, or they are designated national parks and as such excluded. The total area excluded from wood extraction is assumed 4.1% or 427,700 ha. The Base Scenario assumes that these

[8] WEHAM Base Scenario parameters may be found here: https://bwi.info/WehamParameter.aspx (accessed on 23. August 2016).

areas are subject to natural forest development only. Details on area selection may be found in Chapter 3.4.

3.2. Timber Scenario

The Timber Scenario characterises the forest based on the overall assumption of intensified management. In reference to the Base Scenario, use is distinctly increased by intensified thinning and use while maintaining similar target diameters. In addition, regeneration efforts focus on the promotion of conifers. The assumptions and principles for a silviculture concept focused on maximised timber production are based on current forestry regulations and guidelines of several federal states (ForstBW Praxis 2014; Hessen-Forst 2008) as well as forestry concepts of private forest owners. Management practices in the Timber Scenario seek to maximise timber production.

3.2.1. Forest restructuring

The Timber Scenario does not assume any forest restructuring. However, existing conifer stands are promoted. Furthermore, a shift and increase of fast-growing tree species such as Douglas fir is deliberately supported at existing conifer sites. However, there are no selective plantings.

3.2.2. Management intensity

The Timber Scenario focuses on high increment, primarily realised by cultivation of Douglas fir, spruce and fir. Anticipated use leads to a complete harvest of the increment, and thus to stocks remaining approximately constant. Intense maintenance of the nursery stock and during thinning is the rule. In reference to the Base Scenario, the latter increases in intensity by 80% for broadleaf stands and by 40% in conifer stands, respectively. The production periods are relatively short; however, harvest is limited to target diameter use only. The pre-defined targets were set according to growth dynamics and economic conditions. In fact, their averages are even slightly above those of the Base Scenario (63 cm for broadleaf and 56 cm for conifers, respectively). However, the intensity of the target diameter use is 100 % (Table 3-1). Details on management intensity parameter settings may be found in Table A-4.

3.2.3. Areas excluded from wood extraction

Similar to the Base Scenario, the only areas excluded from wood extraction for forestry purposes in this scenario are existing conservation areas and areas with severely limited use. Correspondingly, these areas make up about 4.1% of the forested area. No additional areas are expected to be taken out of use. Details on area selection may be found in Chapter 3.4.

3.3. Forest Vision

The concept of ecological forest management modelled in the Forest Vision Scenario is based on the concept of integrated protection of natural processes by Sturm (1993). Its primary focus is on the natural processes in a primary forest or natural forest with the aim of promoting the development of near-natural, dynamic forest ecosystems and their self-regulatory mechanisms. Thus, the three pillars of sustainable development (economy, ecology, society) receive equal consideration. Optimising functional ecology is the prerequisite for positive economic outcomes and thus the achievement of social and cultural expectations and demands on forests.

This form of forest use was rated and accepted as environmentally sound in 1996 by environmental groups and NGOs such as Greenpeace, BUND, WWF and Robin Wood. Moreover, such forest use meets the criteria of the “Naturland” certification for ecological forest use and in part exceeds the criteria of the Forest Stewardship Council (FSC). Currently, this form of forest management is put into practice in several urban forests in Germanys including Göttingen and Lübeck.

3.3.1. Forest restructuring

The Forest Vision Scenario distinctly favours broadleaf species over other trees. Tree species of the natural forest community that would have prevailed without human influence are promoted in nursery stands and during thinning. Compared to the Base Scenario, broadleaf trees in their native habitat are subject to dedicated regeneration efforts with the aim to displace introduced non-native conifers. Natural regeneration processes safeguard forest renewal. Planting of trees does not occur.

3.3.2. Management intensity

The Forest Vision Scenario assumes the implementation of ecological forestry across all of Germany. Forests maintenance and management efforts aim to boost the viability and reproductive capacity of natural forest communities and improve the wood quality of harvest trees. Interventions are kept to a minimum, i.e. only where non-native, site-incompatible and low-quality trees threaten to outcompete high-quality, native trees. In this scenario, an increase of the stock per hectare in line with growing stocks in natural forests is intended.

For this purpose, the target diameters in all stands under management are increased by an average of 20%, and the intensity and frequency of management activities are reduced by 50% on average. Thus, the average target diameter is about 64 cm for conifer wood and 76 cm for broadleaf. The use strategy is limited to harvesting of individual trees or small groups of trees only. In consequence, harvestable wood volumes in the Forest Vision Scenario are likely to be distinctly lower. Table A-3 summarises all management parameter settings.

3.3.3. Areas excluded from wood extraction

The implementation of the Forest Vision Scenario in the model also includes the designation of additional areas excluded from wood extraction. A percentage of the forested area is designated as reference areas and released from management. These areas serve to observe and document natural development processes. Moreover, additional nature reserves and conservation areas with rare forest communities and old-growth stands are established.

The selection of additional conservation areas follows the Federal Nature Conservation Act § 30 (legally protected biotopes) and focuses on certain natural forest communities worth protecting, such as riparian, ravine and alluvial forests, but also on their actual condition, i.e. forest structure and tree species composition in these areas. The survey of these protected areas was carried out in a multi-stage selection process, based on the individually assigned forest communities. The protected areas modelled in the Forest Vision Scenario result in an area of 1,714,100 ha, which corresponds to 16.6% of the forested area in Germany. This total includes 10.5 % of public forest and 6.1% of private forest. Details on area selection may be found in Chapter 3.4.

Table 3-1: Overview of average settings for key control parameters defining management in the scenarios

Parameter		Base	Timber	Reference to Base [%]	Forest Vision	Reference to Base [%]
Forest restructuring		-	Promoting conifers		Promoting broadleaf	
Thinning intensity [%]	Nursery maintenance (broadleaf)	20	17	83%	13	63%
	Thinning (broadleaf)	20	36	181%	13	64%
	Stock maintenance (broadleaf)	20	21	103%	7	34%
	Nursery maintenance (conifers)	20	26	130%	18	90%
	Thinning (conifers)	20	28	140%	26	128%
	Stock maintenance (conifers)	20	23	115%	22	108%
Target diameter [cm]	broadleaf	59	63	108%	71	122%
	conifers	54	56	103%	64	117%
Intensity of target diameter use [%]	broadleaf	79	100	127%	75	95%
	conifers	76	100	131%	92	120%
Areas excluded from wood extraction [%]		4.1%	4.1%		16.6%	

Source: own compilation

3.4. Selection of areas excluded from wood extraction in the scenarios

The National Forest Inventory distinguishes four classes of use restrictions: unrestricted wood use, wood use neither permitted nor expected, about 1/3 of the usual volume expected, about 2/3 of the usual volume expected. According to the results of the BWI-3, wood use is not permitted or expected on approx. 450,000 ha of forested area (4.1%) of the accessible forest (BWI-3). These areas include sites on which the use of wood is prohibited for conservation purposes. For instance, about 150,000 ha are subject to external regulations and for a further 62,000 ha, there is an internal commitment to nature conservation. These areas account for 1.9% of the total forested area in 2012 and they may be considered under permanent protection. Only these designated conservation areas meet the requirements of the National Strategy on Biological Diversity for areas where natural forest development (NFD) is to take place (NFD5 project or *NWE5 Projekt*, Engel et al. 2016).

The BWI shows additional areas on which the use is not to be expected for other reasons, e. g. because of steep slopes. These areas do not have a permanent protection status, but can for the most part be seen as potential NFD areas (Engel et al. 2016). For the selection of areas without timber production in the scenarios, additional areas were chosen which are designated as national park areas, but in which wood may still be extracted. These areas amount to 25,100 ha and cover 0.2% of the forest area in Germany. Overall, the area in which no use is assumed in all scenarios covers 4.1 % or 432,100 ha of forest area.

Table 3-2 reports existing protected areas and areas with restricted use. In addition to the areas excluded from wood extraction, the National Forest Inventory identifies 4.3% of restricted-use areas, some of which are located in protected areas. Here, the wood use can be considered lightly (1/3) or strongly (2/3) restricted for a number of reasons. Areas with restricted use will not be treated separately but considered in use, unless they are located in protected areas or otherwise in need of protection.

Protected areas which have been taken out of use after the most recent data collection for the National Forest Inventory, e.g. the Black Forest National Park in Baden-Württemberg established in 2014, or the transregional Hunsrück-Hochwald National Park in Rhineland-Palatinate and Saarland opened in 2015, are in fact not excluded from wood extraction, as these areas are could not be exactly aligned with the National Forest Inventory sampling grid and section points.

The implementation of ecological forest management principles requires a designation of additional areas excluded from wood extraction. They are required for both the protection of biodiversity and the observation and documentation of natural development processes. The selection of these areas was based on criteria adapted from the National Forest Inventory data. The selection criteria for areas excluded from wood extraction and their ranking may be found in Table 3-3.

Table 3-2: Overview of existing conservation areas and restricted-use areas in 2012 in ha

Description	BWI-3			NWE5		
	Public forest	Forest total	%	Public forest	Forest total	%
1) Existing conservation areas, excluded from wood extraction	250,800	323,900	3.1	172,921	213,145	1.9
2) Excluded from wood extraction due to reasons other than nature conservation	38,400	83,100	0.8			
3) National parks, restricted use	22,500	25,100	0.2			
Total existing areas excluded from wood extraction / restricted wood extraction	***311,700***	***432,100***	***4.1***	***172,921***	***213,145***	***1.9***
4) Other conservation areas, restricted use	200,400	353,900	3.4			
5) Restricted use due to reasons other than nature conservation	36,900	92,000	0.9			
Total existing areas excluded from wood extraction / restricted wood extraction	***549,000***	***878,000***	***8.4***			

Source: own presentation, based on BWI-3 https://bwi.info/ and Engel et al. 2016 data

In addition to existing protected areas and use restrictions, additional areas are put under protection in the scenarios, i.e. excluded from wood supply. The selection of additional conservation areas follows the Federal Nature Conservation Act § 30 (legally protected biotopes) and focuses on certain natural forest communities worth protecting, such as riparian, ravine and alluvial forests, but also on their actual condition, i.e. forest structure and tree species composition (naturalness) in these areas. The selection of these protected areas was carried out in a multi-stage process (see selection criteria in Table 3-3), based on individually assigned forest communities. For this purpose, the 40 forest communities in the National Forest Inventory dataset were conflated into twelve forest types (see Annex Table A-5).

Areas excluded from wood extraction were selected following the criteria detailed in Table 3-3 und Table 3-4. As a first step, areas already excluded from wood extraction in 2012 according to BWI-3 were selected (level 1). Next, forested areas in protected areas that were previously used (level 2) were added. Then, all rare forest types were excluded from use in both public and in private forests (e.g. see ravine forests in Table 3-4, level 3). Furthermore, individual forest types such as, e.g. acidophilous mixed oak forest, were factored in with 10 % of the natural areas of this type in public forests and 5 % in private forests excluded from wood extraction. The same rationale was applied for 10 % of the non-natural areas of acidophilous mixed oak forest in public forests and 5 % in private forests (level 4). For this purpose, forest types were subdivided into the types of ownership, and natural versus non-natural stands, to achieve the intended percentages of public and private forest (see Table 3-4). Forested areas that are already excluded from wood extraction (level 1 - 3) were credited here. Within the natural and non-natural forested areas, the factors restricted use, protection status, forest development stage and age (for example beech stands> 180 years) were gradually taken into account to arrive at the intended percentage excluded from wood extraction.

The potential areas excluded from wood extraction together amount to 1,715,100 ha. This corresponds to 16.6% of the total forested area in Germany, of which 10.5% are public forests and 6.1% in private ownership (see Table 3-4). The percentage of protected areas in private forest assumes appropriate incentives in place (e.g. via contractual conservation agreements). This is a key assumption underlying nature conservation on private land.

The distribution over individual federal states is not uniform. The natural environment varies, i.e. forest species are unlikely to be equally common in every state (Figure 3-1). However, it is obvious that states with extended areas of forest like Bavaria, Baden-Württemberg, Hesse and Thuringia harbour fewer areas excluded from wood extraction in the Forest Vision Scenario. Figure 3-2 illustrates the geographical distribution of the existing and additional conservation areas.

Table 3-3: Selection criteria for areas excluded from wood extraction

Rank	Criteria
1	Areas excluded from wood extraction according to the National Forest Inventory (i.e. wood use not permitted or unlikely)
2	Protection status reported in the National Forest Inventory (i.e. national parks, nature conservation areas and Natura 2000 habitats)
3	Forest communities worthy of protection (i.e. ravine forests, thermophilic mixed oak forest, carr and natural areas of floodplain forests and wetlands, as well as ¾ of humid mixed oak forest)
4	Forest development stage (stand in late succession stages preferred)
5	Tree age median in a stand exceeds that of a species-specific age (e.g. beech stand >180 years)

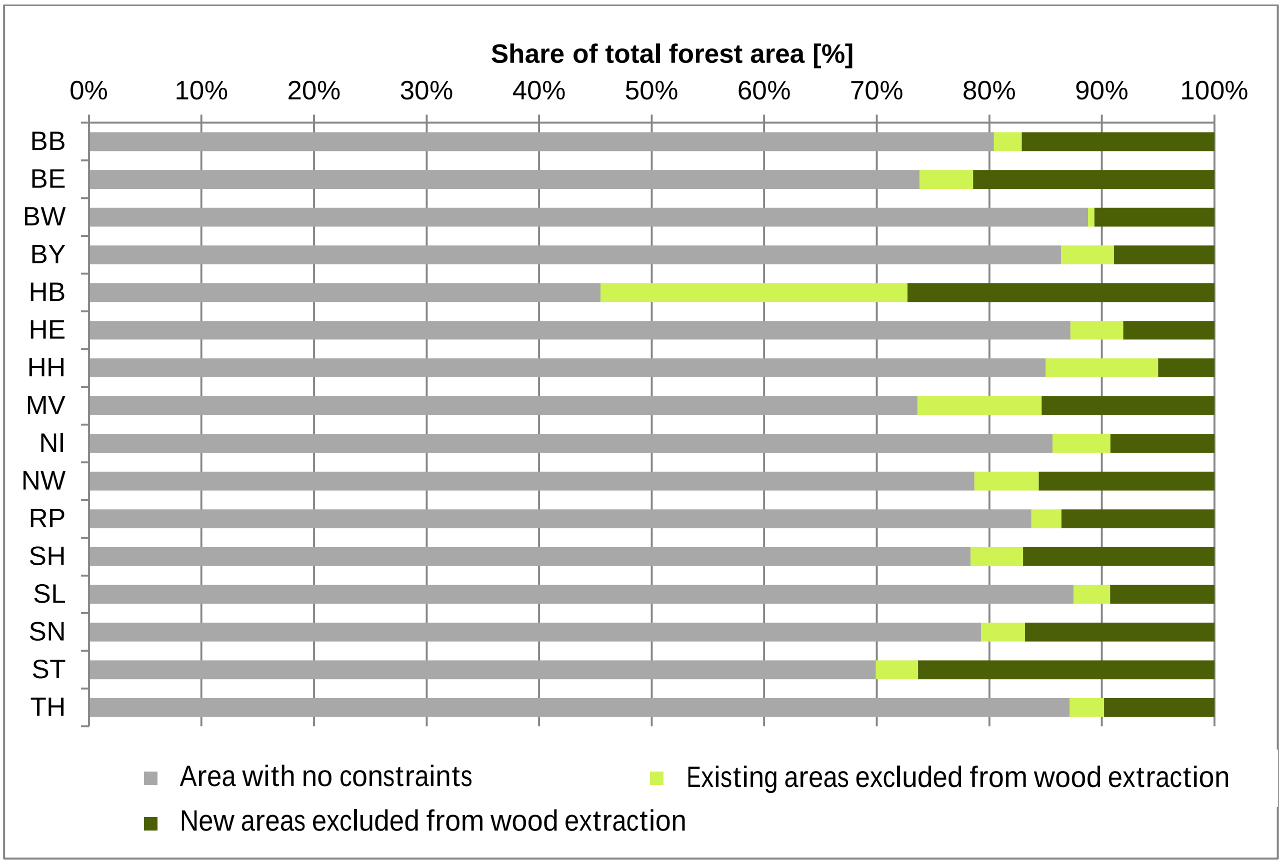
Source: own compilation

Table 3-4: Assumptions on areas excluded from wood extraction

Forest type	Ownership and area excluded from wood extraction	Area[ha]	Percentage of protected area from total
Floodplain forest and wetlands	Public forest (natural areas only)	101,100	0.98 %
	Private forest (natural areas only)	93,900	0.91 %
Ravine forest	Public forest (all areas)	99,100	0.96 %
	Private forest (all areas)	93,900	0.91 %
Thermophilic mixed oak forest	Public forest (all areas)	8,300	0.08 %
	Private forest (all areas)	5,200	0.05 %
Humid mixed oak forest	Public forest (natural areas only)	106,300	1.03 %
	Private forest (natural areas only)	93,900	0.91 %
Mesophilic mixed oak forest	Public forest (natural: 10 %; non-natural 10 %)	16,500	0.16 %
	Private forest (natural: 5 %; non-natural 5 %)	10,300	0.10 %
Acidophilous mixed oak forest	Public forest (natural: 10 %; non-natural 10 %)	41,300	0.40 %
	Private forest (natural: 5 %; non-natural 5 %)	34,000	0.33 %
Acidophilous mixed beech forest	Public forest (natural: 10 %; non-natural 5 %)	339,500	3.29 %
	Private forest (natural: 5 %; non-natural 2.5 %)	104,200	1.01 %
Mesophilic mixed beech forest	Public forest (natural: 10 %; non-natural 5 %)	102,100	0.99 %
	Private forest (natural: 5 %; non-natural 2.5 %)	39,200	0.38 %
Basic and calcareous mixed beech forest	Public forest (natural: 10 %; non-natural 5 %)	81,500	0.79 %
	Private forest (natural: 5 %; non-natural 2.5 %)	32,000	0.31 %
Carr	Public forest (all areas)	94,900	0.92 %
	Private forest (all areas)	118,700	1.15 %
Montane spruce forest	Public forest (natural: 50 %; non-natural 50 %)	86,700	0.84 %
	Private forest (national park)	1,000	0.01 %
Pine forests	Public forest (natural: 50 %; non-natural 50 %)	9,300	0.09 %
	Private forest (restricted use)	2,100	0.02 %
Total		1,715,000	16.6 %

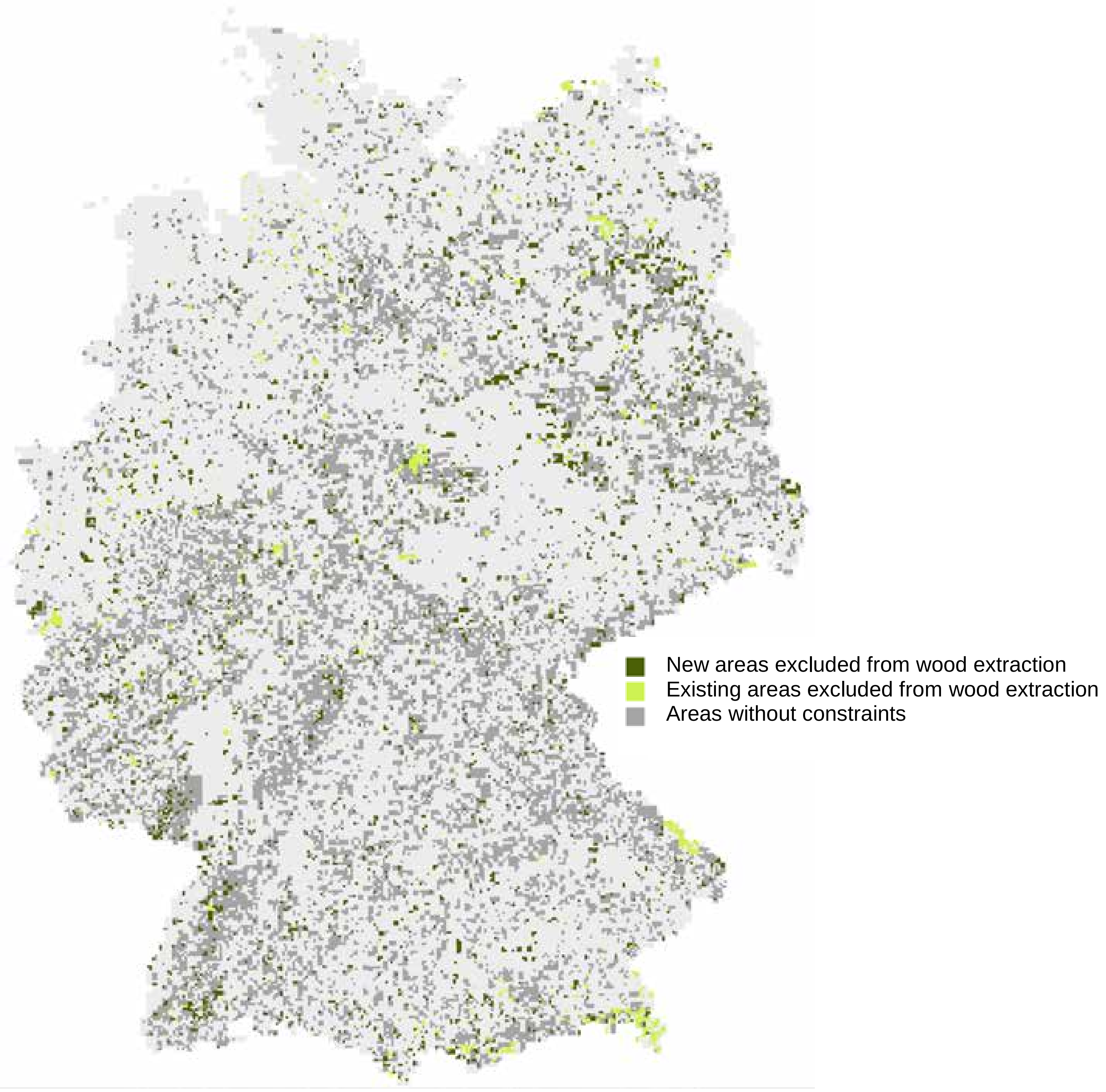
Source: own presentation based on BWI3 data https://bwi.info/

Figure 3-1: Relative percentage of existing and new areas excluded from wood extraction of the total forest area for different federal states



Source: own illustration based on BWI3 data https://bwi.info/

Figure 3-2: Geographic distribution of the forest area with and without constraints on wood extraction



Source: own illustration based on BWI3 data https://bwi.info/

3.5. Assumptions on temporal transitions into the scenarios

All scenarios assume immediate implementation of the measures described above. In consequence, the underlying assumption is that as of 2013, the stipulated management rules will immediately apply across all areas. Moreover, areas excluded from wood extraction are expected to remain excluded from forestry activities. This has the advantage that the transition takes place equally across all areas and there are no prioritised areas. In addition, the effects are much more visible, can be quantified sooner and are easier to analyse. A disadvantage, however, is that this assumption is not realistic. In the case of an actual implementation, no measure would immediately be applied across the entire area. It must therefore be assumed that all the effects of the scenarios would in fact be associated with considerable delay in reality.

An exception may be found in the implementation of wood removal in the model. If new management rules were implemented immediately, large shares of “over mature” trees would be harvested at once leading to a sharp increase in the potential harvest volume of wood. To buffer these sudden jumps in the model indicators, a diameter window was defined for the transition from high-intensity to reduced-intensity use. This window limits the harvest diameter not only with a lower, but also an upper threshold. The upper limit will be gradually increased over a period of 40 years. Thus, it can be assumed that changes in management intensity after this transitional stage were implemented over the whole area, while simultaneously avoiding abrupt jumps in the growing stock development from one year to another. In addition, the results are reported in 10-year increments. Annual change of variables was either averaged over this period (e.g. for increment, mortality or potential harvest quantities) or reported as the last value of the period (e.g. for the growing stock or carbon stocks).

All scenarios assume a constant forest area over the simulation period. In reality, new forests in Germany presently increase by several thousand hectares every year. To simplify the calculations, however, these areas are not included.

4. System boundaries

4.1. Indicators and input data

The indicators introduced above were selected based on a number of criteria. Two key factors governing the choice were **representability** in the model and above all, **data availability**. Some principles of ecological forest use cannot be quantified in the model and therefore could not be considered. Among those are, e.g. conservation of habitat trees, but also width of logging trails and distance between trails, which can be important parameters in practice. The density of logging trails may profoundly influence productivity. In addition, there is a distinct lack of data on initial conditions for many potentially relevant indicators. In the case of soil carbon stocks and initial carbon stocks of the wood product pool, model-specific equilibrium runs were used because initialization based on empirical data was not possible.

The model does not include any **economic indicators**, such as revenues or costs associated with the proposed measures. Although there are sufficient data for modelling costs and revenues, so that in the future appropriate model algorithms can be implemented. In general, economic considerations and influences such as the development of price and demand, or even basic forestry conditions such as terrain slope or the degree of stock development were not included for focusing the analysis on environmental indicators.

Furthermore, the selected settings do not take into account preferences of individual private forest owners, e.g. regarding the intensity of management or selection of tree species, as these details are usually not known. For the interpretation of the scenario results, it should be kept in mind that owners may not realise the full potential of timber harvest. In general, the assumptions on forest management disregard aspects of **ownership** (exception: selection of areas excluded from wood extraction). All the measures described are based on the simplified assumption that appropriate incentives and funding schemes exist. Thus, implementation of measures is promoted and facilitated in both public and private forests.

The Forest Vision Scenario seeks to implement a considerable change in forest structures. These structures currently exist in very few actual stands. Consequently, the number of datasets exemplifying growth and competitive behaviour of trees in such forests is scarce. Due to lack of data, these stands are expected to be associated with higher uncertainties in the modelling process. The selected growth model has the potential to model these relationships by modelling single trees, as opposed to age class models based on yield tables. An adequate description of the growth dynamics in forests under natural management, however, requires a more detailed modelling of resource utilisation, e.g. with a distance-dependent model and the use of more suitable datasets for parameterisation (Fichtner et al. 2012). The goal was to use a simple, Germany-wide model based on BWI data. By comparison with independent inventory data from natural forests, at least the plausibility of the model results for the most important tree species can be tested.

4.2. Project period and uncertainties

Uncertainties of model applications are diverse and highly relevant for the interpretation of results. The simplest representation is that of a margin or data range (minimum and maximum). With the use of error propagation methodology, the margin can be qualified in confidence intervals, i.e. indicating a probability that the value falls within the interval range. The uncertainty of random samples can also be described statistically. Moreover, uncertainties can be addressed by sensitivity analyses, which can be used to assess how sensitively indicators react to changes in input parameters. Sensitivity analyses further allow conclusions on the contribution of individual parameters. Such sensitivity analyses were performed here to test the plausibility of the model.

The uncertainties of model applications increase with a departure from the original model purpose and the input data. The sample size of the National Forest Inventory, which provides the input data for this model, is representative of the total forest in Germany and of the larger federal states. For smaller regions, however, the representativeness of the sample is not guaranteed, so that statements for small-scale questions cannot be reliably inferred. In consequence, a presentation of the results of individual federal states is not valid.

Uncertainties of the model results also increase with the length of the projection period. This uncertainty cannot be quantified in error percentages. The reason for these uncertainties is the reductionist focus of the model on essentials, so that not all influencing factors can be included in the projection. However, model results of this kind are not intended as predictions with a certain probability, but rather as a description of a development assuming certain circumstances and boundary conditions. Nevertheless, it is also possible to gain insight into important trends and patterns from longer simulation runs, which may be important for decision-makers.

Due to the extended periods of time required for forest development and thus long production periods, it is legitimate to calculate model runs up to the year 2102 (90 years) despite increasing uncertainties. Thus, the effects of changes in forest management are ultimately more visible and clear. When interpreting the results, however, it should be noted that the model does not take into account important factors such as climatic change, storms or insect calamities that could severely influence the development.

5. Results

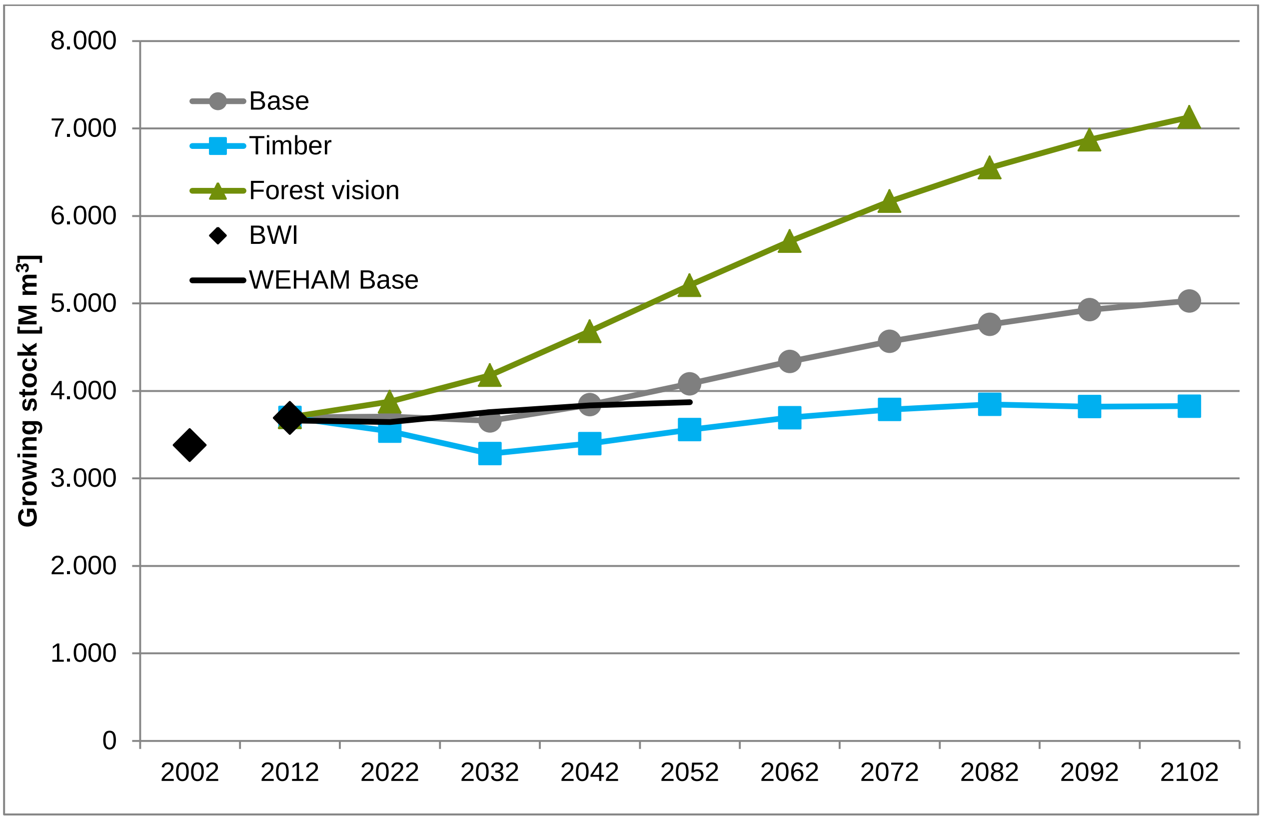
5.1. Thesis 1: Increase of growing stock in the forest

The projected development of growing stocks in forests is a key indicator for the assessment of effects associated with alternative management scenarios. According to the BWI-3, the increase of the growing stock between 2002 (3.4 billion m^3) and 2012 (3.7 billion m^3) was 9 %. Figure 5-1 illustrates the development between 2012 and 2102 for the projected scenarios in 10-year steps. In the Base Scenario, total growing stocks in forest in 2052 reach 4.1 billion m^3 and continue to grow to 5.0 billion m^3 in 2102. This equals an increase of 11 % by 2052, or 35 % in 2102 in comparison to 2012. In contrast, the Timber Scenario causes an initial decrease of 11% across all tree species by 2032. In 2052, the Scenario arrives at the starting level of 2012 and continues to grow to 3.8 billion m^3 by 2102, i.e. an effective increase of 3 % in comparison to 2012. For the Forest Vision Scenario however, the model calculates a distinct increase from 3.7 billion m^3 to 5.2 billion m^3 by 2052 (a 40 % rise). By 2102, stocks in this scenario reach 7.1 billion m^3, which equals a 92 % increase and thus an effective doubling of stocks in reference to 2012. At the end of the simulation period, the Forest Vision Scenario achieves a growing stock that exceeds that of the Base Scenario by 42 %. A comparison with WEHAM results reveals that the FABio model output for the Base Scenario produces results comparable to the WEHAM Base Scenario for the period between 2012 and 2052 (Figure 5-1). A comparison between the models at the level of tree species groups showed a good match between results. On average, the models deviated by less than 10 %. At the aggregate level, the two scenarios can be considered comparable.

Per hectare, the Forest Vision Scenario achieves an average growing stock von 501 m^3/ha in 2052, whereas average stocks in 2102 are expected to reach 686 m^3/ha. For the Base Scenario, the same area holds 484 m^3/ha in 2102, whereas the Timber Scenario comes to 368 m^3/ha (Figure 5-2). The three scenarios differ considerably in the expected tree species composition of the growing stock (Table 5-1). The average of 356 m^3/ha in 2012 consisted of 18 % beech, 10 % oak, 11 % other broadleaf trees, 32 % spruce, 21 % pine and 8 % other conifer species. Thus, broadleaf trees accounted for 39 % of the total, whereas Douglas fir reached 2 %. In the Base and Timber Scenario, there is an increase of the relative share of growing sock of broadleaf trees per hectare. In the Timber Scenario, this increase takes place until 2052, mainly due to a decrease in conifers due to intensive management. In the Base Scenario, the share of broadleaf trees reaches 48 % of the stock in 2102, whereas the Timber Scenario achieves an even higher 54 %.

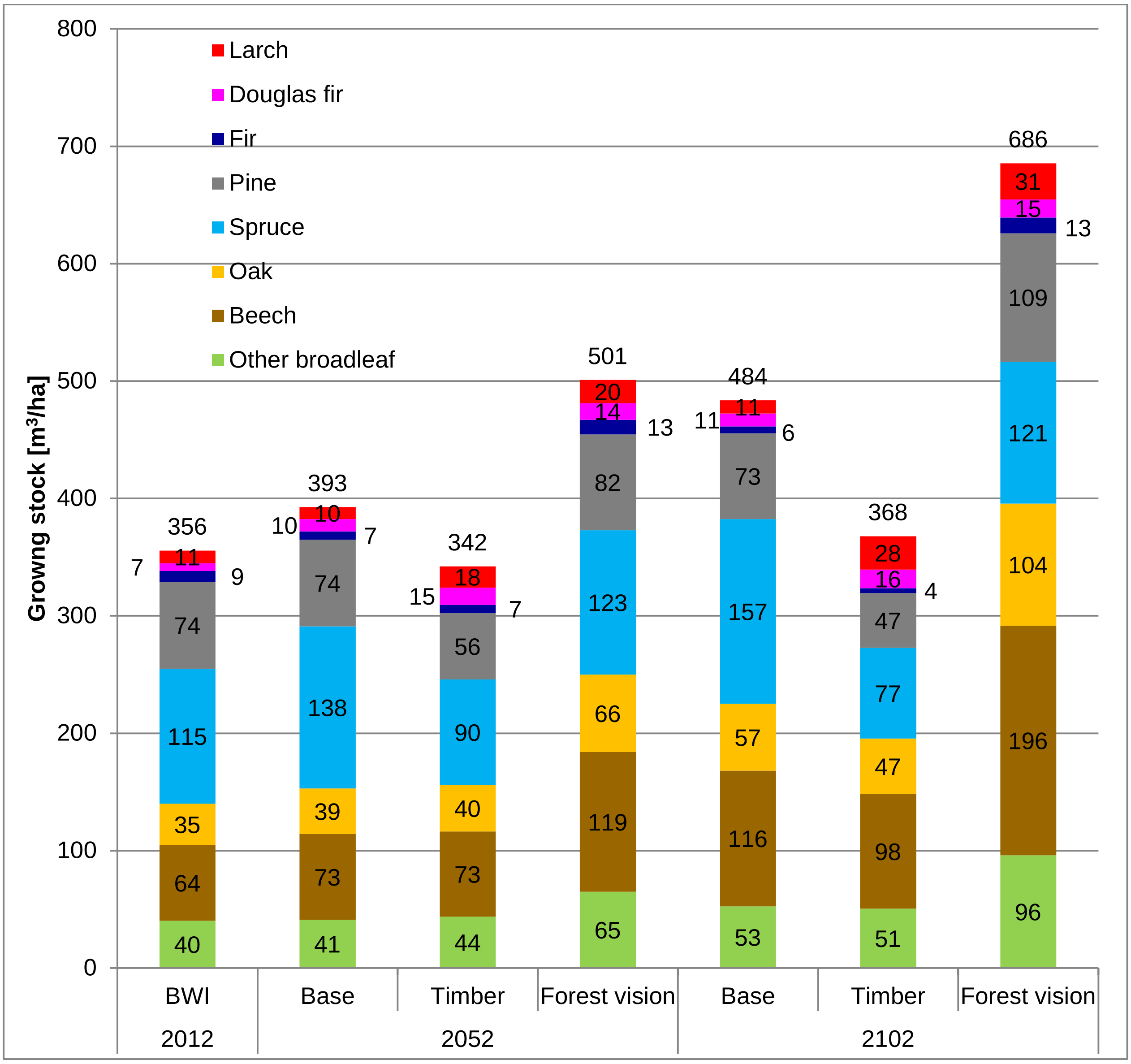
The average growing stock across all tree species groups in the Forest Vision Scenario increases in absolute terms, except for spruce, which remains constant (Figure 5-2, Table 5-1). However, the relative share of spruce decreases distinctly from 32 % in 2012 to 18 % in 2102. The relative share of pine equally decreases (16 % in 2102), whereas other conifers retain their percentage on average. The total share of broadleaf trees increases by 58 % in 2102. Beech alone increases by 29 %, which equals half of the total growing stock of broadleaf trees. The absolute figures for the growing stock of broadleaf trees are also of interest—in 2102, the Forest Vision Scenario expects an absolute rise of beech by 69 %, oak by 55% and other broadleaf trees by 81 %, respectively, in reference to the Base Scenario.

Figure 5-1: Growing stocks in forests, trajectory 2002-2102, data for 2002 and 2012 from the National Forest Inventory (BWI)



Source: own illustration, results of the FABio model and data from BWI results database and WEHAM model results https://bwi.info/

Figure 5-2: Average growing stocks in Germany in 2102 according to BWI-3, and in different scenarios in 2052 and 2102, respectively for different tree species groups



Source: own illustration, results of the FABio model and data from BWI results database https://bwi.info/

Table 5-1: Relative percentage of tree species from the total stock

		Other broadleaf trees	Beech	Oak	Spruce	Pine	Fir	Douglas fir	Larch
2012	BWI-3	11%	18%	10%	32%	21%	3%	2%	3%
2052	Base	10%	19%	10%	35%	19%	2%	3%	3%
	Timber	13%	21%	12%	26%	17%	2%	4%	5%
	Forest Vision	13%	24%	13%	25%	16%	3%	3%	4%
2102	Base	11%	24%	12%	33%	15%	1%	2%	2%
	Timber	14%	27%	13%	21%	13%	1%	4%	8%
	Forest Vision	14%	29%	15%	18%	16%	2%	2%	4%

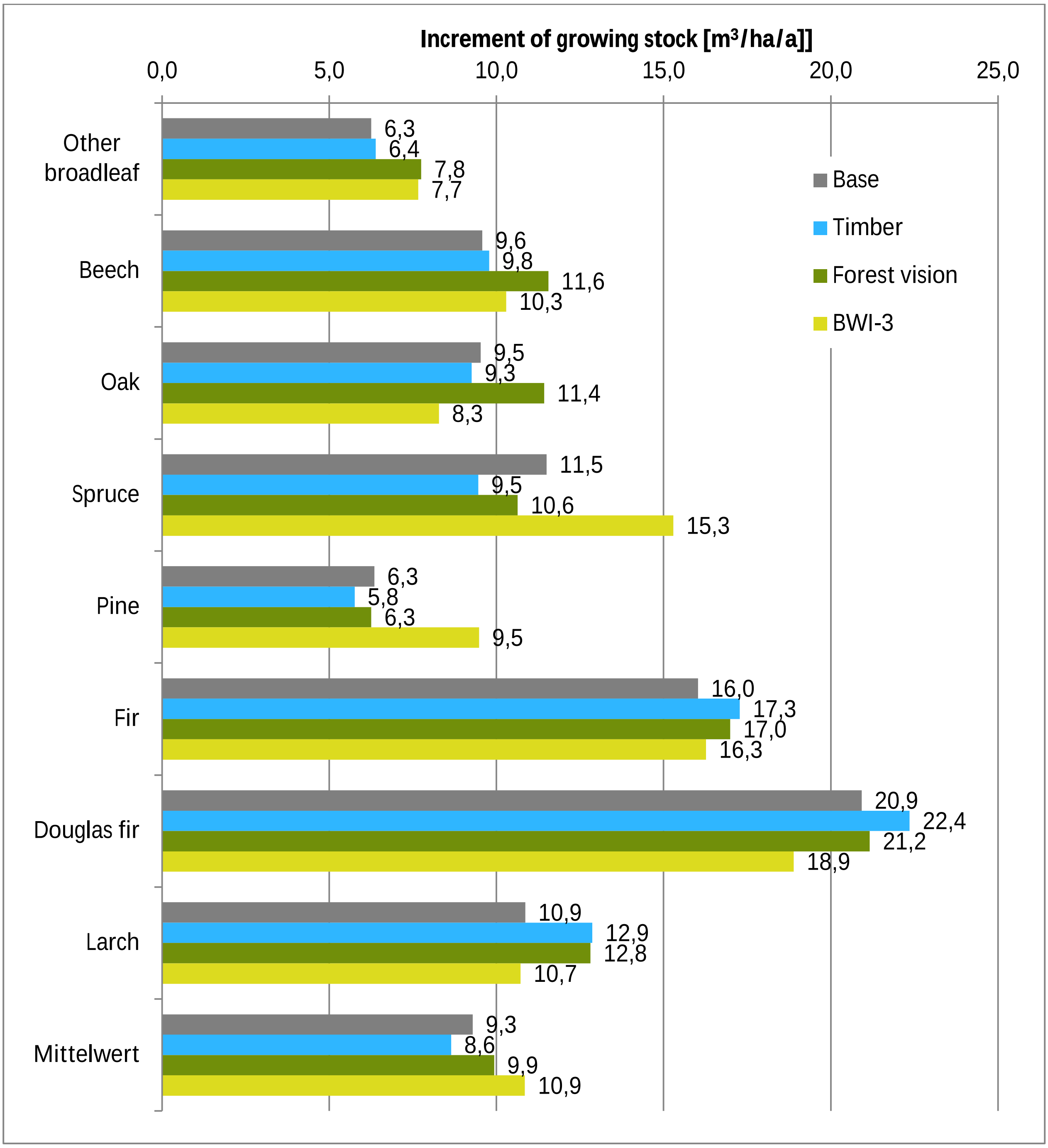
Source: own presentation, results of the FABio model and data from BWI results database https://bwi.info/

5.2. Thesis 2: Maintenance or increase of increment

The impacts of different management strategies on increment are overall less pronounced (Figure 5-3) than those on growing stock. However, several trends are apparent nonetheless. The most productive tree species in all scenarios is Douglas fir with an average increment of about 22 m^3/a/ha between 2012 and 2102. In contrast, the least productive tree species is the pine. With an average increment of 5.8-6.3 m^3/a/ha, it is distinctly outperformed by all other tree species. Changes in management strategies as stipulated in the Forest Vision Scenario result in increased increments for broadleaf trees, which yield average increments over 90 years (2012-2102) that are 20-24 % higher than those expected in the Base Scenario. In contrast, the average increment of broadleaf species in the Timber Scenario barely changes in comparison to the Base Scenario. Conifer increment in the Forest Vision Scenario, however, shows only a slight increase in reference to the Base Scenario (fir, Douglas fir), or even decreases (spruce, pine). Averaged across all the tree species, the Forest Vision Scenario is the most productive of all scenarios. During the simulation period, trees grow an annual average of 9.9 m^3/ha. This average increment exceeds the Base Scenario by 7 % (9.3 m^3/a/ha) and the Timber Scenario by 15 % (8.6 m^3/a/ha).

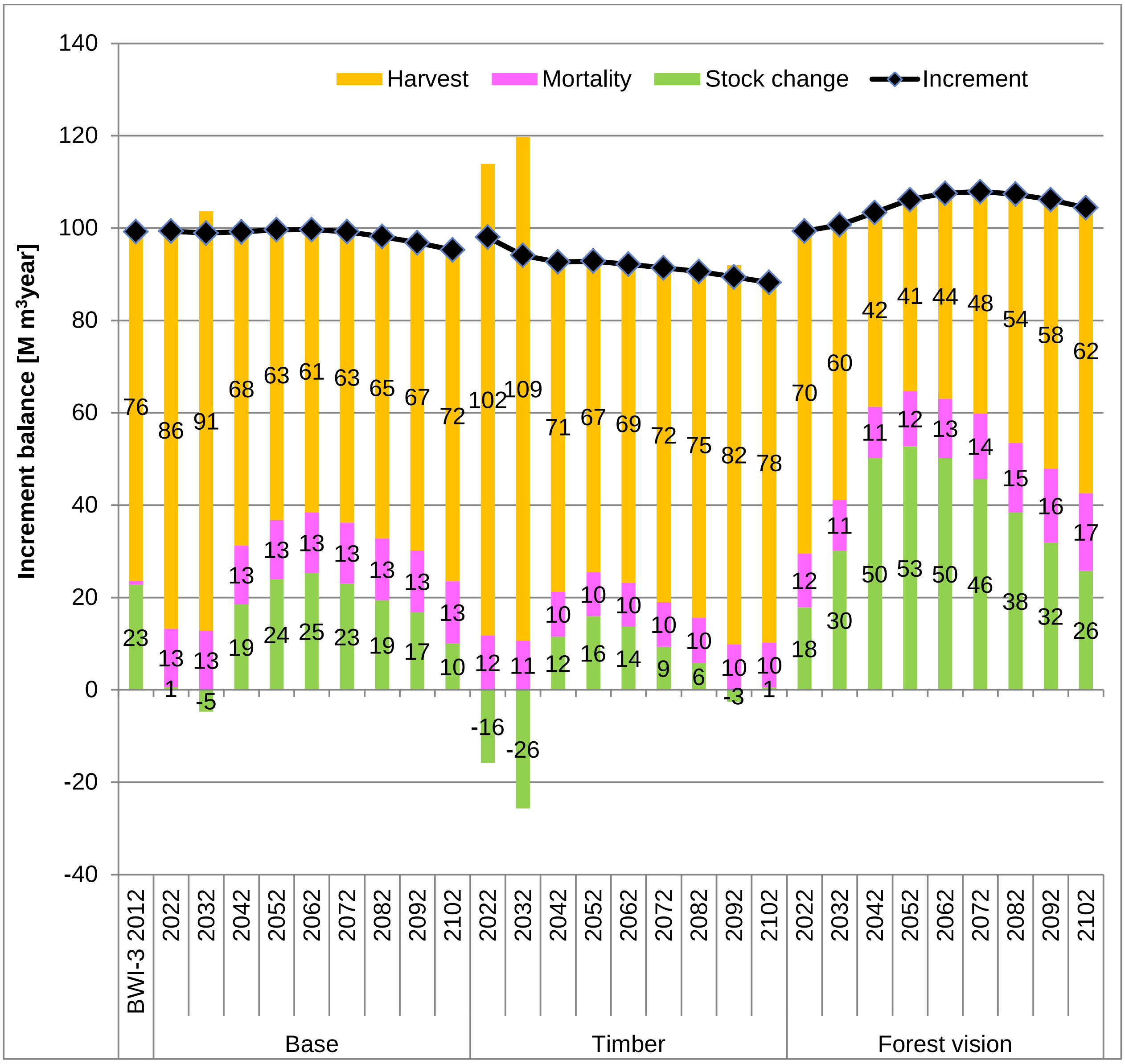
In the increment balance, the change in growing stocks (Figure 5-4) forms a result of increment, mortality and harvest (including harvest losses). If mortality and harvest remain below increment, the growing stock change is positive (stock build-up). If mortality and harvesting exceed increment, the result is a negative change of growing stock (stock reduction). The Timber Scenario in particular highlights that timber harvesting is very high at the beginning of the simulation, since a considerable number of old-growth stands are utilised (Figure 5-4). The use of over 100 million m^3 thus exceeds the forest increment in the first two decades that amounts only 94 to 98 million m^3. In consequence, a reduction of the growing stock in forests takes place. In the decades from 2042 to 2082, a slight increase in growing stocks is expected in the Timber Scenario. In contrast, the increment balance of the Base Scenario leads to a significantly higher stock build-up compared to the Timber Scenario, mainly due to lower timber harvest projections, on average 25 % less. Finally, although a 53 million m^3/a stock build-up in 2052 in the Forest Vision Scenario more than doubles the Base Scenario, the harvestable timber of 41 million m³ in 2052 falls below the Base Scenario (63 million m³, Figure 5-4) by 35 %.

Figure 5-3: Average annual increment of the growing stock in the scenarios (2012-2102) and the BWI-3 (2002-2012) for tree species groups



Source: own illustration, results of the FABio model and data from BWI results database https://bwi.info/

Figure 5-4: Annual increment balance in 2012 and in the scenarios to 2102 in million m³



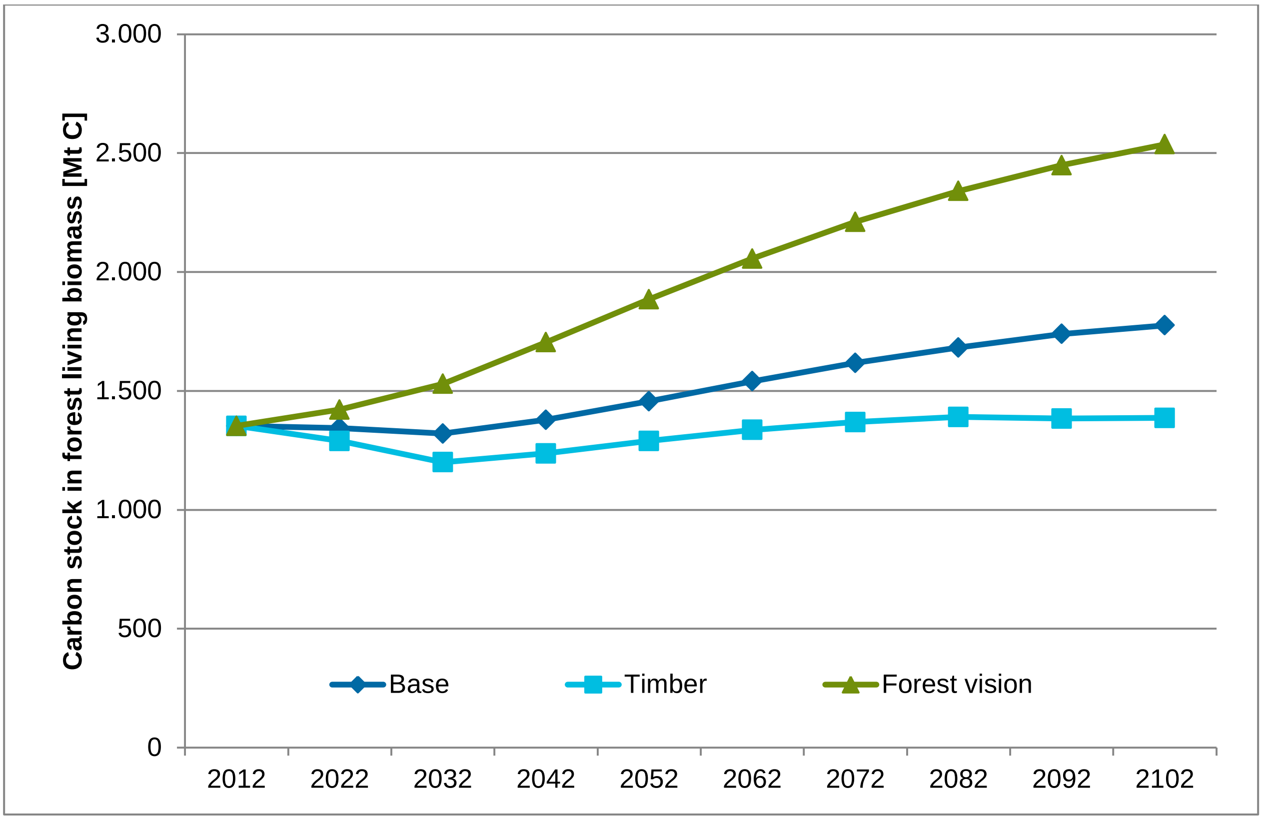
Source: own illustration, results of the FABio model and data from BWI results database https://bwi.info/

5.3. Thesis 3: Increase of carbon stock and CO_2 sequestration in the forest, improvement of the extended CO_2 balance

The increased stock productivity in the Forest Vision Scenario is also reflected in the CO_2 sequestration of these forests. When the amount of carbon dioxide that is captured from the atmosphere by photosynthesis exceeds the amount of carbon dioxide that escapes in the event of tree death and through respiration processes, the forest is a carbon sink. Figure 5-5 describes the development of carbon stocks in living biomass in the three scenarios. In the Forest Vision Scenario, carbon stocks in above- and below-ground biomass show an increase of 40 % by 2052 in reference to 2012, which equals 1.9 billion t C. By 2102, the increase reaches almost 90 %, i.e. stocks almost double to a total of 2.5 billion t C. In contrast to effects of increment (see Figure 5-1), the increase of carbon stocks is even more pronounced due to the fact that the share of broadleaf trees also increases. The specific wood density of broadleaf trees is naturally higher and thus, the associated carbon content per cubic metre wood also increases. The Base Scenario achieves between 1.5 billion t C and 1.8 billion t C in the same period of time (Figure 5-5). In contrast, there is no increase of carbon stocks in the Timber Scenario at all. On the contrary, slight decreases are expected until 2052, then emissions stabilise near zero by 2102.

The implementation of the Forest Vision across the entire forested area in Germany results in the creation of an average CO_2 sink of 48 million t CO_2 per year captured by living biomass in the period between 2012 and 2102. During this time, the scenario expects capture of 4.5 billion t CO_2 in biomass from the atmosphere. If living biomass is combined with deadwood, soil and wood products and included in the balance, the total carbon capture rises to 56 million t CO_2 per year. However, wood products are a source of 7.4 million t CO_2/a in the balance (Figure 5-7, Table 5-2). Thus, the carbon sink of 54 million t CO_2 reported by Germany in 2015 may be realised with the Forest Vision Scenario, yet there is essentially no potential for any major increase. In contrast, emissions from intensified timber use in the Timber Scenario virtually compensate any additional carbon sequestration from increased increment. The average carbon sequestration of living woody biomass over 90 years comes to 1.4 million t CO_2/a. In combination with the slight carbon sink of 1.4 million t CO_2/a stored in wood products and considering expected soil sequestration, the average sink in the Timber Scenario totals at 17 million t CO_2/a. However, please note that forests act as a carbon source until 2032 in this scenario. The Base Scenario achieves a total sequestration of 32 million t CO_2/a, half of which is captured by living biomass.

Figure 5-5: Development of carbon stock in forest living biomass



Source: own illustration, results of the FABio model

The calculation of the carbon sequestration (see Figure 5-6 and Figure 5-7) is carried out by comparison of periodic carbon stocks over time (stock change approach). This implies that no carbon sequestration value can be determined for the first year, or the first period. Therefore, the first value for carbon sequestration is reported in 2022, which consequently refers to the period between 2012 and 2022.

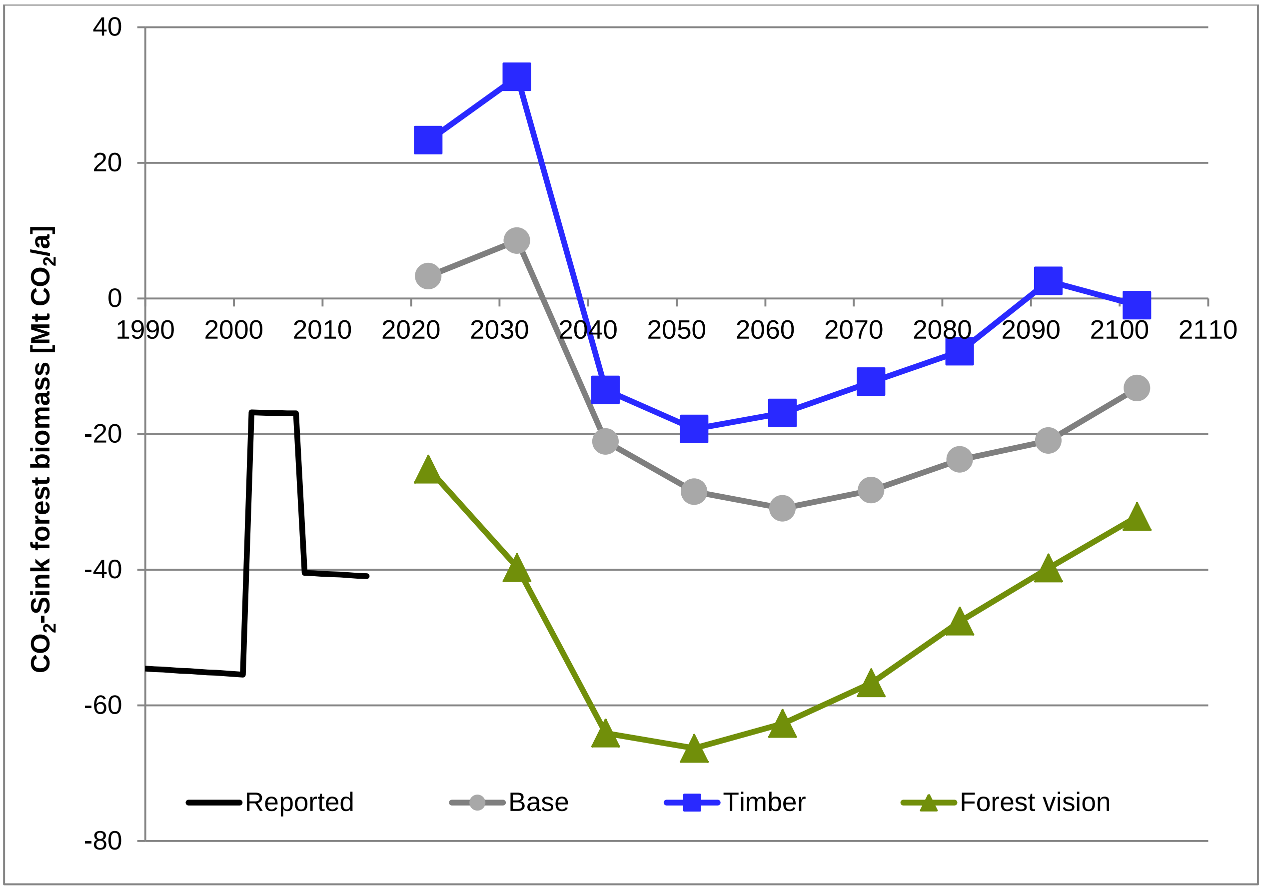
The historical trajectory of the forest as a carbon sink in Germany is part of the annual reporting to the UNFCCC in the form of the National Inventory Report (NIR 2017). The historical development in Figure 5-6 is based on the evaluation of historical forest inventories. The strongly fluctuating course may be explained by the calculation methodology. In fact, both inventories determined by the National Forest Inventories and interim inventories are used as a reference. Resulting changes in inventories are not interpolated between survey dates, but assumed at a constant rate. In consequence, there are jumps in the carbon balance in the event of an inventory (Figure 5-6).

Table 5-2: Average CO_2 sequestration of forests and in harvested wood products in the scenarios. Positive values are CO_2 emissions, whereas negative values are CO_2 removals. Unit million t CO_2 per year.

	Scenario	Living biomass	Soil and litter*	Deadwood	Wood products	Total
2012-2052	Base	-9.4	-15.5	0.1	-0.6	-25.5
	Timber	5.8	-15.8	1.1	-2.9	-12.8
	Forest Vision	-48.8	-15.2	0.5	13.9	-50.2
2012-2102	Base	-17.2	-14.8	-0.1	0.2	-31.9
	Timber	-1.4	-15.0	0.6	-1.4	-17.2
	Forest Vision	-48.2	-15.0	-0.5	7.4	-56.3

Source: own presentation, results of the FABio model, soil data include changes between the scenarios as calculated by the model, and an empirical value of the past CO_2 sequestration of -14.6 million t CO_2/a, which was factored into all scenarios (UBA 2017).

Figure 5-6: CO_2 sequestration living biomass in different scenarios. Historic data adapted from data reported by Germany to the UNFCCC in the current inventory report (UBA 2017). Negative values equal a carbon sink, positive values a carbon source.



Source: own illustration, results of the FABio model and data from the National Inventory Report 2017 (UBA 2017)

Both deadwood and harvested wood are excluded from the balance of living biomass in the scenarios. The underlying assumption is that such woody biomass either enters the deadwood pool or exits the forest. The harvested wood is used for various products, i.e. not all carbon sequestered in the wood is released as CO_2 immediately after harvest. Even wood that remains in the forest does not release all carbon immediately. After completion of various stages of decomposition - and CO_2 release - poorly degradable carbon finally enters the soil carbon pool as humus. Figure 5-7 illustrates the CO_2 balance of forest biomass, wood sequestration and soil over the period between 2012 and 2102. Immediate implementation of measures proposed in the Forest Vision Scenario may retain the current carbon sequestration of 54 million t CO_2 per year, or even extend it. Both Base and Timber Scenario are associated with reduced carbon sequestration, the former achieving half and the latter one third of the Forest Vision Scenario (see Table 5-2).

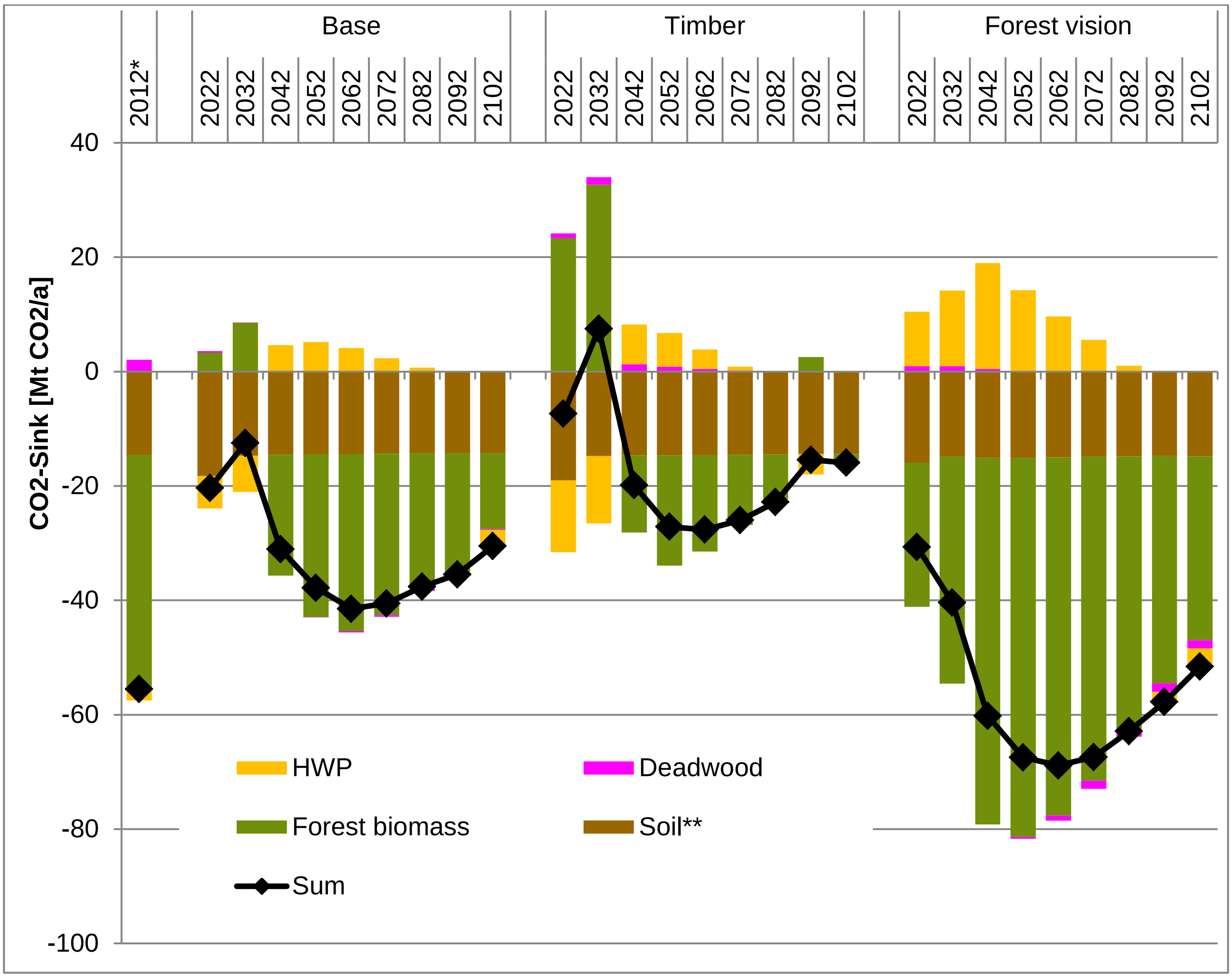
In the Forest Vision Scenario, emissions from the wood product pool increasingly occur because the pool levels are lower, and therefore the rate of decomposition exceeds the inflow. However, the capture of carbon in the forest is considerably higher than these losses. These emissions from wood products can be reduced by increased cascading use that renders wood products usable for longer periods of time, as well as reusable and recyclable. Finally, energy use should only be considered at the very end of wood use. However, assumptions on such developments have been excluded from the Forest Vision Scenario modelled here.

In 2015, soil contributed approx. 14 million t CO_2 to sequestration. Changes in soil carbon stocks were determined with the YASSO 05 soil model. The model was initialised with a spin-up run (see Chapter 2.3.2). This run causes carbon stocks in the model to be almost at equilibrium, i.e. neither to rise nor fall under the same management conditions. However, the mineral soil supporting forest habitats in Germany is probably a considerable carbon sink. In fact, the Germany annual inventory report (NIR 2017) to the UNFCCC included statements to that effect. The origin of this carbon sink may be found in its use history. For comparison of the current forest sink with historical data, the change of carbon stocks in the model was corrected for historical emissions. The differences between the individual scenarios are very slight. This observation matches literature data, which have so far failed to identify any major impacts of soil carbon management as long as forest residues remain in the forest (e.g. Achat, Fortin et al. 2015).

The 2015 Paris Agreement on Climate Change, an agreement between 195 member countries of the United Nations Framework Convention on Climate Change (UNFCCC), aims to limit anthropogenic global warming to well below 2 °C compared to pre-industrial levels. It is the successor of the Kyoto Protocol. As a contribution to the Paris Agreement, the European Union has set itself the goal of reducing its greenhouse gas emissions by 40% by 2030 in reference to levels recorded in 1990. In this context, forest management is expected to play a major role. In July 2016, the EU Commission published a proposal to integrate forest management into climate change mitigation efforts. For this purpose, similar to the Kyoto Protocol, reference levels that estimate future carbon emissions and removals of forests under the assumption of constant management intensity are to be determined. The proposal does not include any assumptions on future demand for wood but, similar to the present study, maintains current management practices as a forward-looking reference. The net emissions and removals actually achieved in the accounting period from 2021 to 2030 are then compared to this reference level. A positive deviation would be credited, whereas a negative deviation would count as a debit.

The Base Scenario applied here represents a projection of the historical management intensity of 2002 to 2012, so that the results of the Base Scenario can serve as a reference level for the accounting period. The reference level of German forests for forest biomass, soil and wood products would thus amount to 22 million t CO_2/a 2021 to 2030 (see Base Scenario for the years 2022 and 2032 in Figure 5-7). In reference to this, Germany could expect a 16 million t CO_2/a debit in case of the implementation of the Timber Scenario. In contrast, the implementation of the Forest Vision Scenario would result in a credit of 28 million t CO_2/a for the accounting period between 2021 to 2030.

Figure 5-7: CO_2 balance of forest biomass, deadwood, soil and wood product sequestration over time inferred from changes in carbon stocks



Source: own illustration, results of the FABio model. * Values reported by Germany to the UNFCCC in 2012 from the National Inventory Report 2017 (UBA 2017). **Changes in soil were estimated and extrapolated based on national reporting

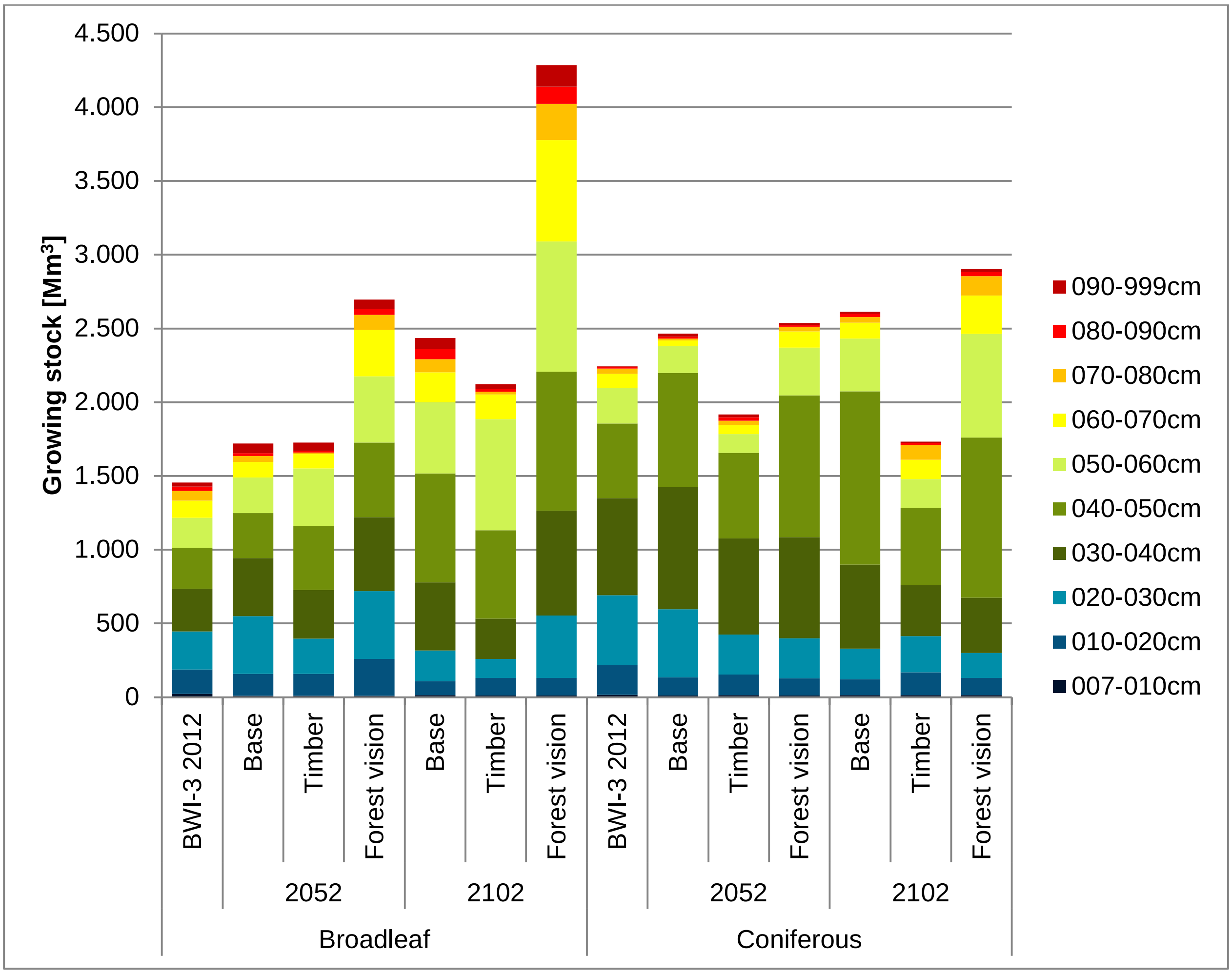
5.4. Thesis 4: Increase of the percentage of large trees in the forest

Figure 5-8 illustrates the growing stock itemised by diameter class for broadleaf and conifers separately for the years 2012, 2052 und 2102. Table 5-2 reports the corresponding distribution of the percentages. The distribution of the growing stock over different diameter classes reveals information on large-dimensioned trees in the forest. The type of management has a major influence on this. In the Base Scenario, 45 % of the growing stock of conifers falls into the diameter class between 40 to 50 cm. The percentage of conifer stock with a diameter up to 50 cm reaches 79 % in 2102, whereas its total is 74 % in the Timber Scenario. In contrast, the Forest Vision Scenario expects a distinct increase of large-dimensioned timber. Here, the diameter classes up to 50 cm account for only 61 % of the stock.

For broadleaf trees in the Base Scenario, the major share of the growing stock, i.e. 81 %, fall into the diameter classes up to 60 cm in 2102. In the Timber Scenario, diameter classes up to 60 cm account for an even larger percentage, 89 % of broadleaf trees are expected to measure below 60 cm in diameter. In contrast, the Forest Vision Scenario forecasts 72 % of broadleaf trees in diameter classes up to 60 cm in 2102. Nature conservation calls for trees in the diameter class of broadleaf trees over 80 cm in particular, since large-dimensioned trees provide considerably more habitat structures for endangered species. Broadleaf trees over 80 cm in diameter account for 2.4 % (50 million m^3) of the stock in the Timber Scenario in 2102, 5.9 % (144 million m^3) in the Base Scenario and 6.1 % (262 million m^3) in the Forest Vision Scenario. The absolute increase of broadleaf trees larger than 80 cm in the Forest Vision Scenario corresponds to an increase of 80 % in reference to the Base Scenario.

The Forest Vision Scenario sees a particularly strong development of mature broadleaf trees due to the fact that there is less harvesting of the medium diameter classes, more broadleaf trees can "grow up". In the Timber Scenario, this development trajectory is prevented by strong thinning activities in medium diameters. In addition, existing trees in strong diameter classes in the Forest Vision Scenario are used sparingly or not at all. Another contribution is made by the additional areas excluded from wood extraction, which harbour mainly old-growth stands.

Figure 5-8: Diameter distribution of the growing stock (remaining trees) for broadleaf and conifer species in 2012 and the scenarios in 2052 and 2102



Source: own illustration, results of the FABio model and data from BWI results database https://bwi.info/

Table 5-3: Diameter distribution of the remaining stands for broadleaf and conifer wood in 2012 and the scenario predictions for 2102 in %

Tree species group	Broadleaf				Conifer wood			
Year	2012	2102			2012	2102		
Scenario	BWI-3	Base	Timber	Forest Vision	BWI-3	Base	Timber	Forest Vision
007-010cm	1.6%	0.5%	0.5%	0.3%	0.7%	0.5%	0.9%	0.5%
010-020cm	11.3%	4.0%	5.6%	2.8%	9.0%	4.1%	8.9%	4.0%
020-030cm	17.8%	8.5%	6.0%	9.9%	21.1%	7.9%	14.1%	5.9%
030-040cm	19.8%	18.9%	12.9%	16.6%	29.4%	21.8%	20.1%	12.9%
040-050cm	19.0%	30.3%	28.1%	22.0%	22.6%	45.0%	30.2%	37.4%
050-060cm	14.1%	19.8%	35.6%	20.6%	10.7%	13.7%	11.2%	24.2%
060-070cm	8.0%	8.4%	7.8%	16.0%	4.3%	4.1%	7.6%	9.0%
070-080cm	4.5%	3.6%	0.9%	5.7%	1.6%	1.4%	5.7%	4.5%
080-090cm	2.0%	2.8%	0.9%	2.7%	0.5%	0.9%	0.9%	0.9%
090-999cm	1.9%	3.2%	1.5%	3.4%	0.2%	0.5%	0.4%	0.7%

Source: own presentation, results of the FABio model and data from BWI results database https://bwi.info/

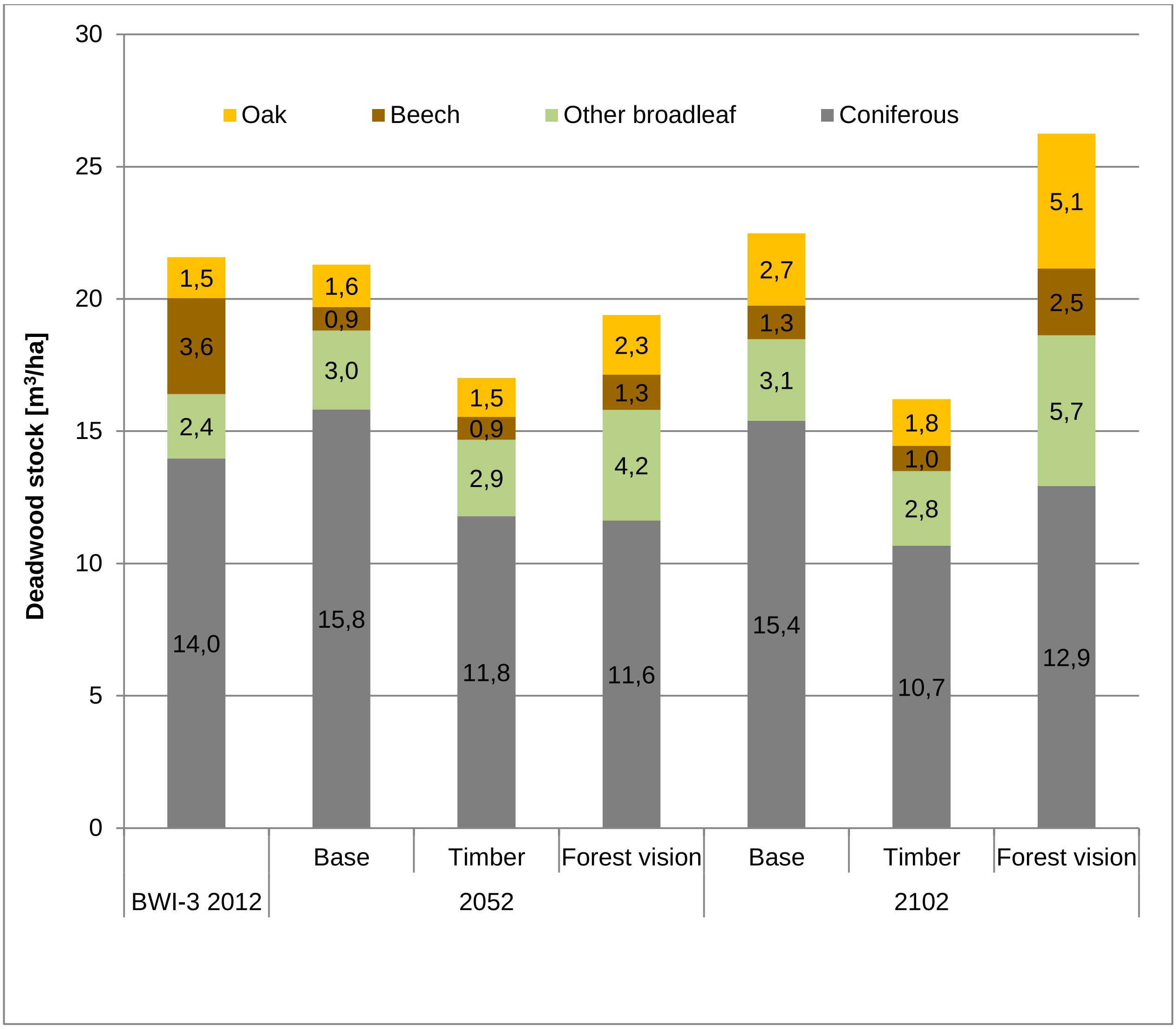
5.5. Thesis 5: Increase of deadwood stock

Figure 5-9 illustrates deadwood stocks as modelled in 2052 and 2102 for all three scenarios. BWI-3 values for 2012 are included for comparison. In the Forest Vision Scenario, the average deadwood volume in 2052 reaches 19 m³/ha. In the Timber Scenario, it is slightly lower with 17 m³/ha, whereas the Base Scenario with 21 m³/ha achieves slightly more. In 2102, the stocks show a more differentiated response. Then, the Base Scenario harbours an average deadwood stock of 22 m^3/ha, whereas Timber Scenario and Forest Vision Scenario reach 16 m^3/ha and 26 m^3/ha, respectively.

However, shifts in the species composition occur early on. For instance, in the Forest Vision Scenario, there is a particularly strong increase of the percentage of oak in the average deadwood stock. In 2052 , oak stocks amount to 2.3 m^3/ha and further rise to 5.1 m^3/ha in 2102, which equals a 40 % or almost 90% increase, respectively, in reference to the Base Scenario (1.6 or 2.7 m^3/ha). Beech deadwood stocks in the Forest Vision Scenario also exceed those of the Timber and Base Scenario on a similar scale. In comparison with the BWI-3 data, deadwood stocks for beech decrease until 2052 and continue to fall until 2102 in all scenarios. Reasons for this trend include a relatively low mortality in beech trees, and a relatively fast degradation rate compared to other tree species groups. It is difficult to initialise the model with average deadwood stocks adapted from the National Forest Inventory because the model logic cannot necessarily explain the observed stocks. This would require extensive modelling of historical management not feasible here. In consequence, the decrease and other changes compared to 2012 are partly an artefact of the model algorithms.

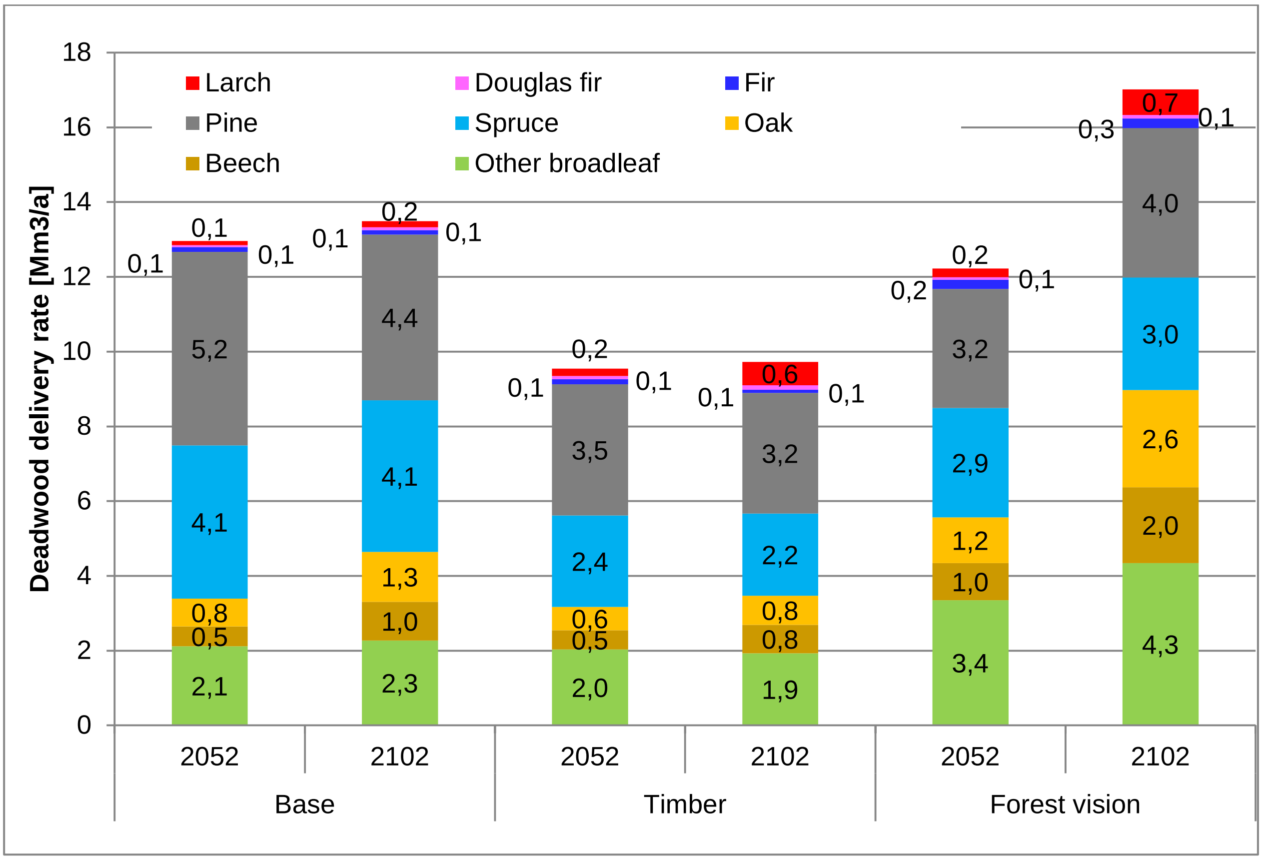
Figure 5-10 shows the delivery rate for deadwood, or natural mortality, over time for the three scenarios. The mortality model calculates tree death depending on tree species, age, diameter, and also stock density. In the Base Scenario, the latter rises slightly between 2052 and 2102 with the growing stocks. In the Timber Scenario, it remains below the Base Scenario in both years. In the Forest Vision Scenario, mortality in 2052 equals that of the Base Scenario, then increases sharply, especially for broadleaf tree species.

Figure 5-9: Shares of key tree species groups on the average deadwood stock in 2012 (BWI-3), 2052 and 2102



Source: own illustration, results of the FABio model and data from BWI results database https://bwi.info/

Figure 5-10: Deadwood delivery rate of different tree species in 2052 und 2102 for the three scenarios



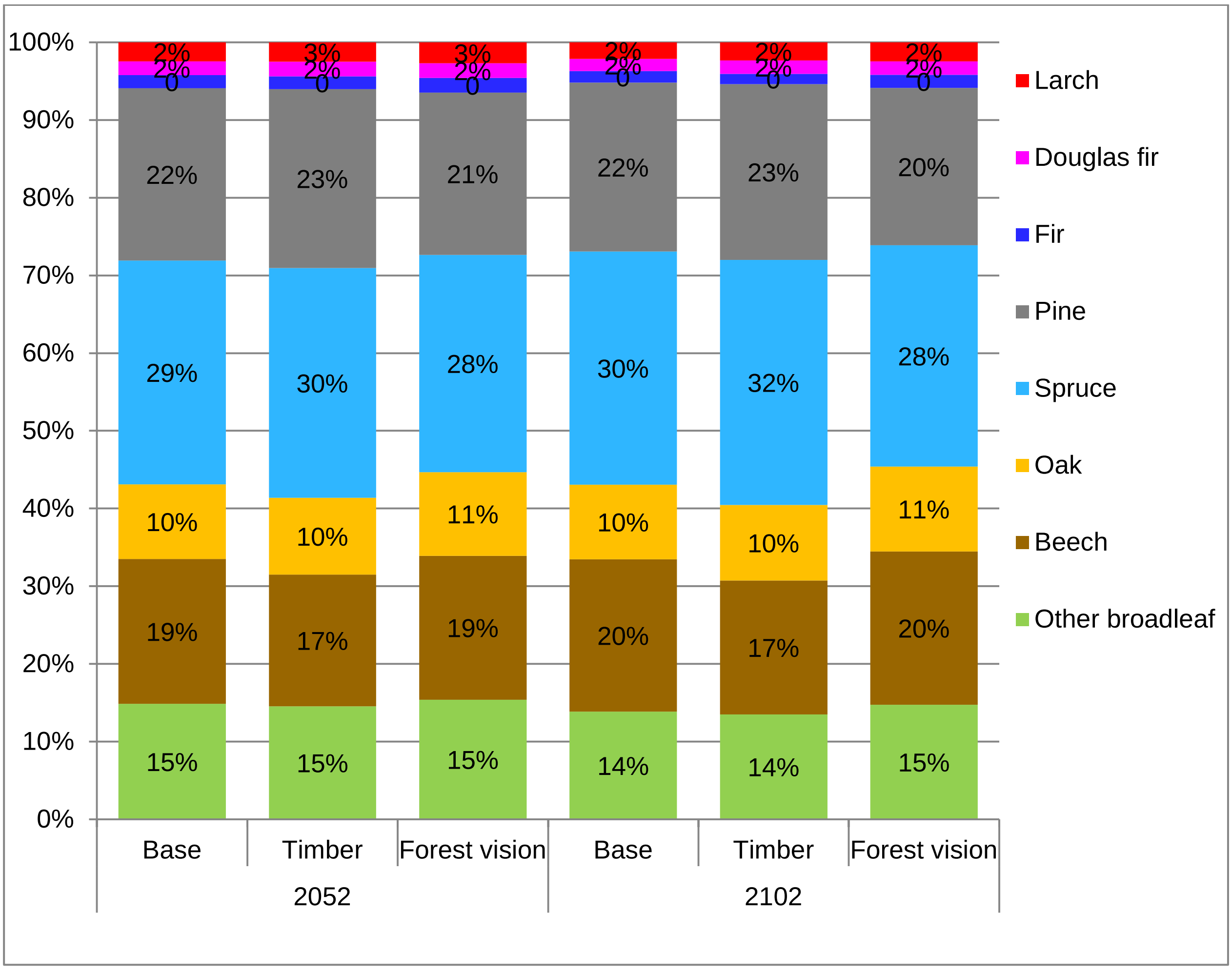
Source: own illustration, results of the FABio model

5.6. Thesis 6: Increase of naturalness and share of broadleaf tree species

Figure 5-11 reveals that the distribution of tree species in percent of the area shifts less than the stock percentages (see Figure 5-2). In the Base Scenario, there is a slight shift to more broadleaf area over the model period from 2012 to 2102 (+ 100,000 ha or approx. 0.9 % of the forested area in Germany). In contrast, areas with Broadleaf stands decrease by 140,000 ha (1.4%) in the Timber Scenario. Spruces are the main beneficiaries of this trend. In the Forest Vision Scenario, however, the share of broadleaf trees of the total area in the year 2102 exceeds the level of 2012 by approx. 350,000 ha (3.3 %). Moreover, it exceeds the level expected in the Base Scenario by 250,000 ha (2.4 %), mainly at the expense of the area supporting conifer forest. In consequence, broadleaf trees cover 47 % of the area in the Forest Vision Scenario in 2102. Beech stands in particular increase in comparison with the initial conditions of the model (approx. 250,000 ha, or 2.4 %). The increase of broadleaf area is expected at sites where broadleaf trees are part of the natural vegetation. Thus, forest naturalness increases for these locations. However, during the implementation of forest restructuring, no deliberate planting takes place and measures are limited to a tending of tree species already present. First, the existing tree species in the old stand are expected to regenerate. Then randomly new species are added. Therefore, species shifts in the Forest Vision Scenario take place with relatively minor annual changes in area.

In sum, the combination of results for the change in stocks and the change in the composition of the diameter classes per tree species in the Forest Vision Scenario reveals that increasing forest naturalness is not a function of increasing the area covered in broadleaf trees per se. In fact, increasing naturalness is correlated with the change in stock percentages. Broadleaf forests are most likely to evolve towards more natural stands characterised by increased stocks of large-dimensioned broadleaf trees in particular.

Figure 5-11: Share of tree species of total forest area



Source: own illustration, results of the FABio model, results of the FABio model

5.7. Thesis 7: Decrease and shift of potential wood supply

As expected, the implementation of the assumptions of the Forest Vision Scenario leads to a lower potential wood supply due to the fact that an additional 12% of the forested area are no longer managed or used for forestry purposes. Moreover, the management intensity of the remaining forest is substantially reduced. Figure 5-12 illustrates the average timber yield of the period 2012-2102 for the individual tree species groups in the three scenarios.

Over the simulation period of 90 years (2012-2102), the average potential wood supply in the Forest Vision Scenario amounts 5.1 m^3/a/ha. This value about 25 % lower compared to the Base

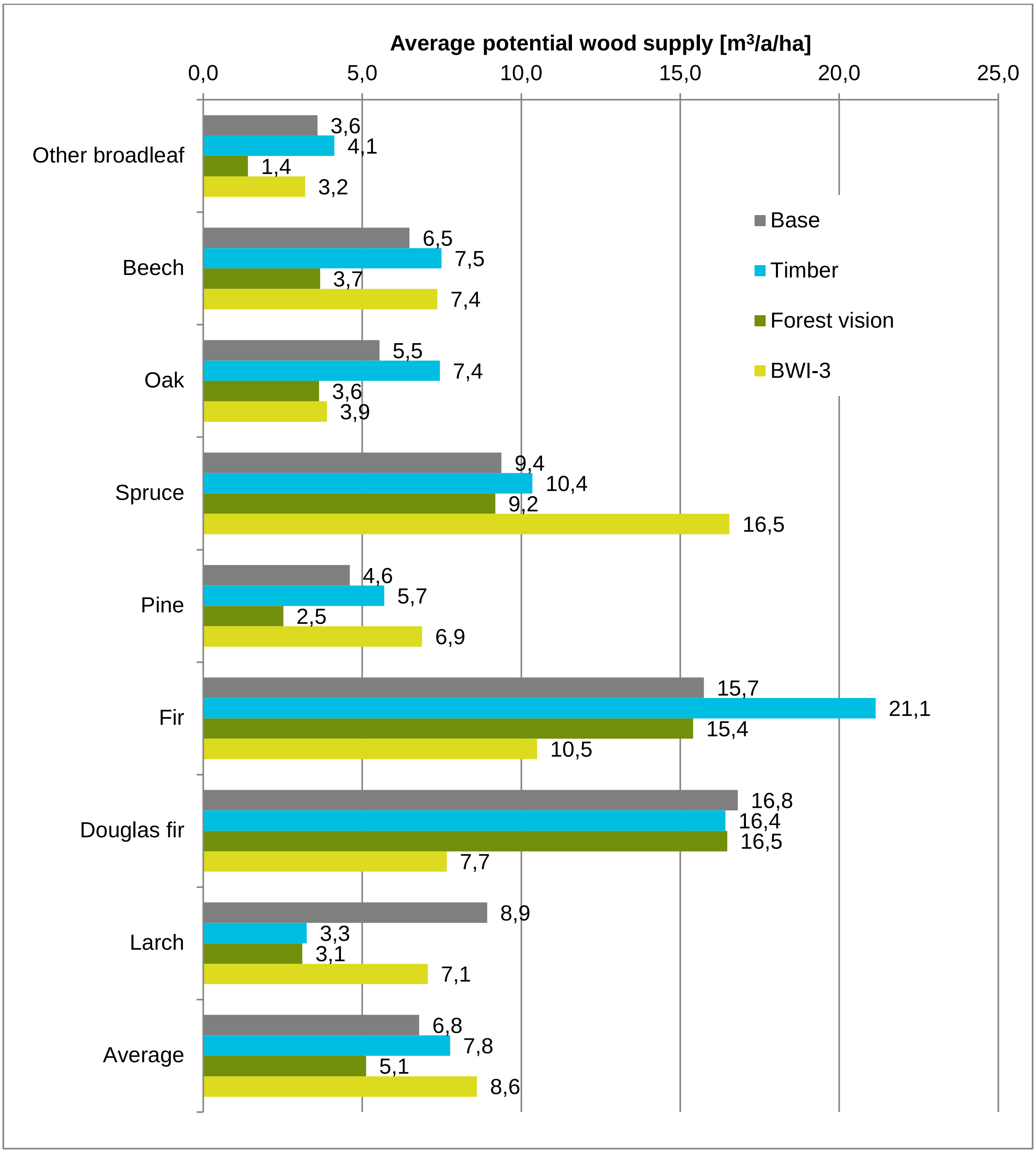
Scenario (6.8 m^3/a/ha). In contrast, with an expected yield of 7.8 m^3/a/ha in the Timber Scenario, the increase in potential wood supply is 14% compared to the Base Scenario. On average wood supply expected in the Base Scenario is as high as the inventory recorded between 2002 and 2012 as realized harvest rate (8.6 m^3/a/ha). Lately wood production in Germany decreased slightly (Jochem et al. 2013) and was about 8 m^3/a/ha in 2015.[9] The scenarios describe the potential wood supply that can sustainably be realized following the management rules implemented in the model. These figures form the potential and not the eventually realized removal from the forest as they depend on demand and other influencing factors that have not been included in the model.

Analysis of the timeline for yield presented in Figure 5-4 (see Chapter 5.2) reveals that from 2023 to 2052, the expected harvest volume in the Forest Vision Scenario is 36 % lower than that of the Base Scenario. In the last three decades, this difference is reduced to 15 %. In all likelihood, this difference in yield will continue to decrease in the period after 2102. In addition, significantly more large-dimensioned trees are harvested in the Forest Vision Scenario. This can potentially increase the value of timber production despite lower yields. The wood volume for spruce barely changes compared to other scenarios due to the expected intensive use of this tree species.

Figure 5-13 shows the harvest volume in the first half and the second half of the simulation period. It clearly illustrates that the initial reduction in harvested wood volume in the Forest Vision Scenario is not permanent, but will increase again towards the end of the projection period. At this time, there is also a shift of harvested timber to more large-dimensioned wood, especially in the broadleaf tree species. In fact, the Forest Vision Scenario expects the harvesting of an average of 9 Mm^3 broadleaf trees in the diameter class 60-70 cm and 1.7 Mm^3 broadleaf trees in the diameter class 70-80 cm in the period from 2053 to 2102. In the Base Scenario, the expected volumes for these diameter classes only amount to 1 Mm^3 and 0.2 Mm^3, respectively. A change in the use of wood was not explicitly modelled. Due to the higher proportion of large-dimensioned timber, however, there are automatically slight changes in the sorting of wood. Indeed, the increased emergence of large-dimensioned timber represents a technological challenge for harvesting and sawmill industry. The harvesting methods with so-called full harvesters developed in Germany in recent years as a result of mechanisation are suitable for small and medium-dimensioned timber. Therefore, a higher volume of large-dimensioned timber would require more motor-manual processes that would also benefit soil protection. Larger timber does not always generate higher revenues. A devaluation of the wood at a later age is also a risk. Accompanying measures for the activation of value-added potential in the use of large-dimensioned timber are therefore important (Bäuerle et al. 2009).

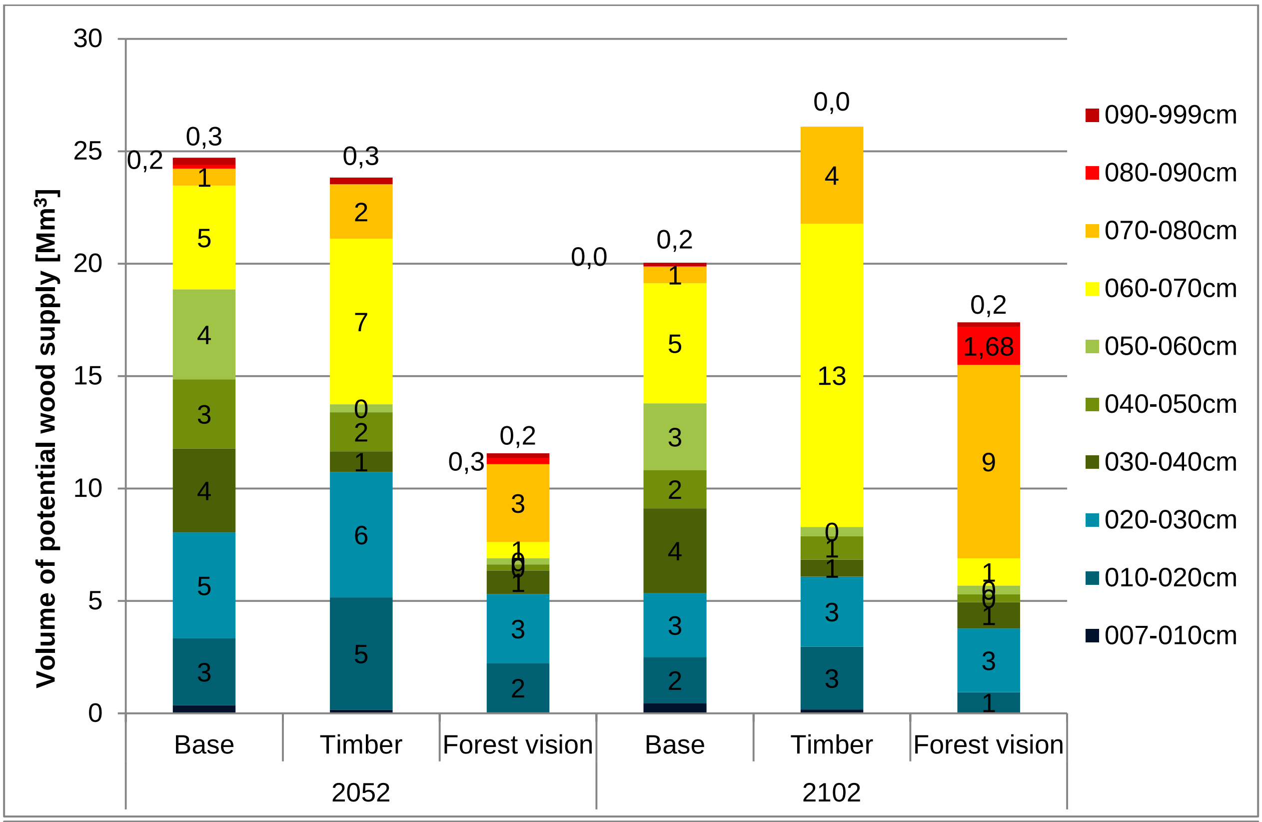
[9] https://www.thuenen.de/de/wf/zahlen-fakten/waldwirtschaft/holzeinschlag-und-rohholzverwendung/

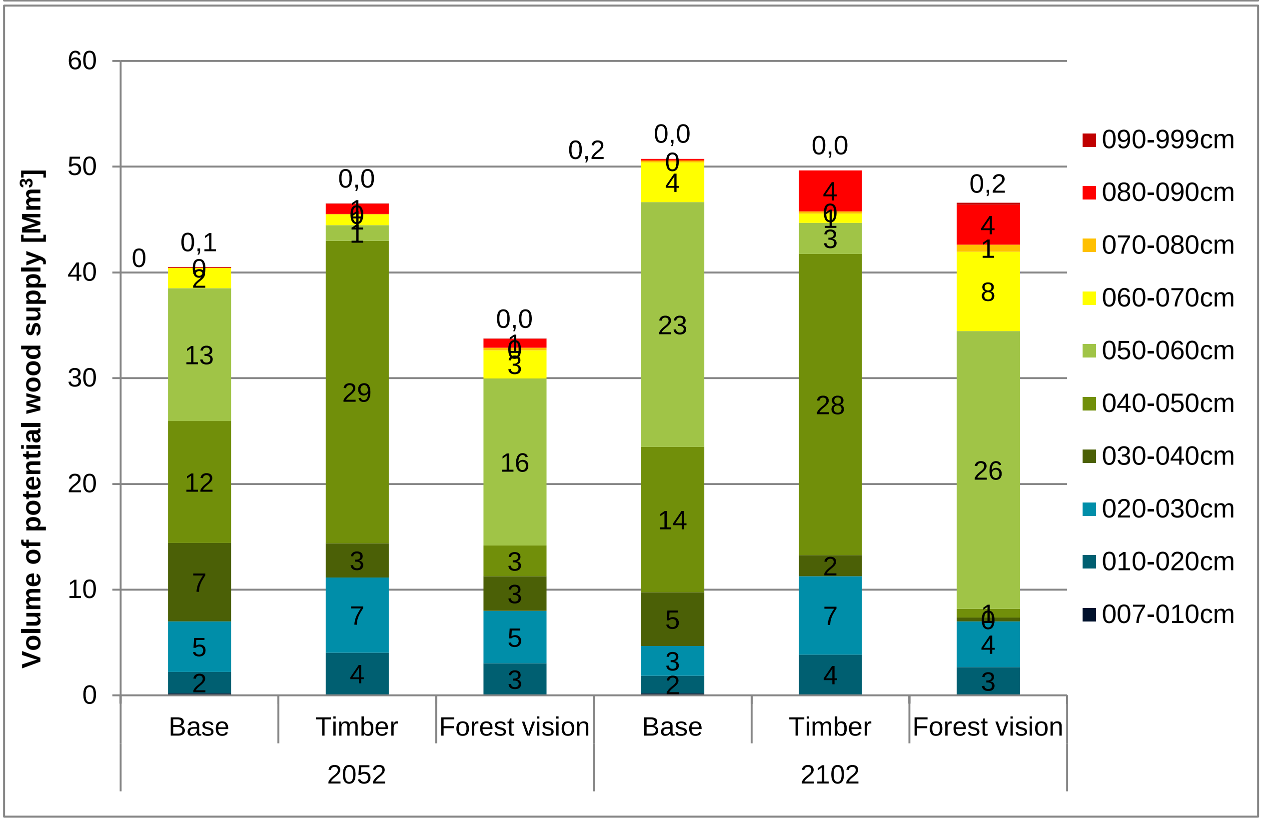
Figure 5-12: Average potential wood supply in the scenarios (2012-2102) and in comparison with BWI-3 data on wood production for tree species groups



Source: own illustration, results of the FABio model and data from BWI results database https://bwi.info/

Figure 5-13: Volume of potential wood supply by diameter class in 2052 and 2102 (broadleaf top, coniferous bottom) in million m³ per year





Source: own illustration, results of the FABio model

6. Discussion

The FABio model was parameterised based on the dataset provided by the National Forest Inventory in the censuses carried out for the BWI-2 (2002) and BWI-3 (2012). As explained in the chapter on model boundaries, the results of the model runs have to be interpreted in reference to this database. The system boundaries of the model, especially with regard to the carbon balance and the assumptions in the scenarios, are also important framework conditions for interpretation. The following discussion addresses the results for stock and increment development, considers nature conservation aspects, in particular deadwood, as well as the carbon balance of the forest.

6.1. Development trajectory of growing stock and increment

The model estimate of 686 m^3/ha of average stock across the total forested area in the Forest Vision Scenario in 2102 is high. It results from growing stocks in forest stands excluded from wood extraction that occupy 16.6 % of the area and areas under forest management and extensive timber production over the course of 90 years. Average stocks per hectare in 2102 achieve levels that equal natural forests, but do not occur in commercial forests as a rule. In the Forest Vision Scenario, beech stocks in the year 2102 average 990 m^3/ha. Such stocks are known from core areas in natural forests, but also from primary beech forests. Tabaku (1999) found growing stocks of 800 m^3/ha in primary beech forests in Albania, whereas Drössler (2006) reported growing stocks of up to 1000 m^3/ha in the optimal succession stage of primary beech forests in Slovakia.

Beech stands under natural development conditions were modelled with an average of 600-700 m3/ha across succession stages (Rademacher & Winter 2003). BWI-3 data reveal that 4 % of section points harbour stocks exceeding 800 m^3/ha. A further 12 % of stocks exceed 600 m^3/ha, primarily spruce and beech stands.

The high stock levels expected in the Forest Vision Scenario are rarely observed in managed forests in Germany. Therefore, the growth of such stands can only be validated with anecdotal data from very few sites. In the literature, high increments are frequently observed in natural beech forests, even at high stock densities (Korpel 1995). The deciding factor is not density, but the succession stage (Rademacher & Winter 2003). During the optimal stage, increment can reach up to 15 m^3/a/ha, yet it decreases sharply in the decay phase. Due to the ongoing management of beech forests in the Forest Vision Scenario, it is safe to assume that the decay phase plays a minor role for no more than a few of the naturally managed stocks during the simulation period. However, please note that the inference of model parameters from National Forest Inventory data leads to assumptions with high uncertainties for the development of near-natural stocks because conditions in the few existing stands with high growing stock in Germany are not captured sufficiently by the inventory.

The annual stock increment is in fact governed by factors such as climate and site-specific soil ecology, but also by stand structure, which is ultimately influenced by management. In the model, increment specifically depends on the height and diameter of the individual tree, site productivity, and the density of the surrounding stand. With higher growing stocks and share of broadleaf tree species, the increment increases as the growth curve of broadleaf trees typically has later culmination points (Kramer 1988). Many conifers culminate earlier; in consequence, longer rotations or higher target diameters are usually associated with a reduction in the average increment. Due to different demands on the habitat, a mixture of tree species often results in the different tree species complementing each other in increment and stock development, i.e. compensation of mortality or disturbance (Pretzsch 2003). The growth behaviour in mixed and pure stocks was not part of the investigation here. However, in natural forest development, the percentage of mixed stocks increases over time, which also contributes to the development of stocks and increment, but this effect cannot be quantified separately.

6.2. Considering nature conservation aspects - deadwood

From a nature conservation perspective, the supply of deadwood as both habitat and food for countless deadwood specialists in the forests in Germany is insufficient, particularly for broadleaf trees. For example, about half of the endangered xylobiont beetle species in Germany included on the IUCN Red List depend on deadwood structures, and in particular on the deadwood of native broadleaf tree species. Oaks are particularly important in this context (Reise et al. 2017). The absolute increase of deadwood volumes of relevant tree species in the Forest Vision Scenario can be seen as a contribution to nature conservation. However, the relative percentage of dead trees in the total stock does not increase, and at 5% is far below the levels of 20-40 % expected in primary forests (Nilsson et al. 2002).

Deadwood stocks in the model are most strongly correlated with mortality in forest stands, which is the underlying cause of deadwood supply and depends on the diameter, basal area of the larger trees (a measure of the density of the stands), and tree age. The intensified use in the Timber Scenario leads to the lowest deadwood volumes, since density and consequently mortality are reduced by intensified harvesting of trees. However, the substantially reduced use in the Forest Vision Scenario is also not associated with an immediate increase. In the period up to 2052, the mortality of relatively young trees does not rise significantly despite increasing stocks. Although mortality levels reach on average about 15 % of the increment after 2052 and thus exceed the Base Scenario, they are still very low in comparison to primary forests (Drössler 2006; Tabaku 1999).

The deadwood stocks in natural forest in Lower Saxony measured by Meyer (1999) ranged between 9 and 79 m^3/ha. The Forest Vision Scenario achieves an average of 26 m^3/ha by 2102. However, especially for oak forests, tree mortality cannot be explained by competition alone, and disturbances seem to play a major role (Meyer & Mölder 2017). Disturbance as an explicit factor is excluded from the model, although they are implicitly incorporated into the parameterisation of mortality based on BWI data. Therefore, the results of the calculated amounts of deadwood in modelled oak stands, especially in the uncultivated areas, are associated with considerable uncertainties.

Deadwood stocks measured in primary beech forests in Slovakia ranged between 30 and 130 m^3/ha (Drössler 2006). However, the beech deadwood stocks in the Forest Vision Scenario are distinctly lower. Again, it can be assumed that natural mortality is underestimated in the model due to the fact that the only factors defining mortality here are density of stands, age and diameter. Deadwood stocks in forests that have been extensively managed or excluded from wood supply only build up through the natural aging process and as a result of disturbance. In consequence, it is all the more important to protect and develop existing old-growth forests and deadwood stocks.

6.3. Forest sink and carbon balance

The development of the carbon sequestration capacity of forest biomass is highly correlated with the stock development. The average sequestration of 48 million t CO_2/a over the 90-year period calculated in the Forest Vision Scenario is similar to that of previous years. The annual net CO_2 uptake increases initially to 65 million t CO_2/a and then continuously decreases. Simultaneously, stocks almost double and forests reach a greater age on average. This observation reveals that old-growth forests are not only important carbon sinks, but are able to still absorb considerable quantities of carbon in later stages of development. This persistent sequestration capacity was also demonstrated in natural forests with gas exchange measurements (Knohl et al. 2003) Overall, there is increasing evidence contradicting the widespread assumption that old-growth forests lose the ability to absorb carbon (Köhl et al. 2017; Luyssaert et al. 2008; Stephenson et al. 2014). Instead of tree age, the forest structure determines the net exchange between atmosphere and plants, i.e. via the existing leaf area (Schulze et al. 2009).

The saturation effects of the forest sink observed by some authors in managed forests also (Nabuurs et al. 2013) do not necessarily imply that the sink can only be maintained by intensified use (Nabuurs et al. 2015). Instead, more extensive management is required to replenish carbon stocks depleted in the past (Naudts et al. 2016).

In addition to storing carbon in forest biomass, dead wood and soil, the use of harvested wood is also an important component for the overall climate impact, i.e. the effect of the forest and its use on the CO_2 concentration in the atmosphere. From a climate protection point of view, a long carbon residence time in wood products is important. The residence time depends on the lifespan of the wood products and the degree of recycling. For example, the GHG balance of timber products can be improved through increased cascade use, i.e. the multiple use of wood as a raw material (Gärtner et al. 2013; Sikkema et al. 2013). The use of energy would thus only be put to the very end of the use of wood. Increased recycling and increased durability of wood products can lead to an increase in the resource efficiency of wood utilisation. As a result, the demand for fresh timber could be reduced and thus the pressure on the forest to use it could be reduced. Such accompanying measures are necessary prerequisites for the extensification of forest management, as implemented in the Forest Vision, in order to prevent increased imports of timber and the transfer of negative effects abroad. It should be emphasised that the CO_2 balance of the other scenarios would also benefit from such an increase in resource efficiency. However, the more intensive scenarios are offset by the fact that a high degree of climate protection can be achieved in the forest vision together with a high degree of nature conservation.

In addition to storing carbon in wood products, wood can replace other materials and raw materials such as aluminium, steel and concrete, which require a lot of energy to produce and therefore cause high CO_2 emissions, thus reducing emissions from production. This so-called substitution effect presupposes that these materials cause more emissions than the use of wood. This is still the case for many materials today. Assuming constant substitution factors, the intensification of management over a long period of 50-300 years can be better off than extensification from the perspective of an overall GHG balance (Böttcher et al. 2012; Mund et al. 2014). However, the assumption of constant substitution factors is questionable and only provides a theoretical potential. It is difficult to estimate how much emissions can actually be avoided by substitution. In order to make a solid estimate for the use of wood in Germany as well as abroad (part of the wood harvested in the future is expected to be exported), it would be necessary to establish precise allocations of wood products to non-wood alternatives with regard to their functionality and comprehensive life cycle analyses of the products, by-products and their disposal. Such an analysis could not be carried out in the project. The model therefore does not take into account the substitution effects of the harvested wood, which must be taken into account when interpreting the results. Detailed literature values according to the latest DIN regulations, which require, for example, a distinction to be made between the use of renewable and non-renewable resources, are only available for a few uses, such as timber construction (Hafner et al. 2017). While flat-rate substitution factors for the use of wood do not make an exact allocation to products, but instead describe a theoretical potential (Sathre et al. 2010), a calculation in accordance with standards assigns the wood products to entire functional units and determines the GHG savings through the use of wood for the entire unit, e. g. a prefabricated house. It should be kept in mind that CO_2

emissions from substituted products are likely to be reduced over the next few decades by replacing coal, oil and gas with renewable energy sources. As a result, the contribution to reducing emissions from the use of wood will decrease or could also become negative.

In addition to reducing forest loss and promoting forest reforestation, the potential of natural forest management and regeneration is perceived globally as a cost-effective natural measure for climate change mitigation (Natural Climate Solution). Its contribution to the prevention of dangerous global warming and achievement of the Paris 2 ° goal is calculated to range between 0.5-1.5 Gt CO_2/a (Griscom et al. 2017). Additional benefits associated with this, such as positive effects for nature conservation, are an important argument. The scenario Forest Vision clearly shows that this needs not to be limited to developing countries, but can also be applied in industrialised countries with forests under intensive management.

7. Conclusions

The present study clearly illustrates that measures promoting more nature conservation in forests may be adequately modelled with the forest model FABio based on publicly available input data from the German National Forest Inventories, which provide robust, realistic and informative output. The measures proposed in the Forest Vision Scenario include not only forest restructuring to support the growth of broadleaf trees, but also a reduction of management intensity and an increase of the target diameter, and the protection of areas relevant for nature conservation, such as rare forest types or old-growth forests.

In the Forest Vision Scenario, 84 % of the forested area is extensively used and thus contributes to timber production. However, the model results clearly illustrate that the proposed measures can increase growing stocks in Germany. At the same time, conservation efforts are substantially improved (e.g. due to more mature trees and more deadwood, especially for broadleaf trees) and productivity, especially of broadleaf trees (beech 19 %, oak 25 %, other broadleaf species 20 %), is considerably increased. Below, a specific conclusion for each of the initial theses is drawn:

Thesis 1: Considerable increase of average growing stock in forests

There is strong evidence that a very substantial build-up of growing stock can be achieved with the measures proposed in the Forest Vision Scenario. Compared to the Base Scenario, the average stock could be increased by 28 % and 42 % by 2052 and 2102, respectively. The increased stock development in the Forest Vision Scenario leads to significantly more stock of broadleaf trees and more large-dimensioned trees. In consequence, positive effects for biodiversity conservation may be expected, as old broadleaf trees provide important habitat structures for endangered species.

Thesis 2: Constant or increased forest increment

The results of both the Forest Vision and the Timber Scenario compared to the Base Scenario clearly show that the extensification proposed in the Forest Vision leads to significantly increased increment. In contrast, intensification as proposed in the Timber Scenario reduces wood increment. This result distinctly highlights that forest restructuring towards broadleaf trees and large-dimensioned trees does not reduce forest productivity (in broadleaf and conifer wood). On the contrary, productivity is increased. The long-term perspective beyond the year 2052 suggests that this insight has the potential to restructure forests in Germany into near-natural forest stands with high stocks and high productivity. Such a strategy would be advantageous for both the carbon sink function of the forest and for its biodiversity, since these stocks harbour a much greater number of relevant habitat structures. Such habitat diversity cannot be expected in more intensively managed younger forest stands.

Thesis 3: Increased forest net carbon uptake

The immediate implementation of the measures proposed in the Forest Vision Scenario would lead to a 30 % increase of carbon stocks in the forest by 2102 compared to the Base Scenario. In the Forest Vision, the CO_2 sequestration of the forest sink would remain at similar levels as in the past. The stock of wood products, however, decreases slightly due to reduced wood use. This trend can be neutralised if the average lifespan of wood products is increased, e.g. by reducing the direct use of wood for energy purposes, especially for harvested broadleaf trees. In the Timber Scenario, however, the forest sink in German forests would be reduced to zero.

Thesis 4: Increase of high-diameter trees

The reduction of the thinning intensity and focus on target diameter use, as well as a significant increase of the percentage of protected areas excluded from wood extraction, result in more mature trees remaining in the forest. This effect of the implementation of the measures proposed in the Forest Vision Scenario manifests itself quickly and reflects the urgency of the measure. If the Base Scenario is maintained without change, a major share of the old-growth trees of tomorrow is irretrievably used today. This observation exposes how swift an implementation of the Forest Vision is required to sustainably promote the development of old-growth stands, promptly and in time.

Thesis 5: Increase of forest deadwood volume

The measures in the Forest Vision Scenario do not immediately increase deadwood stocks. In reference to 2012, deadwood stocks are accumulating rather slowly, yet in 2102 do exceed those of the Base and Timber Scenario. Moreover, there is a shift in tree species distribution. Medium deadwood stocks for broadleaf trees species increase, whereas conifer stocks are in decline. This in turn has a positive impact on biodiversity, as endangered xylobiont species are often dependent on broadleaf deadwood.

Thesis 6: Restoration promotes forest naturalness and increases the percentage of broadleaf trees

The implementation of the Forest Vision increases the share broadleaf species of the overall forest growing stock. The increase of both the stock and the area percentage through introduction of extensified management and forest restructuring is often carried out in locations dominated by non-natural conifer wood. However, in the 90-year simulation period, change in use (extensification or zero-use) in existing broadleaf forests is the most relevant factor. In response to such change, naturalness in the respective stands soon develops, in particular through the increase in highly dimensional broadleaf trees, which is strongly correlated with positive effects on biodiversity.

Thesis 7: Decrease of wood volume and shift towards large-dimensioned wood

In the Forest Vision Scenario, an additional 12.5 % of the forest is taken out of use. On a total of almost 84 % of the area, the forest is managed extensively. The model results of the Forest Vision Scenario reveal that the amount of timber produced is about 25 % lower than yields in the Base Scenario. From an economic point of view, the reduction in timber production means a reduction in revenue for forest owners. In order to compensate for this, suitable subsidies for increased climate and nature conservation efforts are advisable.

The necessary restructuring of the wood industry to accommodate modified wood products does not have to happen overnight. Instead, adaptation or conversion of processing methods due to changes in tree species composition can be carried out over several decades. However, in the field of direct energy use of wood, a substantial reduction is definitely required.

At present, approx. half of the wood consumption in Germany is used for energy purposes. However, the energetic use of wood today and in the future can be increasingly replaced by other renewable energy resources, and in all likelihood, future substitution effects in the energy sector will decline. In light of these facts, the climate impacts of the Forest Vision Scenario appear the better choice. Building on substitution effects through the more intensive management of forests as a GHG mitigation measure alone is counter-productive with respect to nature conservation goals.

The implementation of the Forest Vision can make an important contribution to the achievement of nature conservation goals and to climate protection. This makes it clear that ambitious climate and nature conservation goals in the forest do not have to be mutually exclusive. On the whole, however, a significant increase in the efficiency of wood use through more material and less direct energy use and an increase in the cascade use of wood for a more sustainable use of resources and better climate protection are prerequisites.

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Annex 1: Glossary

Basal area — Sum over all stems' cross-sectional area at 1,3 m height above the ground. Included are all stems with a diameter at breast height above 7 cm.

BWI — German National Forest Inventory

Carbon balance — Balance of uptake of carbon as CO_2 through photosynthesis and release through mortality of trees and decay of plant material, as well as harvest removals. In an extended carbon balance of the forestry sector carbon stored in harvested wood products is also considered.

CO_2 sink, sequestration — Net uptake of CO_2 by ecosystems (forests) that absorb more CO_2 through photosynthesis than they emit through processes of decay. Harvest of wood counts as an emission of CO_2. Harvested Wood Products can be considered in the carbon balance of the forestry sector but cannot act as CO_2 sinks.

Cubic meter (over bark) — Metric for measuring timber volume including bark and harvest residues for forest planning, harvest operation and timber sales.

Cubic meter (under bark) — Metric for measuring timber volume excluding bark and harvest residues for forest planning, harvest operation and timber sales.

Diameter at breast height (DBH) — Stem diameter at a height of 1.3 m above the ground.

FABio — Forestry and Agriculture Biomass Model

Forest stand — Management unit of a forest; part of the forest that can be differentiated by tree species, age or structure.

FSC — Forest Stewardship Council

Growing stock — Merchantable timber volume of a forest stand measured in cubic meters.

Growing stock available for wood supply — Potentially sustainably available harvest volumes of solid wood, measured in cubic meters, that can be achieved under the management rules taken into account in the model.

Harvest residues — Primary forestry residues that are a result of harvest operations in the forest. Harvest residues consist of stumps, stem ends, tree tops and other non-merchantable wood as well as lower quality or rotten parts of the stem and small trees.

Industrial timber — Wood of lower dimension or lower quality that is not considered stem wood. It is used for wood-based panels and pulp and paper production. In FABio the amount of industrial timber is estimated based on the diameter of harvested stems.

Merchantable timber volume — Aboveground wood volume with a diameter larger than 7 cm, including bark. Trees with a diameter at breast height below 7 cm are not considered in the merchantable timber volume.

Natural forest development   Forest development without interference by humans through harvest or artificial regeneration.

Natural regeneration   Regeneration of a forest through natural reproduction of the stand, i.e. seed dispersal from remaining trees after harvest or resprouting from tree stumps.

Naturalness   Naturalness compares the currently occurring tree species composition with the potential natural vegetation.

Potential natural vegetation   The vegetation that would be expected given environmental constraints (climate, geomorphology, geology) without human intervention or a hazard event.

Private forest land   Forests in the hands of legal persons, business corporations or foundations under private law.

Public forest land   Forests in the hands of the state, federal state or other public institutions.

Regeneration   Regeneration includes the natural or artificial establishment of a forest stand. Natural regeneration is realized through seed dispersal or resprouting from stumps. Artificial regeneration includes planting or sowing of trees.

Section point   One sampling plot of the German National Forest Inventory.

Site productivity   Classification of forest stands by a relational system. The model considers site productivity of each inventory sample point by normalizing stand volume increment per stand volume into a scale between 0 (lowest productivity) and 100 (highest productivity).

Stand structure   Qualitative and quantitative composition of a forest stand regarding spatial and temporal differentiation.

Stand type   Stand type characterizes the species composition of a forest stand. The model differentiates single-species and mixed stands. In single-species stands the leading tree species occupies at least 80% of the basal area. In mixed stands other species together make up more than 20%. Mixed stands are differentiated by mixed with needle-leaved or broadleaved species. In combination with the eight tree species groups in total 27 stand types are differentiated.

Stem wood   Part of the harvested merchantable timber volume that is considered as sawlogs or veneer logs. In FABio stem wood is estimated based on tree species and minimum stem diameters.

Stock maintenance   Stock maintenance is a treatment type within silvicultural management plans. It aims at supporting the growth of large dimensional timber and foresees the extraction of lower quality stems, early harvest of mature trees and preparation of the regeneration phase.

Target diameter   Diameter at breast height of trees to determine maturity of single trees.

Thinning	Removal of trees, maybe of lower quality and those impeding higher quality trees, before stand maturity. Thinning aims at concentrating stand increment on vital trees of high quality.
Treatment type	The treatment type specifies the silvicultural practice (tending of young stands, thinnings etc.) of forest stands at a certain development stage following a management plan.
Tree species group	FABio differentiates 24 tree species groups that include tree species with similar properties. Results are further aggregated to eight species groups as considered in the German National Forest Inventory (spruce species, pine species, fir species, larch species, Douglas fir, beech species, oak species, other broadleaved species
WEHAM	Forest development and wood supply model developed by Thünen Institute
x-wood	Section of the stem not considered merchantable timber.

Annex 2: Model parameters and settings

Table A-1: List of stand types in FABio

	Name	Description
BU-R	Beech-Pure stand	Share of basal area Beech above 80 %
BU-ML	Beech-Mixed stand with broadleaf trees	Share of basal area Beech under 80 %, Mischbaumarten sind Laubbaumarten
BU-MN	Beech-Mixed stand with conifers	Share of basal area Beech under 80 %, Mischbaumarten sind Nadelbaumarten
EI-R	Oak-Pure stand	Share of basal area Oak above 80 %
EI-ML	Oak-Mixed stand with broadleaf trees	Share of basal area Oak under 80 %, Mischbaumarten sind Laubbaumarten
EI-MN	Oak-Mixed stand with conifers	Share of basal area Oak under 80 %, Mischbaumarten sind Nadelbaumarten
FI-R	Spruce-Pure stand	Share of basal area Spruce above 80 %
FI-ML	Spruce-Mixed stand with broadleaf trees	Share of basal area Spruce under 80 %, Mischbaumarten sind Laubbaumarten
FI-MN	Spruce-Mixed stand with conifers	Share of basal area Spruce under 80 %, Mischbaumarten sind Nadelbaumarten
KI-R	Pine-Pure stand	Share of basal area Pine above 80 %
KI-ML	Pine-Mixed stand with broadleaf trees	Share of basal area Pine under 80 %, Mischbaumarten sind Laubbaumarten
KI-MN	Pine-Mixed stand with conifers	Share of basal area Pine under 80 %, Mischbaumarten sind Nadelbaumarten
AL-R	Other broadleaf trees-Pure stand	Share of basal area Other broadleaf trees above 80 %
AL-ML	Other broadleaf trees-Mixed stand with broadleaf trees	Share of basal area Other broadleaf trees under 80 %, Mixed species are broadleaf trees
AL-MN	Other broadleaf trees-Mixed stand with conifers	Share of basal area Other broadleaf trees under 80 %, Mixed species are conifers
TA-R	Fir-Pure stand	Share of basal area Fir above 80 %
TA-ML	Fir-Mixed stand with broadleaf trees	Share of basal area Fir under 80 %, Mixed species are broadleaf trees
TA-MN	Fir-Mixed stand with conifers	Share of basal area Fir under 80 %, Mixed species are conifers
DGL-R	Douglas fir-Pure stand	Share of basal area Douglas fir above 80 %
DGL-ML	Douglas fir -Mixed stand with broadleaf trees	Share of basal area Douglas fir under 80 %, Mixed species are broadleaf trees
DGL-MN	Douglas fir-Mixed stand with conifers	Share of basal area Douglas fir under 80 %, Mixed species are conifers
LAE-R	Larch-Pure stand	Share of basal area Larch above 80 %
LAE-ML	Larch-Mixed stand with broadleaf trees	Share of basal area Larch under 80 %, Mixed species are broadleaf trees
LAE-MN	Larch-Mixed stand with conifers	Share of basal area Larch under 80 %, Mixed species are conifers

Source: own compilation

Table A-2: Phases of stand development considered in FABio

	Name	Description
JP	Young tree care (Jungwuchspflege)	Tending and maintenance of young stands covers the forest development stage from new seedlings to the first thinning, with the goal to improve wood quality or to influence the distribution ratio of different tree species
DF	Thinning(Durchforstung)	Removal of trees, maybe of lower quality and those impeding higher quality trees, before stand maturity. Thinning aims at concentrating stand increment on vital trees of high quality.
VP	Stock maintenance (Vorratspflege)	Stock maintenance is a treatment type within silvicultural management plans. It aims at supporting the growth of large dimensional timber and foresees the extraction of lower quality stems, early harvest of mature trees and preparation of the regeneration phase.
NZ	Final harvest (Nutzung)	Final harvest either as individual tree removal determined by target diameter, as removal of entire stands (clearcutting), e.g. depending on stand age.

Source: own compilation

Table A-3: Parameter settings for describing management intensity in scenario Forest Vision

Stand type	Management type	Start thinning DBH	End thinning DBH	Intensity of thinning in % of growing stock available	Target diameter	Intensity of target diameter use in % of growing stock available
BU-R	JP	7	15	0	70	50
BU-R	DF	15	35	12	70	20
BU-R	VP	35	70	0	70	20
BU-R	NZ				70	85
BU-R	DW	15	70	12	70	85
BU-MN	JP	4	15	15	65	60
BU-MN	DF	15	35	20	65	30
BU-MN	VP	35	70	20	65	30
BU-MN	NZ				65	70
BU-MN	DW	7	65	12	65	85
BU-ML	JP			0	70	40
BU-ML	DF	15	35	15	70	20
BU-ML	VP	35	70	5	70	20
BU-ML	NZ				70	70
BU-ML	DW	15	70	12	75	70
EI-R	JP			0	80	30
EI-R	DF	7	35	5	80	10
EI-R	VP	35	80	5	80	20
EI-R	NZ				80	75
EI-R	DW	7	80	5	80	75
EI-MN	JP	7	15	10	70	50
EI-MN	DF	15	35	15	70	30
EI-MN	VP	35	70	10	70	30
EI-MN	NZ				70	75
EI-MN	DW	7	70	10	70	75
EI-ML	JP			0	75	30
EI-ML	DF	7	35	5	75	30
EI-ML	VP	35	75	5	75	30
EI-ML	NZ				75	75
EI-ML	DW	7	80	5	80	75
FI-R	JP	7	15	15	50	95
FI-R	DF	15	30	25	50	95
FI-R	VP	30	50	25	50	95
FI-R	NZ				50	95
FI-R	DW	7	50	20	50	90
FI-MN	JP	7	15	15	50	95
FI-MN	DF	15	30	25	50	95
FI-MN	VP	30	50	25	50	95
FI-MN	NZ				50	95
FI-MN	DW	7	50	20	50	90
FI-ML	JP	7	15	20	60	80
FI-ML	DF	15	30	20	60	80
FI-ML	VP	30	50	20	60	80
FI-ML	NZ				60	80
FI-ML	DW	7	50	15	60	80

TA-R	JP	7	15	15	60	90
TA-R	DF	15	30	25	60	90
TA-R	VP	30	60	25	60	90
TA-R	NZ				60	90
TA-R	DW	7	60	20	60	90
TA-ML	JP	7	15	15	70	90
TA-ML	DF	15	30	25	70	90
TA-ML	VP	30	70	25	70	90
TA-ML	NZ				70	90
TA-ML	DW	7	70	20	70	80
TA-MN	JP	7	15	15	60	90
TA-MN	DF	15	30	25	60	90
TA-MN	VP	30	60	25	60	90
TA-MN	NZ				60	90
TA-MN	DW	7	60	20	60	90
DGL-R	JP	7	15	20	80	95
DGL-R	DF	15	40	15	80	95
DGL-R	VP	40	80	15	80	95
DGL-R	NZ				80	95
DGL-R	DW	7	80	10	80	90
DGL-MN	JP	7	15	20	65	95
DGL-MN	DF	15	40	15	65	95
DGL-MN	VP	40	65	15	65	95
DGL-MN	NZ				65	95
DGL-MN	DW	7	70	10	70	90
DGL-ML	JP	7	15	20	80	95
DGL-ML	DF	15	40	15	80	95
DGL-ML	VP	40	80	10	80	95
DGL-ML	NZ				80	95
DGL-ML	DW	7	80	10	80	90
KI-R	JP	7	15	10	60	95
KI-R	DF	15	30	20	60	95
KI-R	VP	30	60	20	60	95
KI-R	NZ				60	95
KI-R	DW	7	60	15	60	90
KI-MN	JP	7	15	15	50	95
KI-MN	DF	15	30	25	50	95
KI-MN	VP	30	50	25	50	95
KI-MN	NZ				50	95
KI-MN	DW	7	50	20	50	90
KI-ML	JP	7	15	5	70	80
KI-ML	DF	15	30	15	70	80
KI-ML	VP	30	70	15	70	80
KI-ML	NZ				70	80
KI-ML	DW	7	70	15	70	80
LAE-R	JP	7	15	25	70	95
LAE-R	DF	15	40	25	70	95
LAE-R	VP	40	70	20	70	95
LAE-R	NZ				70	95
LAE-R	DW	7	70	20	70	90
LAE-MN	JP	7	15	25	60	95
LAE-MN	DF	15	40	25	60	95

LAE-MN	VP	40	60	20	60	95
LAE-MN	NZ				60	95
LAE-MN	DW	7	60	20	60	90
LAE-ML	JP	7	15	25	70	90
LAE-ML	DF	15	40	25	70	90
LAE-ML	VP	40	70	20	70	90
LAE-ML	NZ				70	90
LAE-ML	DW	7	70	20	70	80
AL-R	JP			0	70	75
AL-R	DF	7	30	15	70	75
AL-R	VP	30	70	5	70	75
AL-R	NZ				70	75
AL-R	DW	7	70	5	70	75
AL-MN	JP			0	70	75
AL-MN	DF	7	30	15	70	75
AL-MN	VP	30	70	5	70	75
AL-MN	NZ				70	75
AL-MN	DW	7	70	5	70	75
AL-ML	JP					
AL-ML	DF					
AL-ML	VP					
AL-ML	NZ					
AL-ML	DW					

Source: own compilation

Table A-4: Parameter settings for describing management intensity in scenario Timber

Stand type	Management type	Start thinning DBH	End thinning DBH	Intensity of thinning in % of growing stock available	Target diameter	Intensity of target diameter use in % of growing stock available
BU-R	JP	5	13	10	60	100
BU-R	DF	14	34	40	60	100
BU-R	VP	34	59	25	60	100
BU-R	NZ		60	100	60	100
BU-R	DW					
BU-MN	JP	5	13	10	60	100
BU-MN	DF	14	34	40	60	100
BU-MN	VP	34	59	25	60	100
BU-MN	NZ		60	100	60	100
BU-MN	DW					
BU-ML	JP	5	13	10	60	100
BU-ML	DF	14	34	40	60	100
BU-ML	VP	34	59	25	60	100
BU-ML	NZ		60	100	60	100
BU-ML	DW					
EI-R	JP	7	15	15	70	100
EI-R	DF	16	50	25	70	100
EI-R	VP	51	69	10	70	100
EI-R	NZ		70	100	70	100
EI-R	DW					
EI-MN	JP	7	15	15	70	100
EI-MN	DF	15	35	35	70	100
EI-MN	VP	35	69	20	70	100
EI-MN	NZ		70	100	70	100
EI-MN	DW					
EI-ML	JP	7	15	15	70	100
EI-ML	DF	15	35	40	70	100
EI-ML	VP	35	69	20	70	100
EI-ML	NZ		70	100	70	100
EI-ML	DW					
FI-R	JP	7	12	40	45	100
FI-R	DF	13	34	30	45	100
FI-R	VP	35	44	25	45	100
FI-R	NZ		45	100	45	100
FI-R	DW					
FI-MN	JP	7	12	40	45	100
FI-MN	DF	13	34	30	45	100
FI-MN	VP	35	44	25	45	100
FI-MN	NZ		45	100	45	100
FI-MN	DW					
FI-ML	JP	7	12	50	45	100
FI-ML	DF	13	34	30	45	100
FI-ML	VP	35	44	25	45	100
FI-ML	NZ		45	100	45	100
FI-ML	DW					

TA-R	JP	6	12	20	50	100
TA-R	DF	13	36	25	50	100
TA-R	VP	37	49	25	50	100
TA-R	NZ		50	100	50	100
TA-R	DW					
TA-ML	JP	6	12	20	50	100
TA-ML	DF	13	36	25	50	100
TA-ML	VP	37	49	25	50	100
TA-ML	NZ		50	100	50	100
TA-ML	DW					
TA-MN	JP	6	12	20	50	100
TA-MN	DF	13	36	25	50	100
TA-MN	VP	37	49	25	50	100
TA-MN	NZ		50	100	50	100
TA-MN	DW					
DGL-R	JP	13	18	25	80	100
DGL-R	DF	19	46	25	80	100
DGL-R	VP	47	79	20	80	100
DGL-R	NZ		80	100	80	100
DGL-R	DW					
DGL-MN	JP	13	18	25	80	100
DGL-MN	DF	19	46	25	80	100
DGL-MN	VP	47	79	20	80	100
DGL-MN	NZ		80	100	80	100
DGL-MN	DW					
DGL-ML	JP	13	18	25	80	100
DGL-ML	DF	19	46	25	80	100
DGL-ML	VP	47	79	20	80	100
DGL-ML	NZ		80	100	80	100
DGL-ML	DW					
KI-R	JP	9	13	15	45	100
KI-R	DF	14	38	30	45	100
KI-R	VP	39	44	15	45	100
KI-R	NZ		45	100	45	100
KI-R	DW					
KI-MN	JP	9	13	15	45	100
KI-MN	DF	14	38	30	45	100
KI-MN	VP	39	44	25	45	100
KI-MN	NZ		45	100	45	100
KI-MN	DW					
KI-ML	JP	9	13	20	45	100
KI-ML	DF	14	38	30	45	100
KI-ML	VP	39	44	20	45	100
KI-ML	NZ		45	100	45	100
KI-ML	DW					
LAE-R	JP	4	15	25	60	100
LAE-R	DF	16	42	30	60	100
LAE-R	VP	43	59	25	60	100
LAE-R	NZ		60	100	60	100
LAE-R	DW					
LAE-MN	JP	4	15	25	60	100
LAE-MN	DF	16	42	30	60	100

LAE-MN	VP	43	59	25	60	100
LAE-MN	NZ		60	100	60	100
LAE-MN	DW					
LAE-ML	JP	4	15	25	60	100
LAE-ML	DF	16	42	30	60	100
LAE-ML	VP	43	59	25	60	100
LAE-ML	NZ		60	100	60	100
LAE-ML	DW					
AL-R	JP	7	15	25	60	100
AL-R	DF	16	30	35	60	100
AL-R	VP	31	59	20	60	100
AL-R	NZ		60	100	60	100
AL-R	DW					
AL-MN	JP	7	15	25	60	100
AL-MN	DF	16	30	35	60	100
AL-MN	VP	31	59	20	60	100
AL-MN	NZ		60	100	60	100
AL-MN	DW					
AL-ML	JP	7	15	25	60	100
AL-ML	DF	16	30	35	60	100
AL-ML	VP	31	59	20	60	100
AL-ML	NZ		60	100	60	100
AL-ML	DW					

Source:own compilation

Table A-5: Aggregation of natural forest types from BWI into forest types and areas

Forest types and associated natural forest communities	Area [ha]
(1) Auen und Feuchtwälder	
Bach-Eschenwälder	66.200
Grauerlenauewald	9.900
Hainmieren-Schwarzerlen-Auenwald	22.100
Silberweiden-Weichholzauewald	7100
Stieleichen-Ulmen-Hartholzauewald	39.500
Traubenkirschen-Erlen-Eschenwälder	82000
Sum	**226.800**
(2) Basen- und kalkreiche Buchenmischwälder	
Alpenheckenkirschen-Tannen-Buchenwald	173.200
Seggen-Buchenwald	83.100
Waldgersten-Buchenwald, z.T. mit Tanne	674.600
Sum	**930.900**
(3) Block- und Schluchtwald	
Ahorn-Eschenwald	63.900
Alpenrosen-Latschengebüsche	3.000
Edellaubbaum-Steinschutt- und Blockhangwälder	28.400
Grünerlengebüsch	200
Karpatenbirken-Ebereschen-Blockwald	1.600
Traubeneichen-Linden-Wälder	95.000
Sum	**192.100**
(4) Bodensaurer Buchenmischwald	
Buchen-Traubeneichenwald	254.400
Drahtschmielen-Buchenwald	1.017.100
Fichten-Buchenwald	79.200
Hainsimsen-Buchenwald, z.T. mit Tanne	4.271.800
Sum	**5.622.500**
(5) Bodensaurer Eichenmischwald	
Birken-Stieleichenwald	187.600
Birken-Traubeneichenwald	155.300
Preiselbeer-Eichenwald	402.800
Preiselbeer-Eichenwald und Weißmoos-Kiefernwald	3.100
Bodensaurer Eichenmischwald Ergebnis	748.800
(6) Bruchwald	
Rauschbeeren-Moorwälder	94.700
Schwarzerlen-Bruch- und Sumpfwälder	118.500
Sum	**213.200**
(7) Feuchter reicher Eichenmischwald	
Sternmieren-Hainbuchen-Stieleichenwald	273.000
Sum	**273.000**
(8) Hochlagen Fichtenwald z.T. Tanne	
Alpenlattich-Fichtenwald	9.000
Bergreitgras-Fichtenwald	34.600
Block-Fichtenwald	2.600
Hainsimsen-Fichten-Tannenwald	46.600
Labkraut-Fichten-Tannenwald	30.600
Peitschenmoos-Fichtenwald	9.100
Preiselbeer-Fichten-Tannenwald	87.700

Wintergrün-Fichten-Tannenwald	4.600
Sum	**224.800**
(9) Kiefernwald	
Schneeheide-Kiefernwälder	2.800
Weißmoos-Kiefernwald	130.600
Sum	**133.400**
(10) Mesophile Buchenmischwälder	
Bergahorn-Buchenwald	4.000
Waldmeister-Buchenwald, z.T. mit Tanne	1.442.800
Sum	**1.446.800**
(11) Mesophiler Eichenmischwald	
Waldlabkraut-Hainbuchen-Traubeneichenwald	291.500
Sum	**291.500**
(12) Wärmeliebende Eichenmischwälder	
Xerotherme Eichen-Mischwälder	14.300
Sum	**14.300**
Total sum	**10.318.100**

Source: own compilation