SCALING LAND-BASED MITIGATION SOLUTIONS IN GERMANY

LMT NARRATIVE AND SCENARIOS

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1. Introduction

This document presents the potential of LMTs in Germany identified within the LANDMARC project. It explores the scope for national level simulation modelling, delivers the co-design of LMT narratives and taps into current political measures that will influence the performance of LMTs in Germany. The LMT portfolio and estimates of their potential to remove CO_2 or reduce GHG emissions are based on a thorough literature review and a stakeholder validation. The analysis builds on existing work in ongoing (BioSink[1] and DIFENs[2]) and completed projects (dena 2021).

For the narratives, information collected and provided in the dena-study (dena 2021) was mainly used as this study addresses the main aspects of potential, risks and benefits of LMTs. To estimate risks and opportunities (T.4.1) a questionnaire was distributed to collect expert opinions on each of the LMTs. The results complement the findings from the dena-study.

The identification of stakeholders followed recommendations given in the stakeholder mapping tool. For the case study, a national stakeholder network was established, including stakeholders from forest authorities, private forests, and science were identified. Regarding the continental stakeholder network, actors from governance, NGOs, and science were identified. Interactions with stakeholders were performed in different formats, such as workshops, phone calls, working sessions, work meetings but also on more official occasions such as dialogues organized by ministries.

2. Overview of potential of LMTs in Germany

2.1 Introduction

In 2021 the German government agreed in its Federal Climate Protection Act on the national target of considerable reducing GHG emissions until 2030 and reaching GHG neutrality by 2045. GHG neutrality is planned to be achieved by compensating remaining emissions in 2045 through CO_2 removals by natural sinks. Therefore, the government has also set up net sink targets to be achieved by the sector of Land Use, Land Use Change and Forestry (LULUCF).

In 2018, the land use sector in Germany represented a net sink of approximately -30 Mt CO_2e Significant amounts of CO_2 were captured from the atmosphere by forests (-67 Mt CO_2e) and stored by wood

[1] https://www.ifeu.de/projekt/biosink/
[2] https://www.difens.de

products (-3 Mt CO_2e). Above- and below-ground biomass played a major role in CO_2 sequestration (-50 Mt CO_2e) in the forest. In addition, considerable amounts of carbon were sequestered in the mineral forest soil (-16 Mt CO_2e). In contrast, emissions occurred on land under arable land (16 Mt CO2e), grassland (15 Mt CO_2e), settlements (6 Mt CO_2e) and wetlands (4 Mt CO_2e) (UBA 2020).

Prognos et al. (2020) published pathways for achieving GHG neutrality in Germany until 2045 and 2050.The estimates provide potentials for emission reductions and for LMTs to compensate residual emissions mainly from the agricultural sector. The technological potential for land-based negative emissions is particularly high in the industrial and energy sector by applying BECCS. The scenario also assumes measures to ensure that the LULUCF sector remains a net sink for CO_2. The study assumes that forests in Germany could remove about the same amount of CO_2 as BECCS.

Table 1 gives an overview of German LMTs and their potential for emission reductions and removals. In the following sections, we will discuss options of LMTs in Germany within the context of the LAND-MARC project scope (long-list of options). We then discuss which LMTs seem most promising for sup-porting Germany's target of climate neutrality sin 2045. This set of LMTs is referred to as 'short list' (see Table 1).

Table 1: Overview of LMT potential in Germany

LMT	Source	Area (1.000 ha)		Specific potential* (t CO_2e/ha)		Total potential** (Mt CO_2e)		Additional costs	Biomass
		2030	2050	2030	2050	2030	2050	EUR/t CO_2e	PJ/Mt
BECCS (industry sector)	[1]					15	37		
BECCS (energy sector)	[1]						3		
Re-wetting of organic soils	[2]	-	300-900	-	20–40	-	7,0-15,2	2–380	
	[1]	278	650	25,2	27,7	7	18		
Abandoning peat extraction	[1]	18	18	122	122	2,2	2,2	28	
Avoided conversion of grassland	[2]	34,1	34,1	73 -91		2,5 - 3,1		15 – 60	
Afforestation	[2]	400	850	4,7	4,7	18	120	159	
Managing forests incl. HWP	[4]	10.900	10.900	2,8	2,9	31	32		
	[5]	10.400	10.400	3,8	6,5	40	68		

Increasing SOC on agricultural land	[3]	3.100				0,3 – 0,4			
Total negative emissions		25.130,1	23.152,1 – 23.752,1	231,5 – 249,5	183,8 – 203,8	116 – 116,7	287,2 – 295,4	204 - 627	
Total required biomass									
CO_2-transport per 250 km at 10 Mt/y									
CO_2-storage under sea									

*Specific potential= potential per unit area **Total potential= potential on total area

[1] Prognos et al. (2020)
[2] BMEL (2016b)
[3] Wiesmeier et al. (2017)
[4] Rüter et al. (2017)
[5] (Böttcher et al. 2018b)

2.1.1 Technologies dependent on biomass / photosynthesis

BECCS within the industrial and energy sector

There is technical potential for negative emissions in Germany that is related to the use of biomass and subsequent utilization or geological storage of biogenic carbon (BECCS). In the scenario presented by Prognos et al. (2020) it is assumed that negative emissions of -34 Mt CO_2-eq will be reached within the industrial sector and further -3 Mt CO_2-eq from the energy sector by 2050. The post-CO_2 combustion will largely be applied within the industrial sector while in the energy sector the oxyfuel-technology is applied. Both processes are estimated to reach a removal rate of CO_2 of at least 90 %.

Biomass, most suitable is solid biomass due to transportation reasons, needs to be available in necessary quantities. In 2030, the demand amounts 221 TWh, increasing to 284 TWh in 2050.The biomass feedstock will derive from existing streams of agriculture and forestry primary and secondary residues and waste. It is assumed that the increasing demand is covered by agroforestry systems, hedges and short rotation plantations growing on former cultivation areas of maize used as biogas substrates. This leads to benefits as this implies a reduction in the use of fertilizer, an additional accumulation of humus, and a better adaptability towards climate change.

2.1.2 Land management practices

Managing forests and HWP

German forests currently provide considerable negative emissions causing the LULUCF sector to be a net sink (Prognos et al. (2020). In 2018 forests took up 67 Mt CO_2e (Prognos et al. (2020). In addition, net storage through harvested wood products (HWP) was 3 Mt CO_2e. HWP cannot sequester carbon themselves and are therefore not considered as carbon sinks. But their carbon pool is closely connected to the forest pool of living forest biomass because harvested biomass reduces the living biomass pool but also transfers carbon partly to the HWP pool. The amount of carbon stored in HWPs depends on the allocation pattern of the harvested wood to wood product types and their lifetimes. This net sink could be increased considerably according to the WEHAM-Nature protection preference scenario (WEHAM-NPS) (Oehmichen et al. 2018). The WEHAM-NPS assumes an increasing consideration of nature protection in forests. Compared to current forest management, which is modelled in the WEHAM-Basis scenario (WEHAM-BS) (Oehmichen et al. 2018), harvesting and thinning activities mainly promote more old trees with larger diameters and tree species of the actual forest habitat type. WEHAM-NPS does not assume an increase in protected areas (4,2%) compared to WEHAM-BS but a reduced intensity of harvest, especially for broadleaved trees. Additionally, deadwood occurrence is increased from 20 m^3/ha to 40 m^3/ha on average. Another scenario of forest development is the "Forest vision" (Böttcher et al. 2018a) that assumes high standards of close-to-nature forestry. Under this scenario the forest sink could be substantially increased to -68 Mt CO_2 in 2050. The forest area without timber harvest is higher (16.6 %) compared to WEHAM-NPS. The harvest intensity is also lowered and results in an increase of the average wood stock from 356 m^3/ha in 2012 to 501 m^3/ha in 2052.

Implementing the WEHAM-NPS would lead to net removals of 35 Mt CO_2 in 2050, which is about twice as much compared to the WEHAM-BS (Rüter et al. 2017). HWP do not store carbon but cause net emissions of 2 Mt CO_2 in 2030 and 3 Mt CO_2 in 2050 because less wood is harvested and HWP stocks therefore slightly decreasing. Assumptions for wood assortment are based on current technological requirements but future innovations of wood use, especially for wood from broadleaved trees that are currently to a large degree used for fire wood, might increase carbon storage potentials in harvested products.

There are significant risks for maintaining or even increasing the sink in forests due to natural disturbances (see section "Land use change dynamics").

Rewetting of Organic Soils

In 2018 the LULUCF sector reported emissions of about 43 Mt CO_2e caused by agricultural activities on organic soils in Germany (1.8 Mha), including peat extraction (18,000 ha). Rewetting and abandoning peat extraction on these soils can reduce emissions substantially and therefore increase the net sink in LULUCF. Following the scenario by Prognos et al. (2020) emission reduction of 7 Mt CO_2e (25.2 t CO_2 e/ha) can be achieved by abandoning peat extraction and rewetting 20 % (278,000 ha) of cropland and grassland on former peatlands until 2030. Until 2050, an emission reduction of 18 Mt CO_2e (27.7 t CO_2 e/ha) can be achieved after rewetting 50 % (650,000 ha) of cropland and grassland on organic soils.

Prognos et al. (2020) describes that the total agricultural area will decrease by 7 % in 2050 due to rewetting of organic soils and the expansion of infrastructural areas and settlement. The latter implies that due to less agriculturally used land, less fertilizers are applied. Partially, the rewetted soils will stay in agricultural use (e.g., paludiculture): 0.2 Mha in 2030 and 0.7 Mha in 2050.

In the scenario by Prognos et al. (2020) , the management of the rewetted soils in 2030 is mainly extensive pasture and mowing (40 %). Also, paludicultures can be introduced and 30 % of the rewetted organic soils is left without agricultural management for nature restoration. In 2050, paludiculture use could increase to 50 % on the rewetted area while 50 % is left for nature restoration.

Abandoning peat extraction

The scenario by Prognos et al. (2020) assumes that until 2030 peat extraction will be abandoned and that the areas used for peat extraction will be rewetted.

Another study "Pathways into a resource-saving greenhouse gas neutrality (RESCUE)" carried out by the federal environmental agency (UBA) in 2019 assumes that peat extraction could be stopped by 2040 cutting current emissions from this activity of over 4 Mt CO_2e to zero.

Afforestation / Reforestation

Afforestation potentials is very difficult to assess in a densely populated country like Germany with high land use competition. Estimates by BMEL (2016b) assume an afforestation potential of 5 % of the agricultural area, which corresponds to 850,000 ha (7.7 % of forest area in 2012) until 2050. In 2018 a total of 17,730 ha of mainly grassland was converted into forests according to the latest National Inventory Report (UBA 2020b). However, this option is limited by the availability of land that can be converted to forests. Land area converted to forest land from 1998 to 2018[3] was reported as a net sink of -4.7 Mt CO_2.

Emission reductions by afforestation measures might be counteracted by deforestation emissions. About 5,000 ha of forest area were lost each on average between 1990 and 2012. In 2018 forest area loss amounted to 6,890 ha causing emissions of 1.7 Mt CO_2. Deforestation occurs only in relation to rather big infrastructural projects which are of social relevance and further those deforested areas must be compensated through replanting elsewhere (WBW 2016).

Increasing SOC on agricultural land

Wiesmeier et al. (2017) estimated the C_{org}-storage potential for agricultural soils in the state of Bavaria. His results show that the soils had an average saturation of only 50 % and providing a theoretical

[3] Afforestation is reported as land converted to forest land over a 20-year period.

potential of storage of 108 Mt C_{org} (respectively 395 Mt CO_2 eq). On average 128.3 t CO_2 per hectare could potentially be stored. The authors discuss, however, that this value exceeds by far the C-accumulation rate of different measures increasing soil organic carbon (e.g., extending intercropping, improved cropping sequence, introduction of agroforestry system etc.). Furthermore, the assumptions are that before reaching the maximum C storage potential a new equilibrium will be reached. The estimated overall potential of C_{org} storage is 1.35 Mt CO_2.

Avoided grassland conversion

During the development of this report, the LMT avoided grassland conversion first had been included in the short-listed LMTs but later had been excluded as the potential is very limited. The protection of grassland is already legally binding due to the Common Agricultural Policy (CAP)of the EU in 2013. A mechanism of the "Greening"-measure regulates the conservation of grassland for farmers that receive direct funding through the CAP. Some Federal states in Germany have issued their own regulations and there it is generally prohibited to convert grassland; exemptions must be authorized[4].

[4] https://www.umweltbundesamt.de/daten/land-forstwirtschaft/gruenlandumbruch#okologische-bedeutung-des-grunlands

2.2 Determining the scope for national level LMT portfolio

In this section a short-list of LMTs for Germany is formed. Table 2 summarises identified LMTs and presents the short-list of the LMT portfolio. The criteria for including LMTs in the list are:

- focus on natural sinks,
- availability of data,
- capabilities of tools to assess potentials,
- degree of realism that measures can be implemented, and
- relevance of the option in the policy context.

The application of the criteria resulted in the following short-list of LMTs: peat soil management, including rewetting, reverse drainage, paludiculture of grasslands and croplands, forest management and afforestation and reforestation.

Table 2: Long-list of relevant land based LMTs in Germany

LMTs	Specification	Included in national LANDMARC LMT portfolio
BECCS	BECCS based on domestic biomass (Anaerobic digestion (AD) with CCS based on domestic biomass etc.)	N
	BECCS based on imported biomass	N
Biochar	-	N
Wetlands	Peat soil management, including rewetting, reverse drainage, paludiculture	Y
Cropland	Reduced tillage	N
	Harvest residues, crop rotation	N
	Application of organic fertilizers and anaerobic digestates	N
	Peat soil management	Y
	Agroforestry	N
	Landscape elements (hedgerows etc.)	N
Grassland	Avoided grassland conversion	N
	Peat soil management	Y
	Agroforestry	N
	Landscape elements (hedgerows etc.)	N
Forest land	Avoided deforestation	N
	Afforestation / reforestation	Y
	Forest management (incl. HWP)	Y
	Agroforestry	N
	Landscape elements (hedgerows etc.)	N
Settlements	Reducing net conversion to built-up land	N

BECCS could be a promising technical land-based solution, however, the case study focuses on natural sink solutions. SOC enhancement technologies are not included because the data on this LMT in Germany is very limited.

2.3 Discussion on short-listed LMTs

2.3.1 Land use change dynamics

Almost all selected LMTs imply considerable changes in land use in the future, with LMTs related to forest management and harvested wood products being an exception. In a densely populated country like Germany, land availability is a major challenge. Especially, agricultural land (cropland and grassland) which amounts to 19.7 Mio ha in Germany will be under pressure to be converted or managed differently. For example, organic soils under agricultural land that make up 1.3 Mio ha will have to be rewetted (see section 1.2.3) to reduce emissions from peat decomposition. This might cause land use conflicts because soil rewetting will often make conventional farming impossible. Currently, cattle farming and the production of meat and dairy products are an important income source for the national agricultural sector. Less available grassland for fodder crop cultivation could lead to leakage effects because more animal feed would have to be imported from abroad. Additionally, afforestation will have to be mainly applied on agricultural land (see section 1.2.3), which further reduces the area for crop production, also with possible leakage effects. There are also potential conflicts with nature conservation interests regarding highly divers grasslands or sparsely vegetated heathland. Usually, these kinds of habitats derive from animal herding practices in the past. They are actively kept clear of trees to protect the established habitat and biodiversity.

2.3.2 Land management dynamics

Some of the potential land use change conflicts due to rewetting of organic soils as mentioned above can be avoided when a change of land management is applied which still can generate economic income. For example the introduction of paludicultures like reed, cattail, reed canary grass, alder, peat moss is preserving the existing peat body and therefore an effective climate mitigation measure (Wichtmann et al. 2016). However, implementation of paludiculture will require agricultural policies to set monetary incentives for farmers to rewet drained agricultural organic soils and maintain them as wetlands (O'Brolchain 2020). Also, paludiculture products like insulating material and peat substitute material will have to be mainstreamed. Additionally, rewetting measures will need to change the hydrology of the site and block drainage systems, which can cause conflicts with neighboring cropland or infrastructure.

In the future, it is very likely that there will be even more agricultural management options that compete with the implementation of the LMTs. For example there will be a high demand for bioenergy crops like maize and wood from short rotation plantations (UBA 2021).

Current forest land management can differ substantially in Germany, especially in-between owner ship classes. About 50 % of the forests are privately owned with mainly small forest areas (less than 20 ha). The states own 29 % and the Federal government 4 % of the forests. Communities own about 19 % forests (BMEL 2016a). The intensity of forest management is mainly determined by the economic interest of the forest owner and the market demands which are in favor for coniferous wood of low diameter. To promote higher carbon stocks in the forests (living biomass, deadwood, SOC, litter), incentives for less intensive forest management will be needed in the future. Also, the net effects on the sequestration potential depend on the future tree species composition of forests, the ability of species to adapt (Seidl et al. 2014). Therefore, forest adaptation to climate change will have to be considered in future management regimes to ensure continuous rates of carbon sequestration and to protect forest carbon stocks. These adaptation measures can have synergies with the extensification measures already mentioned. For example, promoting mixed forest stands with deciduous tree species to minimize the devastating effects of natural disturbances like storms or insect pests. Additionally, promoting all tree age classes in the forest stand can reduce the risks against pests and other calamities. Extensification of forest management can also positively affect biodiversity and ecosystem services like elevated water retention by deciduous trees (IPCC 2019; Griscom et al. 2017).

Harvesting wood from forests transfers carbon stored in living biomass into different pools of HWP. From these wood products the stored carbon is released as these products get out of use and are being incinerated or dumped (however, there is a landfill ban for HWP in EU). Given that these products have different lifetimes and there are recycling flows between them, the estimation of total carbon stored in these products can be complex. In case the wood is being used for energy or left in the forest, the stored carbon counts as an emission. Wood products hold back these emissions and can contribute to mitigation, especially when products are long-lasting and recycling rates are high. Wood products can also help reducing emissions in other sectors, like the building industry through substitution of fossil-based products. Changes in forest management will affect wood production potentials in different ways depending on the side conditions and existing trees species composition. Currently wood from broad-leaved trees is to a large extent directly used for energy. Coniferous trees instead are mostly used for construction wood. Extensification of wood harvest can reduce domestic wood supply and thus lead to increased imports.

2.3.3 Projection of land management dynamics

The German Government's most recent projection report on the development of greenhouse gas emissions in Germany covers the period until 2040 (UBA 2021). In the LULUCF-sector four LMTs already addressed by policy measures are considered in the projection (Table 3). Peat soil management on different land types reveal a GHG mitigation of 5.2 Mt CO_2e in 2030. The reduction of the use of peat that is associated with the rewetting of peat extraction areas mitigates another 1.2 Mt CO_2e. The reduction of net conversion to built-up land from 80 ha to 30 ha in 2030 leads to a GHG-mitigation of 2.0 Mt CO_2e. Finally, maintaining grassland areas reduces GHG emissions by 1.3 Mt CO_2e. However, the latter mitigation is derived from a scenario assuming the absence of this grassland measure. As maintaining grassland areas is now part of the good agricultural practice this GHG mitigation should not be considered. In total, the LMTs amount up to about 8.5 Mt CO_2e excluding and 9.7 Mt CO_2 including maintaining grassland area.

Table 3: Land based mitigation technologies (LMT) covered in the Germany GHG projection report

LMT	Description	GHG mitigation in 2030 (MT CO_2e)
Reducing net conversion to built-up land	In 2015 to 2020 about 80 ha/day are converted to settlements. This value is reduced to less than 30 ha/day in 2030.	2.0
Maintaining grassland areas	Within the framework of the Common Agricultural Policy, the net conservation of permanent grassland has been successfully addressed in Germany since 2015. It is assumed that the grassland conversion ban will result in the existing grassland area remaining constant compared to mean losses from 2000 to 2010.[5]	1.3
Peat soil management in cropland, grassland, peat extraction areas and wetland areas	Until 2030: - 12,700 ha of arable land are converted to grassland - 224,000 ha of grassland are moderately and 80,000 ha are fully rewetted - 1,200 ha of peat extraction areas are rewetted - about 73,000 ha of drained wetland areas are rewetting and their water management is optimised.	5.2
Reduction of peat use in cultivation substrates	Compared to 2018, peat extraction and peat use will be reduced to half by 2030.	1.2
Sum		**9.7 (8.5 without maintaining grassland areas)**

Source: (UBA 2021)

UBA (2021) also shows projections of emissions and removals from forests. However, the used forest scenario is based on data from 2012, assuming rather high rates of timber extraction. Moreover, the projection does not reflect strong draughts and beetle calamities from 2018 to 2020 (compare Hennenberg et al. (2021), UBA 2021). Hennenberg et al. (2021) showed that the forest sink in Germany strongly depends on the level of natural disturbances. Assuming a timber harvest of 70 Mio m³ and a low level of natural disturbances (as in the period 2008 to 2017) results in a sink of living biomass of

[5] This contrafact analysis is critical as maintaining grassland is now well established and can be considered as good agricultural practice.

about -46 Mt CO_2. Under strong natural disturbances (as in the period 2002 to 2007) the sink of living trees drops to about -18 Mt CO_2. Assuming higher natural disturbances may result in sink values of -9 Mt CO_2 (very strong disturbances) and 0 Mt CO_2 (extreme disturbances). Thus, the magnitude of uncertainties due to natural disturbances is about 28 Mt CO_2 or even more. Assuming a decrease of timber harvest from 70 to 65 Mm³ implies a change of the sink from -46 to -50 Mt CO_2, and an increased timber harvest of 80 Mm³ reveals a sink of about -40 Mt CO_2.

This shows that the reduction of timber harvest is an important leverage for increasing CO_2 fixation in the LMT forest management. However, the sink benefits targeted by the reduced timber harvest can be reversed by natural disturbances, especially if the increase of growing stock in forests is targeted to forest stands that are not well adapted to climate change risks..

Other scenario studies on the development of GHG emissions in Germany also estimate potentials for LMTs mentioned in Table 3 but with varying intensities. Also additional LMTs are covered, namely increasing harvested wood products (Repenning et al. in press) and establishment of agroforestry systems including short rotation coppices (dena (2021), (Repenning et al. in press).

2.3.4 Policy context for LMT implementation in Germany

The political situation in Germany has changed recently towards a new coalition consisting of the green, socialist, and liberal party. The coalition contract addresses numerous initiatives relevant for LMT implementation in Germany. Additionally, the military conflict between Russia and Ukraine has severe impacts on the energy supply of Germany. In the aftermath of the beginning of the armed conflict big changes took and are still taking place regarding the origin and amount of imported fossil energy. At the same time the demand for alternative energy supply (including wood) increased enormously. Moreover, the conflict resulted in food security becoming an important consideration in national politics. This led to a discussion on the area available for agricultural production and reducing or postponing ambitions regarding the establishment of ecological priority areas.

The coalition contract includes[6] a variety of measures addressing conservation and protection of ecosystems that potentially lead to a reduction of GHG emissions or enhancement of carbon removals.

- Contract nature conservation (Vertragsnaturschutz[7]) is to be strengthened and will be provided with better financial opportunities and more flexibilities in its implementation on a regional scale. The concept of contract nature conservation delivers a scope that for a fixed period (several years) a contracted party commits themself to a certain management method

[6] https://www.bundesregierung.de/resource/blob/974430/1990812/04221173eef9a6720059cc353d759a2b/2021-12-10-koav2021-data.pdf?download=1

[7] https://www.bmuv.de/themen/naturschutz-artenvielfalt/naturschutz-biologische-vielfalt/waelder/nationale-waldschutzpolitik

oriented towards nature conservations goals, e. g. a forest owner selects trees to be designated as biotope trees.

- The Natural Climate Protection Action Program (Aktionsprogramm natürlicher Klimaschutz[8]) is designed to encompass all necessary means to protect and strengthen ecosystems. This includes the capture of the status of an ecosystem and finding the causes, the development of appropriate counter measures, and to build up necessary competences, as well as the permanent implementation of measures and their monitoring. The concrete measures are divided into 10 areas of action, such as implementation of the national peatland protection strategy, restoration of the water balance, promotion of sound forest ecosystems, sea and coastal areas, wilderness areas, etc. The Action Program is strongly connected to a wide range of other governmental programs and strategies to create and use synergies. The draft of the Action Program is currently being discussed in an online dialogue where stakeholders, the interested public, administration etc. can share their ideas and suggestions. It is expected that the cabinet resolution will be in early 2023.
- The development of a long-term approach that monetizes climate protection and biodiversity services that go further than existing certification systems. Thus, it enables forest owners to restructure their forests to increase climate change resilience and to afforest and reforest, if necessary.
- Old growth beech forests owned by the state will no longer be subject to wood extraction and all other publicly owed forests must be managed at least according to FSC- or Naturland[9]-Standards in the medium term.
- In September 2022 the ministries of economy, agriculture, and environment published key points on the National Strategy on Biomass (Nationale Biomassestrategie[10]). The strategies' goal is to provide Germany with a framework that allows in a long run a sustainable use of resources and to protect climate and biodiversity. Principles of the sustainable production and usage of biomass will be developed to set more incentives and targets for sustainable biomass use. The most important guiding principle will be a consequent cascading and multiple usage of biomass. Material use in which C can be stored long-term should always have priority before energetic usage. This strategy serves also to address the increasing pressure on land use by balancing between nature protection and food production..
- The National Peatland Protection Strategy (Moorschutzstrategie[11]) aims to reduce annual greenhouse gas emissions from peatland soils by at least 5 Mio. t of $C0_2e$ by 2030. To achieve

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[8] https://www.bmuv.de/download/aktionsprogramm-natuerlicher-klimaschutz
[9] https://www.naturland.de/en/producers/service-and-expertise/standards.html
[10] https://www.bmwk.de/Redaktion/DE/Publikationen/Wirtschaft/nabis-eckpunktepapier-nationale-biomassestrategie.pdf?__blob=publicationFile&v=18
[11] https://www.bmuv.de/themen/naturschutz-artenvielfalt/naturschutz-biologische-vielfalt/moorschutz#c61293

this, the strategy relies on financial incentives for voluntary rewetting measures of peatlands used for agriculture and forestry as well as for the improvement and restoration of natural peatlands. The strategy also pursues the goal of ending the use of peat in horticulture due to its negative impact on the climate and replacing it with sustainable substitutes. The peat reduction strategy of the Ministry of Agriculture and Food of July 2022 picks up on this goal and sets milestones and measures for phasing out peat use.

- The National Strategy on Bioeconomy (Bioökonomiestrategie[12]) has been adopted in March 2020. Bioeconomy has the goal to sustainably combine economy and ecology. The strategy lays the foundation to develop principles and goals for the implementation of the strategy. Two overarching principles shape the objectives and activities of the strategy. First, available biological knowledge and technologies as the basis towards a sustainable and climate-neutral economic system. And second, resources, which are the base of the economy, need to be directed into sustainable production systems and integrated into a circular economy.

In September 2022, the Bioeconomy Council published a statement[13] on the consequences and global disruptions in food, energy and raw materials supply caused by the armed conflict between Russia and Ukraine. A sustainable bioeconomy can provide solutions and explicitly mentioned are short-, medium-, and long-term strategies to mitigate the effects worldwide and in Germany. Short-term measures comprise, among others, the focus on food security. Agricultural products that can be used as food should no longer be integrated in process for energy production. The number of livestock should be decreased and eventually feed grain could also be used as food grain. The consumption of meat should be reduced by financial incentives set in the plant-based food sector and new innovations regarding meat substitutes. Further, the possibilities of the Common Agricultural Policy[14] of the EU should be better used to increase the agricultural production in Germany sustainably.

A new instrument to push for more climate adapted forest management and a more extensified wood use has been introduced by the ministry of agriculture (BMEL) in July 2022[15]. This instrument rewards forest owners for providing ecosystem services of forests and efforts for additional climate and biodiversity protection[16]. In a long-term this approach addresses concrete measures that go beyond existing legal requirements and certification systems for additional climate and biodiversity services. The goals are:

- to maintain and develop resilient, adaptable, and productive forest,

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[12] https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/nationale-biooekonomiestrategie-langfassung.html

[13] https://www.biooekonomierat.de/media/pdf/stellungnahmen/Stellungnahme_des_BOER_zur_Ernaehrungs-_Energiekrise.pdf?m=1662392320&

[14] https://agriculture.ec.europa.eu/common-agricultural-policy_en

[15] https://www.bmel.de/SharedDocs/Pressemitteilungen/DE/2022/93-wald-foerderprogramm.html

[16] https://www.gstb-rlp.de/gstbrp/Schwerpunkte/Wald im Klimastress/Konzept Finanzierung Klima+Biodiversität Wald für HH-Ausschuss.pdf and it

- stabilization and enhancement of biodiversity also as a basic prerequisite for resilience and vitality of forests and the provision of ecosystem/climate protection services,
- and contributing to the conservation of natural C reservoirs and additional greenhouse gas mitigation, which is aligned with the requirements of the Federal Climate Protection Act, which sets mitigation targets for the LULUCF sector for the years 2030 and 2045.

The step towards the payments of ecosystem services has already been described as a necessary measure to maintain and improve the provision of ecosystem services by an expert opinion of the Scientific Advisory Board for Forest Policy to the BMEL in 2021. It is essential that our forests will have the abilities to buffer negative consequences of increasing temperatures, changes in the precipitation regime but most to comply with extreme events such as storms, insect infestations and fires. The experts advocate a system, which provides forest owners with predictable revenues from the provision of ecosystem services. A pragmatic approach would be to reward the adaptability of forests towards climate change as a basis for all future provisions of all ecosystem services. It is recommended to orientate the payments along the state of a forest.

Implications on the LMT forest management may also have the latest revision of the renewable energy directive (RED III[17]) that is currently in the trilogue negotiations between the EU Council, Commission, and Parliament. The directive sets a target that by 2030 45 % for renewable energy in the EU's energy consumption. Highly debated is the consumption of energy wood, which might no longer be considered as renewable and primary woody biomass thus might not be eligible for funding. Further, it will be mandatory for wood to be used in cascade use and there will be requirements for forest management.

All the above-mentioned initiatives, action plans, and suggestions of expert groups tend all to protect, stabilize, enhance, or re-establish ecosystems that with regard to LMTs, have the potential to increase storage and uptake of CO_2. However, it very much depends on the concrete implementation and interactions among differently targeted policies what exactly impact on emissions and removals from land use will be.

[17] https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en

3. LMT narratives

This section elaborates further on the LMTs identified in the short-list. Information on the potential for emission reductions and increased removals, the durability or reversibility, synergies, and conflicts with other societal goals are provided. The content provided in the sub-chapters on climate related risks and impacts and effects on the local environment derive from expert opinions.

3.1 Afforestation

In 2018, about 17,000 ha of net new forest area was added, mainly from grassland (UBA 2020a). The expansion of forest area allows CO_2 from the atmosphere to be sequestered and stored over a long period of time in growing above-ground and below-ground biomass of forest stands and in the forest soil. In this process, C stocks usually increase continuously compared to previous land use. During the conversion of grassland to forest, temporary emissions from the soil may occur under certain circumstances, e.g., when the soil is tilled for the establishment of the tree stand. In the course of the growing forest stand, possible losses of C stocks due to young growth and thinning measures must then be taken into account. There are hardly any studies available so far for the potential to increase forest area in Germany, but there are estimates from the climate protection report in agriculture and forestry (BMEL 2016b).

The expansion of forest area is countered by land conversions from forest to other land uses. These occur primarily in the course of infrastructure expansions. By law, these losses of forest land must be compensated. Nevertheless, significant emissions are initially generated due to the high losses of carbon stored in biomass. In 2018, approximately 6,890 ha of forest land in Germany was converted into settlement areas, resulting in emissions of approximately 1.7 Mt CO_2e (UBA 2020b).

3.1.1 Potential of the option for climate protection

In the climate protection report of the scientific advisory boards of the German Federal Ministry of Food and Agriculture (BMEL 2016b), a total afforestation area potential of 5% (850,000 ha) of agricultural land was assumed, starting from the year 2012 until 2050. For the year 2030, just under half of the land potential can already be achieved. The average tree species distribution of the first age class (1 to 20 years) from the last federal forest inventory in 2012 was used as a basis for calculating the reduction potential. This showed a proportion of 58% deciduous trees and 42% conifers. Thus, the study indicates a reduction potential of 4.7 t CO2e per ha, or 18 Mt CO_2e by 2030. As forest cover grows, the accumulation of carbon in biomass increases quasi-exponentially and can reach a mitigation potential of approximately 120 Mt CO_2e. for Germany by 2050.

3.1.2 Durability or reversibility of the option

The forest area in Germany is legally protected from larger clearcuts (> 1 ha) as well as forest conversion to other land uses. Therefore, a large-scale reduction of the forest area is not to be expected. Nevertheless, forest areas will continue to be converted primarily to settlement areas in the future. By

2050, BMEL (BMEL 2016b) assumes about 5,000 ha per year. In contrast, natural disturbances such as dry periods, storms, insect pests (e.g. bark beetles), and fire can cause considerable damage even in young forest stands. Dry periods, in particular, can be especially damaging to young trees whose root systems are not yet well developed and can even lead to plant death. As climate change progresses, the frequency and magnitude of natural disturbances such as drought and storms can be expected to increase (Seidl et al. 2014). For this reason, the resilience of future forest stands is crucial to their durability and climate change mitigation performance in afforestation measures. The choice of tree species is therefore of particular importance, as is the method of afforestation, whether from plantations, seeding or natural regeneration.

3.1.3 Synergies and conflicts with other societal goals

In addition to carbon sequestration and the long-term provision of raw material for wood products, forest areas have a positive influence on water infiltration into the soil and thus also on groundwater recharge. Compared to cropland, the rate of groundwater recharge decreases over time as evapotranspiration and interception of growing trees increase. However, by avoiding fertilization and pesticide use, it can be assumed that the quality of the leachate is significantly better (BMUB/UBA 2016). Afforestation areas can also make a positive contribution to the protection of biodiversity due to their succession stages to forest stand. Compared to arable land with few structures, species communities typical of forests can form here. However, conflicts for species protection arise where species-rich grassland is converted into forest. This should therefore be avoided, also with a view to possible losses of soil carbon.

Further conflicts may arise with an increasing demand for agricultural land. This competition for land could be exacerbated by further measures for climate protection, such as the rewetting of organic soils and the extensification of arable land. In addition, negative relocation processes may occur abroad if some agricultural goods, such as meat and dairy products, can no longer be produced in Germany. This could further exacerbate environmental problems such as deforestation and drainage of organic soils for the production of agricultural goods abroad. The extent of these displacement effects from measures such as the expansion of forest area is thus very closely linked to the development of consumption of agricultural goods, especially meat and dairy products, and land for infrastructure. The discussion on how to use land received a new spin as in February 2022 Russia started to invade Ukraine as the questions of food and energy security moved into the focus.

3.1.4 Climate related risks / impacts and effects on the local environment

As a result of the expert interview, the most relevant climate-related extreme events are according to the interviewee heat waves, droughts, fires, strong winds and biotic disturbance events such as insect infestation.

Heat waves lead to the shedding of leaves/needles and tissue damage impairing the capabilities of photosynthesis and growth, which is especially relevant for A/R. Beech and spruce trees are more affected than pine and oak. Within Germany the East, West and Centre are more affected than the North or South.

Droughts occurred in 2003, 2018, 2019 and 2022. Again, beech and spruce trees are more affected than pine and oak. The failure of xylem causes irreversible damage to water conducting tissues, a lack of C leads to reduced photosynthesis activities, and drought-stressed trees are more vulnerable regarding insect attacks. An adaptation needs to consider a higher species diversity.

Natural forest fires hardly occur, largest risk through human causes and land history (e.g. old military areas with old ammunition). Stand structure influences fire behaviour (lot of undergrowth creates fire-ladders for fire to reach canopies) only high forest less susceptible than coppice

The risks regarding damage due to strong storms must be differentiated between species, stand structure, management, and neighbouring effects. Effects of other climatic conditions, such as soil moisture and season (foliaged trees) play a role. Stronger effects occur due to reduced tree vitality and re-enforcing effects in combination with other disturbances, e.g., damage to the fine roots, where no visible damage is detected.

Biotic disturbance events (insects) strongly relate to drought and management. The interviewee expects that biotic disturbances will gain further importance and they are directly affected by climate change (warmer winters, more populations of beetles) and indirectly through changes in forest growth and resilience (e.g., reduced vitality after drought). This category deserves more granularity.

The most important parameters regarding the effects of AR on the local environment are C sequestration, nutrients retention in the soil, water balance, and soil protection.

A/R contribute highly to the parameter of C sequestration mostly in a positive way (increased C sequestration due to growth). The impacts on the nutritious soil level and soil protection depend very much on how A/R is carried out. If it is a plantation or the establishment is industrialized, it might harm the soil and its nutrients but if degraded lands is restored this leads to an improvement regarding nutrient retention and soil protection. Regarding impacts on the hydrologic balance, it also depends very much on the type of A/R and its management, e.g., plantations are water demanding. Coniferous species can decrease soil water status, also in winter as they lose water due to interception.

3.2 Forest Management

Forest management can contribute to the continuous uptake of CO_2 from the atmosphere by trees and to the increase of carbon stocks in the living and dead biomass as well as in the soil through targeted measures. Forest carbon dynamics are very complex and biomass growth and natural mortality are influenced by site factors (climate and soil). For example, beech growth may be lower on average in regions with less precipitation, such as Brandenburg and Saxony-Anhalt, than in low mountain regions with more precipitation (e.g. Hesse and Thuringia) (BMEL 2012). Emissions in forests are predominantly caused by the death and subsequent decomposition of trees, with deadwood also representing a carbon pool. The decomposition of deadwood, and thus the release of emissions, varies by tree species and site conditions.

Harvest intensity has a significant influence on forest carbon capture and storage (e.g. Pilli et al. 2016). If annual biomass removal through timber harvesting remains below the annual net-to-increase (increment minus natural mortality) of wood biomass in the forest, then carbon storage in the forest continuously increases. According to the latest carbon inventory from 2017, wood utilization in Germany has decreased significantly since 2012 (-19%). On average, 74 Mm³ of wood were harvested annually between 2002 and 2012, compared to about 62 Mm³ between 2012 and 2017.

Thus, on average, 76% of the increment was siphoned off. As a result, the average wood stock increased by 6 % to 358 m³/ha from 2012 to 2017, as in the previous ten years (2002 to 2012). A major part of this increase in stock occurred in spruce tree species (+ 54 Mm³) (Hennig et al. 2019). In the future, the carbon sink in the forest is expected to decline, as the stock built up especially in spruce and pine stands of the same age is likely to be reduced by the upcoming timber harvest (UBA 2021). Although actual harvest volumes tended to be lower compared to expected skimming through 2017, a significant increase is expected with the recent forest damage (see below). The effects on the sink capacity of the forest have not yet been estimated.

The carbon stock in wood biomass is directly related to the carbon storage of wood products. When wood is harvested, the wood product store fills up while the carbon store in the forest decreases. From the forest's point of view, timber harvesting represents an emission. By using the wood in products, this emission is delayed. The calculation of carbon dissipated in wood products is complex because the use time of wood products is very different and there are different recycling processes that also must be considered. Finally, if the wood is used for energy, emissions are produced. In Germany, approximately 30 % (23 Mm³)[18] of the total harvested wood was used for energy in 2019. This applies predominantly to hardwood, as around 67 % of the harvested hardwood is used for energy and therefore does not contribute to the wood product store. Long-lived wood products in particular retain emissions. Due to the advantageous product properties and easy processing of softwood, it is preferably used, for example, in timber construction (WBGU 2020). Alone 66 % (37 Mm³)[19] of the harvested softwood in 2019 will be processed as sawnwood. In addition, wood products can contribute to reduce emissions in other sectors by substituting products with a worse climate balance, e.g. concrete in the construction sector. Substitution effects of wood products in the future are very much dependent on the development of renewable energy supply, which can again significantly improve the carbon footprint of non-wood products. In the LULUCF sector, the substitution effects from wood use are not accounted for, but in the respective sectors where they are used.

[18] Thünen-Institut für Internationale Waldwirtschaft und Forstökonomie, Thünen-Einschlagsrückrechnung, BWI3, Amtliche Statistik

[19] https://www.wri.org/blog/2020/06/global-tree-cover-loss-data-2019

3.2.1 Potential of the option for climate protection

Based on data from the 2012 Federal Forest Inventory, the WEHAM-Nature Conservation Preference Scenario (WEHAM-NPS) was developed in a project of the Forest Climate Fund (Oehmichen et al. 2018). This traces the development of the forest starting from 2012 to 2050 and aims at silviculture with a focus on promoting native forest biodiversity. In the WEHAM-NPS, forest conversion towards deciduous and mixed deciduous forests is targeted, with conifers that are ready for cutting being rapidly harvested and replaced with predominantly deciduous species of the natural forest community. Where conifers occur naturally, however, they were also encouraged. Thus, the proportion of coniferous wood was reduced by 19% and the proportion of deciduous trees increased by 15 %. In addition, deciduous trees were harvested less and remained longer in the forest to increase their stock. Overall, the average wood stock increased from 345 m^3/ha in 2012 to 374 m^3/ha in 2052. Deadwood stock was also increased from approximately 20 m^3/ha to 40 m^3/ha to promote biodiversity tied to these structures. In addition, the forest area with use restrictions or without wood use was slightly increased, which also contributed to the build-up of wood biomass. Thus, a total of about 31 million tCO2 by 2030 and 35 Mt CO_2 by 2050 annual sink performance was achieved in the forest. This is about 20 Mt CO_2 more in sink performance in 2050 compared to the WEHAM baseline scenario, which continues the existing forest management from 2012 (Rüter et al. 2017). In the WEHAM-NPS, between 70 and 80 million m^3 of wood was harvested over the simulation period, yet the wood product reservoir is transformed into an emission source of up to about 4 Mt CO_2 (Rüter et al. 2017). This is mainly due to the fact that the assumptions for material and energetic wood use remain the same over time. Thus, the hardwood generated in WEHAM-NPS was predominantly used for energy rather than materials, directly releasing emissions.

The historical sink performance of the forest can likely only be maintained through 2050 via greater extensification. In the "Waldvision" study by Böttcher et al. (2018b), which is also based on data from the 2012 Federal Forest Inventory, timber extraction is reduced by 25 % compared to a baseline scenario. Compared to the WEHAM-NPS, the forest vision shows an even lower logging intensity, especially in hardwoods. This is partly a consequence of the assumption that areas without forestry use are increased to 16.6 %. This increases the average wood stock to 501 m^3/ha in 2052, resulting in an average annual carbon sink of -48 Mt CO_2 in the living forest biomass (-14 Mt CO_2 in the baseline scenario). However, non-utilization is accompanied by reduced carbon sequestration in wood products, which is why approximately 14 Mt CO_2 emissions are recorded annually from these by 2052.

3.2.2 Durability or reversibility of the option

Beech-dominated deciduous and mixed forests are the actual climax society (hypothetical end-state of vegetation development) in Germany (Fischer 2003). Under expected climate changes, this is unlikely to change significantly for many regions, although productivity losses of beech in dry regions are to be expected (Dulamsuren et al. 2017). In addition, the dominance of beech in tree species composition could shift in favor of other broadleaf species, such as sessile oak and field maple (Mette et al. 2013; Walentowski et al. 2017). Therefore, investing in forest carbon stocks as a climate mitigation measure is a good option. The sink potential of forests can decrease in quite short time periods, due to natural disturbances and human interventions. As climate change impacts on forests are likely to increase in the future (Seidl et al. 2017), current and future management decisions are of particular importance to promote and maintain forest resilience and thus forest sink permanence in the long term (Mausolf et al. 2018). Currently, forests in Germany are not in a natural state when the tree species composition is considered, as it is predominantly dominated by spruce and pine (BMEL 2016a). In addition, the distribution of age classes, breast height diameters, and deadwood quantities and dimensions do not correspond to the optimal ecological state on average (Reise et al. 2017b). This can have a direct negative impact on forest resilience to climatic change and other disturbances (Norris et al. 2011; O'Hara und Ramage 2013). The past few years, 2018 to 2020, have demonstrated this very clearly. They were characterized by storm events, prolonged dry periods, and subsequent bark beetle infestations on spruce trees. In combination, these ultimately led to a damaged wood accumulation of 171 Mm^3 on approx. 277,000 ha of forest area, as estimated by the BMEL[20], with spruce being predominantly affected. In contrast, deciduous tree species contributed only about 9 % to the emerging damaged wood[21] . Nevertheless, deciduous trees such as beech have also been affected by the drought and have lost vitality. In addition, their mortality has increased, but it is still significantly lower than that of other broadleaf and conifer species (BMEL 2020a). Currently, no estimates are available on the loss of the carbon sink in the forest. Nevertheless, it is clear that tree species selection and the associated resilience of forests are directly related to the success of the climate change mitigation measure of building carbon stocks in forests. For this reason, forest conversion towards deciduous and mixed forests is a key measure. In addition, it makes sense to promote natural structures such as old and strongly dimensioned trees as well as a higher amount of deadwood in order to support natural biodiversity and increase resilience to natural disturbances.

The conversion to mixed forests and their resilience to climate change are also essential factors in ensuring the continued production of wood products in Germany. In addition, due to an ever-increasing demand for bioenergy, there continues to be competition with energy use, which, however, in the case of direct energy use, usually has no positive effects on climate protection (Hennenberg et al. 2019). The energetic use of wood should be at the end of the utilization cascade in order to increase the retention time of carbon in the wood product store. Therefore, innovations in hardwood utilization are also needed to promote its material use.

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[20] BMEL release (31.12.2020): https://www.bmel.de/DE/themen/wald/wald-in-deutschland/wald-trockenheit-klimawandel.html#doc14830bodyText3

[21] https://www.bmel.de/SharedDocs/Pressemitteilungen/DE/2020/040-waldschaeden.html

3.2.3 Synergies and conflicts with other societal goals

The measures to promote carbon sinks in the forest can be implemented on the existing forest area, which means that, compared to other land-based climate protection measures, there is no direct competition for land.

In addition, synergies for the protection of biodiversity can result if native deciduous tree species are promoted in the future and, above all, a higher proportion of older deciduous trees is left in the forest. In addition, a higher proportion of deadwood and a higher diversity of deadwood structures (lying, standing, different dimensions) also contribute (Reise et al. 2017a; Reise et al. 2019). In addition, promoting more deciduous trees in the forest can lead to higher groundwater percolation rates, compared to conifer stands (Müller 2019).

A key conflict of the option to increase carbon stocks in the forest is with economic interests in timber harvesting, especially for conifers. Currently, timber production is the main source of income for forest owners. New models of financing are needed and as described in section 7 are already being discussed. Politics already promised that there will be payments for ecosystem services.

Increased use of durable wood products and recycled wood can make an important contribution to climate protection, especially in the building sector (WBGU 2020). However, the sustainability of wood use is highly dependent on overall consumption. Should the demand for wood products increase to such an extent that domestic forests and those abroad have to be managed intensively, then disadvantages for the protection of biodiversity may occur and the forest sink would decrease (Verkerk et al. 2014).

3.2.4 Climate related risks / impacts and effects on the local environment

The most relevant climate-related extreme events are according to the interviewee heat waves, droughts, fires, strong winds and biotic disturbance events such as insect infestation.

Heat waves lead to the shedding of leaves/needles and tissue damage impairing the capabilities of photosynthesis and growth. Beech and spruce trees are more affected than pine and oak. Within Germany the East, West and Center are more affected than the North or South.

Droughts occurred in 2003, 2018, 2019 and 2022. Again, beech and spruce trees are more affected than pine and oak. The failure of xylem causes irreversible damage to water conducting tissues, a lack of C leads to reduced photosynthesis activities (carbon starvation), and drought-stressed trees are more vulnerable regarding insect attacks. An adaptation needs to consider a higher species diversity.

Natural forest fires hardly occur, largest risk through human causes and land history (e.g., old military areas with old ammunition). Stand structure influences fire behavior (lot of undergrowth creates fire-ladders for fire to reach canopies) only high forest less susceptible than coppice

The risks regarding damage due to strong storms must be differentiated between species, stand structure, management, and neighboring effects. Effects of other climatic conditions, such as soil moisture and season (foliaged trees) play a role. Stronger effects occur due to reduced tree vitality and re-enforcing effects in combination with other disturbances, e.g., damage to the fine roots, where no visible damage is detected.

Biotic disturbance events (insects), strongly relate to drought and management has an effect of this event. The interviewee thinks that biotic disturbances will gain further importance and they are directly affected by climate change (warmer winters, more populations of beetles) and indirectly through changes in forest growth and resilience (e.g. reduced vitality after drought). This category deserves more granularity.

The most important parameters, seen by the expert, regarding the effects of FM on the local environment are C sequestration, nutrients retention in the soil, water balance, and soil protection.

Forest Management contributes highly to the parameter of C sequestration in a positive and negative way. The impacts on the nutritious soil level and soil protection depend very much on the harvest regime. A higher harvesting frequency is probably more damaging to the nutrient soil status in comparison to a careful management that brings in nutrients from harvesting residues. The type of management strongly influences the hydrologic balance, especially in water scarce situations.

3.3 Conservation and improvement of carbon content in agricultural mineral soils

Organic carbon (C_{org}) is stored in soils in the form of dead soil organic matter (humus), e.g. consisting of plant residues or animal excreta and their microbially transformed components. Humus consists of approximately 58% carbon and is formed on agriculturally used soils mainly from crop residues and organic fertilizers (e.g. manure and compost) (Thünen Institut für Agrarklimaschutz 2018). Due to the microbial degradation of the C_{org}, CO_2 is released and only a smaller fraction remains in the soil and is stored there in the long term. The humus content of soils is determined in principle by the amount and type of organic matter input and its decomposition. The main factors influencing this, and thus the C_{org} storage potential, are climate and soil properties (Kolbe 2012). Soil management also influences humus content through factors such as tillage, crop rotation, and fertilization. A good example of this are the mineral soils of permanent grassland, which have up to one-third higher C_{org} stocks compared to soils under average cropland use. This is mainly due to the year-round vegetation cover and intensive rooting as well as the lack of soil tillage (Poeplau et al. 2011). Therefore, maintaining permanent grassland on mineral soils is an important measure to avoid emissions from mineral soils and to store C_{org}. Furthermore, the conversion of arable land to grassland can have a positive impact on climate protection.

To maintain a positive climate impact by storing C_{org} in the soil, more carbon must be sequestered from the atmosphere via humus build-up and the existing C_{org} must be protected (Chen et al. 2019). However, the build-up of soil C_{org} is limited in time and quantity as a new equilibrium is established between carbon input and C_{org} removal. To maintain the level of C_{org} storage, the constant input of carbon into the soil is necessary. If the humus enrichment measure is abandoned, then a rapid degradation of C_{org} stocks occurs again (Thünen Institut für Agrarklimaschutz 2018).

According to the German BBodSchG §17, it is part of good professional practice to ensure the long-term preservation of the site-typical humus content, whereby two measures are essentially emphasised: One is the sufficient supply of organic matter and the reduction of tillage intensity. Extensive tillage reduces the mineralisation of the C_{org} by microbes and the associated CO_2 emissions. A sufficient supply of organic matter can be achieved primarily through efficient and low-loss recycling of nutrients in the arable soil, e.g. through the following measures (Sykes et al. 2020; Thünen Institut für Agrarklimaschutz 2018):

- intercrop cultivation and undersown crops for revegetation,
- cultivation with perennial crops such as clover grass,
- leaving crop residues on the field,
- organic fertilization,
- planting hedges and trees (agroforestry).

3.3.1 Potential of the option for climate protection

There are no studies that present the overall potential of mitigation measures from arable soils and the accumulation of humus as carbon storage in soils for Germany as a whole. In a study by Wiesmeier et al. (2017), the C_{org} storage potential for agricultural soils in Bavaria was determined. In the results, it is clear that these have a high storage potential, as they are only about 50% saturated with carbon. In determining the total potential, the measures implemented were expansion of intercropping and organic farming, improved crop rotation, introduction of agroforestry systems, and conversion of arable land to grassland for humus enrichment. Thus, Wiesmeier et al. (2017) assume a total annual potential for C_{org} storage in Bavaria of 0.37 Mt C (1.3 Mt CO_2).

A long-term cultivation of catch crops on arable land could increase C_{org} stocks in the soil by an average of 8 t C/ha (29 t CO_2/ha) in the topsoil within 20 years (Poeplau und Don 2015).

The positive effect for humus build-up in organic farming is probably related to the use of organic fertilizer and the increased cultivation of clover grass and alfalfa. This can result in an increase in soil carbon stocks of 3 to 4 t C/ha (11 to 15 t CO_2/ha), compared to conventionally managed cropland (Gattinger et al. 2012). However, it should be noted that humus build-up through organic fertilizer does not result in net CO_2 uptake from the atmosphere, but rather in nutrient recycling and thus the transfer of fertilizer carbon to the soil (Rumpel et al. 2020).

Despite individual studies and model results on possible developments of the C_{org} soil stock in agriculturally used soils, the question of potential cannot be answered with certainty at present. Overall, however, the potentials of C_{org} accumulation in arable soil through targeted measures seem to be very uncertain (BMEL 2016b; Rumpel et al. 2020) and are probably subject to quite high regional variability.

Further research is needed to obtain better, regionalised asbestos estimates for humus build-up potentials in Germany and to develop measures to protect existing stocks (Thünen Institut für Agrarklimaschutz 2018).

3.3.2 Permanence or reversibility of the option

Soil C_{org} stocks generated by humus-enhancing measures are depleted very quickly if the measures are discontinued or substantially changed. Therefore, comprehensive humus management concepts for farms are necessary, but would require long-term compliance with the measures (Thünen Institut für Agrarklimaschutz 2018). This could possibly be a barrier for farmers.

3.3.3 Synergies and conflicts with other societal goals

Building up C_{org} stocks in arable soil has many positive effects for soil properties, which may even outweigh climate change mitigation effects (Rumpel et al. 2020). Overall, soil structure and fertility can be improved, as well as water absorption and storage capacity. This, in turn, can contribute to the resilience of arable soils to the impacts of climate change. In addition, high soil carbon levels protect against soil erosion. In sum, the improvement of soil properties can also contribute positively to agricultural productivity and thus further guarantee the food supply (Frank et al. 2017).

Conflicts can arise, above all, from an excess of organic fertiliser, as this can upset the nutrient balance of the soil and lead to N_2O emissions. In addition, nitrogen can enter the groundwater, but also heavy metals, hormones and microplastics, if compost or biogas waste is used for fertilisation in addition to manure. The positive effect of biochar to build up humus on nutrient-rich soils of the temperate climate zone is also questionable, as this has so far only been proven in nutrient-poor, tropical soils (Jeffery et al. 2011). Further, there are many open questions regarding the suitable pollutant-free initial substrate, the profitability, and the overall ecological assessment.

3.4 Conservation of carbon in organic soils and restoration of wetlands

In contrast to mineral soils, organic soils contain a high proportion of organic matter (> 12%, IPCC 2014). Organic soils are formed in peatlands by the formation of a peat layer of at least 30 cm and 30% organic matter over thousands of years. These peats consist of plant biomass (e.g., peat mosses) that does not decompose under the water-saturated conditions and associated lack of oxygen. As a result, peatlands can store carbon for thousands of years (Michel et al. 2011). Because of their high water content, peatlands are considered as wetlands. Due to agricultural use and the construction of settlement structures, the drainage of peatlands in Germany began many centuries ago. As a result, the water table in the organic soil decreases and the stored carbon escapes into the atmosphere via oxidation. A large part of the drained organic soils is located in the northwest of Lower Saxony, Mecklenburg-Western Pomerania and Brandenburg but also in the foothills of the Alps in Bavaria (BMEL 2016b). If the water table is ≥ -0.1 m, then the soils are considered undrained, which applies to only 8% (150,000 ha) of organic soils in Germany. These are located on unused land but also in forests and grassland (Tiemeyer et al. 2020). The average water table in grassland is -0.5 m and in cropland -0.6 m. While undrained organic soils produce hardly any CO_2 emissions, when drained to -0.9 m, emissions of up to 40 t CO_2/ha/a can occur (Tiemeyer et al. 2020).

Therefore, avoiding emissions from drained organic soils in grassland, cropland, and wetlands is of high importance to maintain the net sink in the land use sector in Germany. If the water table is raised again to the point where peatlands regenerate, then they can additionally contribute to the capture and storage of carbon from the atmosphere.

In addition, emissions arise from the extraction of peat. In Germany, about 4 million m³ of peat was extracted in 2018, mainly in Lower Saxony, and about the same amount was imported, mainly from the Baltic States[22]. Since 1980, peat extraction has largely been carried out on drained and fallow agricultural land, which is subsequently rewetted if there is still a layer of peat about 50 cm thick. Peat is used as an important basic substrate, especially in private and commercial horticulture (BMEL 2020c). The German Federal Ministry of Food and Agriculture (BMEL) will develop a peat reduction strategy with the aim of discontinuing peat use in the private sector and significantly reducing it in commercial horticulture. In the long term, the aim is to reduce peat use in Germany (BMEL 2020b). The use of peat moss from paludiculture cultivation (see below) is being researched as a possible substitute substrate (Krebs et al. 2015).

After raising the water table on managed organic soils, emissions can be effectively avoided (Tiemeyer et al. 2020). However, intensive use as pasture and fodder cropland or the cultivation of common crops is no longer possible. In contrast, grassland management as extensive pasture can be an alternative use even with higher water levels. In addition, extensively used wet grasslands are a species-rich ecosystem that contributes to the protection of a variety of species (Isselstein 2018). Another alternative form of management can be the cultivation of paludicultures such as cattails (Typha), reeds (Phragmites) and peat mosses (Sphagnum). They are cultivated under rewetted conditions, which protects the still existing peat body and thus emissions from peat decomposition can be avoided (Wichtmann et al. 2016).

3.4.1 Potential of the option for climate protection

In a study by Prognos et al. (2020), measures to avoid emissions from cultivated organic soils are implemented, which by 2030 could reduce emissions by 7 Mt CO_2e (25.2 t CO_2e/ha) can be achieved. To achieve this, peat cutting was stopped in this scenario and 20% (278,000 ha) of arable land and grassland was rewetted by 2030. Of this land, 40 % is used for extensive grazing or mowing and 30% is used for paludiculture. The remaining 30 % of rewetted land will be permanently removed from use. By 2050, the rewetted area will be increased to nearly 50% (650,000 ha) and half of it will be used for

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[22] Bundesinformationszentrum Landwirtschaft

paludiculture, while the remaining rewetted areas will no longer be cultivated. As a result, 18 million t CO_2e (27.7 t CO_2e/ha) of emission reduction can be achieved.

In the climate protection report of the scientific advisory board at the BMEL (BMEL 2016b), three measure scenarios for achieving emission reductions on organic soils are presented.

In these scenarios, rewetting and extensification of the use of organic soils are implemented on different proportions of land, with total emission reductions approximately 20 years after implementation of the measure, ranging from 7 to 15.2 Mt CO2e per year (BMEL 2016b). For the calculations of these mitigation potentials, it was assumed that rewetting , depending on the depth of the water level, has between 20 and 40 t CO_2e/ha of potential savings (see Table 4). In the potential effect of extensification measures, water levels are also crucial, as well as the type of change in land use. For example, raising the water level and changing the use from cropland or intensive grassland to extensive grassland can result in a reduction of up to 20 t CO_2e/ha (BMEL 2016b).

Table 4: Scenarios illustrating mitigation potentials for rewetting and extensification of organic soils (BMEL 2016b).

Scenarios for reducing emissions from organic soils	Agricultural area for rewetting in Mha	Assumption of reduction potential in t CO_2e/ha for rewetting	Area for extensification in million ha	Assumption of reduction potential in t CO_2e/ha for extensification	Total reduction potential in Mt CO_2e/year
Scenario a)	0.1	40	0.2	15	7
Scenario b)	0.2	30	0.4	10	12
Scenario c)	0.3	20	0.6	6	15.2

In a publication by Tanneberger et al. (2021), two scenarios are considered to achieve emission reductions on organic soils under cropland and grassland. With a complete conversion of cropland on orgenic soils to grassland and an abandonment of peat cutting by 2030. In addition, water levels in grassland are raised to an annual average of -30 cm (wet) to 15 % completely rewetted by 2030. This will result in emission reductions of up to 17 Mt of CO_2 by 2030. Finally, all organic soils in grassland (including cropland) will be rewetted by 2050. This will save a total of 35.8 Mt CO_2 emissions compared to 2020 (Tanneberger et al. 2021).

3.4.2 Durability or reversibility of the option

In principle, the measure is reversible, as emissions can be released again through renewed direct or even indirect drainage (e.g. interventions in the water catchment area of the peatland). Therefore, the permanent change in the use of organic soils is a necessary prerequisite to ensure the long-term nature of the climate protection effect (BMEL 2016b). Due to ongoing climate change and the resulting lower precipitation in some regions, there could be a seasonal lowering of the water table on rewetted areas. This effect may be exacerbated if the hydrology of peatlands is compromised by human impacts (e.g.

high water use in settlements). Therefore, it is important to restore the natural water balance in the catchment area of rewetted peatlands, if possible (Swindles et al. 2019).

Emission reduction potential can be reduced due to methane emissions that may occur after rewetting. These emissions are caused by methanogenic bacteria in the uppermost soil layer (Hendriks et al. 2007). Therefore, removal of the top soil layer prior to rewetting can reduce up to 99 % of methane emissions (Harpenslager et al. 2015).

3.4.3 Synergies and conflicts with other societal goals

Many synergies arise for the water balance and especially for nature conservation (BMEL 2016b). The rewetting of organic soils with subsequent extensive use as wet grassland, creates valuable habitats that can be used by many meadow bird species that have become rare (e.g. lapwing) (Oppermann et al. 2020). For reasons of meadow bird protection, sufficiently extensively managed grassland areas should therefore be preserved and not completely rewetted. Complete rewetting with renaturation and subsequent protection of peatlands also makes an important contribution to achieving national and European biodiversity goals (BMU 2007; European Commission 2020). However, the implementation of these measures may lead to competition for arable land, especially for animal feed, field crops and intensive pasture. This can cause economic disadvantages for some rural regions, e.g. in the northwest of Lower Saxony (BMEL 2016b). In addition, if a substantial part of organic soils under agricultural use is rewetted, cultivation on mineral arable land and grassland could intensify, which may be detrimental to environmentally sound production (Tanneberger et al. 2021). In addition, this may lead to further relocation of agricultural production abroad, which could possibly lead to additional emissions, such as deforestation and peatland drainage. Therefore, measures to reduce emissions from organic soils should be implemented together with accompanying measures to reduce the consumption of all meat and dairy products (WBGU 2020). The cessation of peat extraction and subsequent rewetting of land has a positive impact on nature conservation goals (see above). However, as long as no cost-effective and high-quality substrate alternatives for horticulture are available, peat imports may still occur in the medium term, which also lead to emissions (BMEL 2016b).

3.4.4 Climate related risks / impacts and effects on the local environment

The most approved relevant climate-related extreme events are according to the interviewee droughts and fires. Other extremes, such as heat and cold waves, frosts, very mild winters, and landslides are likely to have an impact but still lack the scientific experience.

Droughts have an impact on the water supply and on productivity and **fire** is occurring on peatland. **Heat waves** effect the water supply as well and have an impact on the productivity of grassland if on organic soil.

The expert concludes that the most important parameters regarding the effects of Rewetting on the local environment are water balance, soil protection, bird diversity, climate resilience and fire risk reduction.

Rewetting contributes highly to the **water balance**. Vegetation that is adapted to wet conditions show higher evatranspiration than grassland on drained soils. It might be necessary to store "winter water" onsite to have a full inundation (aboveground water levels of >50cm) during the winter time to avoid too low water tables in summer. The impacts on **soil protection** depend very much on the intensity of rewetting measures. The nearer the water tables get to the soil surface, the higher the emission reductions on GHG will be. The effects on the birdlife of rewetted areas will be important for aquatic bird species (and ornithologists) but also managed rewetted areas are a prerequisite for the re-introduction of rare bird species such as the aquatic warbler (*Acrocephalus paludicola).* Regarding **climate resilience,** when an area is fully rewetted, N_2O emission will immediately stop, CO_2 emissions are reduced with every increase in water levels up to 5 cm below the soil surface. If water tables rise above this threshold, CH_4 emission occur. Rewetting has a negative effect on the occurrence of peat **fires**.

3.4.5 Socio-economic risks and uncertainties

The expert sees the main constraints regarding the implementation of rewetting are the acceptance of land users and landowners, the lack of sufficient incentives, the missing of political willingness and a missing market for products from paludiculture. The most promising opportunity seems to be the potential to reduce GHG emission and mitigate climate change. The expert currently sees problems as there is still an underestimation by the population of drainage-based management of peatlands and thus there is not enough support for rewetting and the implementation of paludiculture.

4. Conclusions

4.1 Contribution of LMTs in Germany to climate protection

The land-based mitigation technologies reported in the land use change and forestry (LULUCF) sector in Germany still form a net sink and can thus contribute to Germany's path to climate neutrality. The most important LMT in Germany is the forest. The sink capacity of the forest is projected to decline. In order to achieve a sufficient net sink capacity in the future, emissions from land use from arable land and grassland, among other things, must be more than halved from the current level of over 40 million tonnes of CO2e In addition, the sink capacity of forests would have to be restored to approximately the current level.

Ambitious protection of organic soils, e.g. through rewetting, can avoid emissions from land use and at the same time create valuable habitats for various wetland species. In addition, carbon can be sequestered in wood in the long term through more extensive management in already resilient mixed and deciduous forests, through afforestation and via the establishment of woody structures on agricultural land. These LMTs can also contribute to the protection of biodiversity in forest stands of relatively high density and create new valuable habitats.

4.2 Limitations to the LMT potential

The potential of LMTs in Germany is limited. All mitigation measures will require significant changes in management to some extent, and they conflict directly or indirectly with each other or with other land uses such as settlement expansion in relation to land demand. Where mitigation measures affect agricultural or forestry production, displacement effects need to be taken into account, e.g. through accompanying measures such as livestock reduction and changing consumption patterns.

The need for financial investments for e.g. compensation payments will depend on many different factors. In general, mitigation measures in the land use sector can trigger opportunities for development in rural areas and be of social benefit. They are often not quantifiable but are likely to have a positive impact.

Climate change will affect all investigated LMTs in the medium to long-term perspective. Impacts on plant growth may be positively influenced by higher average temperatures, whereas acceleration of decomposition, especially in wetlands, may lead to net emissions over time. Increasing natural disturbances are also expected to have a negative impact on the carbon stored in trees.

5. References

BMEL (2012): Ergebnisdatenbank der Bundeswaldinventur. Bundesministerium für Ernährung und Landwirtschaft. Online verfügbar unter https://bwi.info/, zuletzt geprüft am 31.08.2017.

BMEL (2016a): Der Wald in Deutschland. Ausgewählte Ergebnisse der dritten Bundeswaldinventur. Bundesministerium für Ernährung und Landwirtschaft.

BMEL (2016b): Klimaschutz in der Land- und Forstwirtschaft sowie den nachgelagerten Bereichen Ernährung und Holzverwendung. Bundesministerium für Ernährung und Landwirtschaft, zuletzt geprüft am 03.04.2017.

BMEL (2020a): Ergebnisse der Waldzustandserhebung 2019, zuletzt geprüft am 20.05.2020.

BMEL (2020b): Gärtnern ohne Torf - Schützt das Klima! Online verfügbar unter https://www.torffrei.info/fileadmin/torfminderung/dateien/Torf_Flyer_DIN_Lang.pdf, zuletzt geprüft am 08.06.2021.

BMEL (2020c): Torf und alternative Substratausgangsstoffe. Bonn. Online verfügbar unter https://www.ble-medienservice.de/0129/torf-und-alternative-substratausgangsstoffe, zuletzt geprüft am 07.06.2021.

BMU (2007): Nationale Strategie zur biologischen Vielfalt. Vom Bundeskabinett am 7. 11. 2007 beschlossen. Berlin.

BMUB/UBA (2016): Die Wasserrahmenrichtlinie – Deutschlands Gewässer 2015. Bonn, Dessau.

Böttcher, Hannes; Hennenberg, Klaus Josef; Winger, Christian (2018a): FABio-Waldmodell - Modellbeschreibung Version 0.54. Öko-Institut e.V. Berlin. Online verfügbar unter https://www.oeko.de/fileadmin/oekodoc/FABio-Wald-Modellbeschreibung.pdf.

Böttcher, Hannes; Hennenberg, Klaus Josef; Winger, Christian (2018b): Waldvision Deutschland - Beschreibung von Methoden, Annahmen und Ergebnissen. Öko-Institut e.V. Berlin. Online verfügbar unter https://www.oeko.de/fileadmin/oekodoc/Waldvision-Methoden-und-Ergebnisse.pdf.

Chen, Songchao; Arrouays, Dominique; Angers, Denis A.; Martin, Manuel P.; Walter, Christian (2019): Soil carbon stocks under different land uses and the applicability of the soil carbon saturation concept. In: *Soil and Tillage Research* 188, S. 53–58. DOI: 10.1016/j.still.2018.11.001.

dena (2021): dena-Leitstudie Aufbruch Klimaneutralität. Eine gesamtgesellschaftliche Aufgabe. Hg. v. Deutsche Energie-Agentur GmbH.

Dulamsuren, C.; Hauck, M.; Kopp, G.; Ruff, M.; Leuschner, C. (2017): European beech responds to climate change with growth decline at lower, and growth increase at higher elevations in the center of its distribution range (SW Germany). In: *Trees* 31 (2), S. 673–686. DOI: 10.1007/s00468-016-1499-x.

European Commission (2020): Stepping up Europe’s 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people. Impact Assessment accompanying the document

Communication from the Commission to the Europe-an Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Commission Staff Working Document (SWD(2020) 176 final Part 1/2).

Fischer, A. (2003): Forstliche Vegetationskunde. Eine Einführung in die Geobotanik. 3. Aufl. Stuttgart: Eugen Ulmer.

Frank, S.; Havlík, P.; SOUSSANA, J.-F.; Wollenberg, E.; Obersteiner, M. (2017): The potential of soil organic carbon sequestration for climate change mitigationand food security (CCAFS Info Note).

Gattinger, Andreas; Muller, Adrian; Haeni, Matthias; Skinner, Colin; Fliessbach, Andreas; Buchmann, Nina et al. (2012): Enhanced top soil carbon stocks under organic farming. In: *Proc. Natl. Acad. Sci. U.S.A.* 109 (44), S. 18226–18231. DOI: 10.1073/pnas.1209429109.

Griscom, Bronson W.; Adams, Justin; Ellis, Peter W.; Houghton, Richard a.; Lomax, Guy; Miteva, Daniela A. et al. (2017): Natural climate solutions. In: *Proceedings of the National Academy of Sciences* 114 (44), S. 11645–11650. DOI: 10.1073/pnas.1710465114.

Harpenslager, S. F.; van den Elzen, E.; Kox, M.A.R.; Smolders, A.J.P.; Ettwig, K.; Lamers, L.P.M. (2015): Rewetting former agricultural peatlands: Topsoil removal as a prerequisite to avoid strong nutrient and greenhouse gas emissions. In: *Ecological Engineering* (84), S. 159–168.

Hendriks, D. M. D.; van Huissteden, J.; Dolman, A. J.; and van der Molen, M. K. (2007): The full greenhouse gas balance of an abandoned peat meadow, Biogeosciences. In: *Biogeosciences* (4), S. 411–424.

Hennenberg, K.; Böttcher, H.; Reise, J.; Herold, A.; Bohn, F.; Gutsch, M.; Reyer, C. (2021): Interpretation des Klimaschutzgesetzes für die Waldbewirtschaftung verlangt adäquate Datenbasis – Reaktion auf die Stellungnahme des Wissenschaftlichen Beirats für Waldpolitik beim BMEL (vom 22.06.2021). Hg. v. Öko-Institut e.V. (Öko-Institut Working Paper 3/2021). Online verfügbar unter https://www.oeko.de/fileadmin/oekodoc/03-WP-Klimaschutzgesetz-Waldbewirtschaftung.pdf.

Hennenberg, Klaus; Böttcher, Hannes; Wiegmann, Kirsten; Reise, Judith; Fehrenbach, Horst (2019): Kohlenstoffspeicherung in Wald und Holzprodukten. In: *AFZ-DerWald* (17), S. 36–39.

Hennig, P.; Schnell, S.; Riedel, T. (2019): Rohstoffquelle Wald - Holzvorrat auf neuem Rekord. In: *AFZ-DerWald* 74 (14), S. 24–27.

IPCC (2014): 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). Intergovernmental Panel on Climate Change. Switzerland.

IPCC (2019): Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change. Online verfügbar unter https://www.ipcc.ch/srccl/.

Isselstein, J. (2018): Protecting biodiversity in grasslands. In: Athole Marshall und Rosemary Collins (Hg.): Improving grassland and pasture management in temperate agriculture. Cambridge: Burleigh Dodds Science Publishing (Burleigh Dodds Series in Agricultural Science, Number 51), S. 381–396.

Jeffery, S.; Verheijen, F.G.A.; van der Velde, M.; Bastos, A. C. (2011): A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. In: *Agr. Ecosyst. Environ.* 144 (1), S. 175–187. DOI: 10.1016/j.agee.2011.08.015.

Kolbe, H. (2012): Zusammenführende Untersuchungen zur Genauigkeit und Anwendung von Methoden der Humusbilanzierung im konventionellen und ökologischen Landbau. In: Bilanzierungsmethoden und Versorgungsniveau für Humus. Hg. v. Schriftenreihe des Sächsischen Landesamtes für Umwelt, Landwirtschaft und Geologie. Dresden.

Körschens, M.; Breitschuh, G.; Eckert, H. (2018): Agrarfakten-Humus als CO2-Senke-eine fatale Illusion. Online verfügbar unter http://files.agrarfakten.de/200000233-3eaf83faaa/AF%20Senke%2036%202018_07_24.pdf, zuletzt geprüft am 26.03.2021.

Krebs, M.; Gaudig, G.; Wichmann, S.; Joosten, H. (2015): Torfmooskultivierung: Moorschutz durch Moornutzung. In: *TELMA - Berichte der Deutschen Gesellschaft für Moor- und Torfkunde* Beiheft 5, S. 59–70. DOI: 10.23689/fidgeo-2927.

Mausolf, K.; Härdtle, W.; Jansen, K.; Benjamin M. Delory; Dietrich Hertel; Christoph Leuschner et al. (2018): Legacy effects of land-use modulate tree growth responses to climate extremes. In: *Oecologia* 187 (3), S. 825–837. DOI: 10.1007/s00442-018-4156-9.

Mette, T.; Dolos, K.; Meinardus, K.; Achim Bräuning; Björn Reineking; Markus Blaschke et al. (2013): Climatic turning point for beech and oak under climate change in Central Europe. In: *Ecosphere* 4 (12), S. 1–19. DOI: 10.1890/ES13-00115.1.

Michel, B.; Plättner, O.; Gründel, F. (2011): Klima-Hotspot Moorböden (Forschungs Report, 2). Online verfügbar unter https://www.thuenen.de/media/institute/ak/Projekte/moor/Klima-Hotspot_Moorboeden.pdf, zuletzt geprüft am 04.06.2021.

Müller, J. (2019): Die forsthydrologische Forschung im Nordostdeutschen Tiefland. Veranlassung, Methoden, Ergebnisse und Perspektiven. (Habilitationsschrift). Hg. v. Agrar- und Umweltwissenschaftliche Fakultät Universität Rostock. Rostock (SchrR Umweltingenieurwesen 91).

Norris, Catherine; Hobson, Peter; Ibisch, Pierre L. (2011): Microclimate and vegetation function as in-dicators of forest thermodynamic efficiency. In: *Journal of Applied Ecology* 102, no-no. DOI: 10.1111/j.1365-2664.2011.02084.x.

O'Brolchain, N. (2020): CAP Policy Brief Peatlands in the new European Union Version 4.8. Online verfügbar unter https://www.eurosite.org/wp-content/uploads/CAP-Policy-Brief-Peatlands-in-the-new-European-Union-Version-4.8.pdf.

Oehmichen, K.; Klatt, S.; Gerber, K.; Polley, H.; Röhling, S.; Dunger, K. (2018): Die alternativen WEHAM-Szenarien: Holzpräferenz, Naturschutzpräferenz und Trendfortschreibung. Szenarienentwicklung, Ergebnisse und Analyse. Johann Heinrich von Thünen-Institut. Braunschweig (Thünen report 59). Online verfügbar unter https://www.thuenen.de/media/publikationen/thuenen-report/Thuenen-Report_59.pdf.

O'Hara, K. L.; Ramage, B. S. (2013): Silviculture in an uncertain world: utilizing multi-aged management systems to integrate disturbance. In: *Forestry (Lond)* 86 (4), S. 401–410. DOI: 10.1093/forestry/cpt012.

Oppermann, R.; Pfister, S. C.; Eirich, A. (2020): Sicherung der Biodiversität in der Agrarlandschaft - Quantifizierung des Maßnahmenbedarfs und Empfehlungen zur Umsetzung. Institut für Agrarökologie und Biodiversität (IFAB). Mannheim.

Pilli, R.; Grassi, G.; Kurz, W., A.; Jose V. Moris; Raúl Abad Viñas (2016): Modelling forest carbon stock changes as affected by harvest and natural disturbances. II. EU-level analysis. In: *Carbon Balance Manage* 11 (1), S. 1–19. DOI: 10.1186/s13021-016-0059-4.

Poeplau, Christopher; Don, Axel (2015): Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. In: *Agr. Ecosyst. Environ.* 200, S. 33–41. DOI: 10.1016/j.agee.2014.10.024.

Poeplau, Christopher; Don, Axel; Vesterdal, Lars; Leifeld, Jens; van Wesemael, Bas; Schumacher, Jens; Gensior, Andreas (2011): Temporal dynamics of soil organic carbon after land-use change in the temperate zone - carbon response functions as a model approach. In: *Glob. Change Biol.* 17 (7), S. 2415–2427. DOI: 10.1111/j.1365-2486.2011.02408.x.

Prognos; Öko-Institut; Wuppertal-Institut (2020): Klimaneutrales Deutschland. Studie im Auftrag von Agora Energiewende, Agora Verkehrswende und Stiftung Klimaneutralität. Online verfügbar unter https://www.agora-energiewende.de/veroeffentlichungen/klimaneutrales-deutschland.

Reise, J.; Wenz E; Kukulka F; Linde A; Winter S (2017a): Bewertung der Waldbiodiversität der WEHAM-Szenarien. Hg. v. Allgemeine Forstzeitschrift (13).

Reise, Judith; Hennenberg, Klaus; Winter, Susanne; Winger, Christian; Höltermann, Anke (2017b): Analyse und Diskussion naturschutzfachlich bedeutsamer Ergebnisse der dritten Bundeswaldinventur. BfN-Skript 427. Bundesamt für Naturschutz.

Reise, Judith; Kukulka, Florian; Flade, Martin; Winter, Susanne (2019): Characterising the richness and diversity of forest bird species using National Forest Inventory data in Germany. In: *Forest Ecology and Management* 432, S. 799–811. DOI: 10.1016/j.foreco.2018.10.012.

Repenning, J.; Harthan, R.; Blanck, R.; Böttcher, H.; Braungarth, S. Bürger, V.; Cook, V. Emele, L. et al. (in press): Klimaschutzinstrumente-Szenario 2030 (KIS-2030) zur Erreichung der Klimaschutzziele 2030. Teilbericht.

Rumpel, Cornelia; Amiraslani, Farshad; Chenu, Claire; Garcia Cardenas, Magaly; Kaonga, Martin; Koutika, Lydie-Stella et al. (2020): The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. In: *Ambio* 49 (1), S. 350–360. DOI: 10.1007/s13280-019-01165-2.

Rüter, Sebastian; Stümer, Wolfgang; Dunger, Karsten (2017): Treibhausgasbilanzen der WEHAM-Szenarien. In: *AFZ-DerWald* (13), S. 30–31. Online verfügbar unter https://www.weham-szenarien.de/fileadmin/weham/Ergebnisse/AFZ_13_17_7_Treibhausgasbilanzen_der_WEHAM-Szenarien.pdf, zuletzt geprüft am 27.10.2017.

Seidl, Rupert; Schelhaas, Mart-Jan; Rammer, Werner; Verkerk, Pieter Johannes (2014): Increasing forest disturbances in Europe and their impact on carbon storage. In: *nature climate change* 4 (9), S. 806–810. DOI: 10.1038/nclimate2318.

Seidl, Rupert; Thom, Dominik; Kautz, Markus; Martin-Benito, Dario; Peltoniemi, Mikko; Vacchiano, Giorgio et al. (2017): Forest disturbances under climate change. In: *nature climate change* 7, S. 395–402. DOI: 10.1038/nclimate3303.

Swindles, G. T.; Morris, P. J.; Donal J. Mullan; Richard J. Payne; Thomas P. Roland; Matthew J. Amesbury et al. (2019): Widespread drying of European peatlands in recent centuries. In: *Nat. Geosci.* 12 (11), S. 922–928. DOI: 10.1038/s41561-019-0462-z.

Sykes, Alasdair J.; Macleod, Michael; Eory, Vera; Rees, Robert M.; Payen, Florian; Myrgiotis, Vasilis et al. (2020): Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology. In: *Glob. Change Biol.* 26 (3), S. 1085–1108. DOI: 10.1111/gcb.14844.

Tanneberger, Franziska; Abel, Susanne; Couwenberg, John; Dahms, Tobias; Gaudig, Greta; Günther, Anke et al. (2021): Towards net zero CO2 in 2050: An emission reduction pathway for organic soils in Germany. In: *Mires and Peat* 27, S. 1–17. DOI: 10.19189/MaP.2020.SNPG.StA.1951.

Thünen Institut für Agrarklimaschutz (2018): Humus in landwirtschaftlich genutzten Böden Deutschlands. Ausgewählte Ergebnisse der Bodenzustandserhebung. Hg. v. BMEL. Bonn. Online verfügbar unter https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/Bodenzustandserhebung.html, zuletzt geprüft am 09.06.2021.

Tiemeyer, Bärbel; Freibauer, Annette; Borraz, Elisa Albiac; Augustin, Jürgen; Bechtold, Michel; Beetz, Sascha et al. (2020): A new methodology for organic soils in national greenhouse gas inventories. Data synthesis, derivation and application. In: *Ecological Indicators* 109, S. 105838. DOI: 10.1016/j.ecolind.2019.105838.

UBA (2020a): Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto-Protokoll 2020. Nationaler Inventarbericht zum Deutschen Treibhausgasinventar 1990 – 2018. CLIMATE CHANGE 22/2020. Hg. v. Umweltbundesamt (UBA). Dessau-Roßlau, Germany.

UBA (2020b): National Inventory Report for the German Greenhouse Gas Inventory 1990 -2018. Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2020.

UBA (2021): Projektionsbericht 2021 für Deutschland. Gemäß Artikel 18 der Verordnung (EU) 2018/1999 des Europäischen Parlaments und des Rates vom 11. Dezember 2018 über das Governance-System für die Energieunion und für den Klimaschutz, zur Änderung der Verordnungen (EG) Nr. 663/2009 und (EG) Nr. 715/2009 des Europäischen Parlaments und des Rates sowie §10 (2) des Bundes-Klimaschutzgesetzes. Hg. v. Umweltbundesamt (UBA). Online verfügbar unter https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/projektionsbericht_2021_bf.pdf.

Verkerk, P. J.; Mavsar, R.; Giergiczny, M.; Lindner, M.; Edwards, D.; Schelhaas, M. J. (2014): Assessing impacts of intensified biomass production and biodiversity protection on ecosystem services provided by European forests. In: *Ecosystem Services* 9, S. 155–165. DOI: 10.1016/j.ecoser.2014.06.004.

Walentowski, H.; Falk, W.; Mette, T.; Jörg Kunz; Achim Bräuning; Cathrin Meinardus et al. (2017): Assessing future suitability of tree species under climate change by multiple methods: a case study in southern Germany. In: *Annals of Forest Research* 60 (1), S. 101–126. DOI: 10.15287/afr.2016.789.

WBGU (2020): Landwende im Anthropozän: Von der Konkurrenz zur Integration. Berlin. Online verfügbar unter https://www.wbgu.de/fileadmin/user_upload/wbgu/publikationen/hauptgutachten/hg2020/pdf/WBGU_HG2020_ZF.pdf, zuletzt geprüft am 02.06.2021.

Wichtmann, W.; Schröder, C.; Joosten, H. (2016): Paludiculture - productive use of wet peatlands. Climate protection - biodiversity - regional economic benefits.

Wiesmeier, M.; Burmeister, J.; Treisch, M. und Brandhuber, R. (2017): Klimaschutz durch Humusaufbau – Umsetzungsmöglichkeiten der 4 Promille-Initiative in Bayern. Online verfügbar unter https://www.researchgate.net/publication/321141231_Klimaschutz_durch_Humusaufbau_-_Umsetzungsmoglichkeiten_der_4_Promille-Initiative_in_Bayern, zuletzt geprüft am 26.03.2021.

Annex I Validation of Germany's LMT shortlist through stakeholders

The validation of the LMTs was done by stakeholders with whom contact was already established due to other projects. Several meetings were held and discussions took place in the context of those other projects and thus were also used for extracting the information needed regarding the validation of LMTs.

LMT	Meeting / Event	Stakeholders	Discussion	Conclusion
BECCS	6	4,5	Not in favor of a technical solution on bio energy; OI has no own capacities to follow up	Not to be considered further in LandMarc CS
Rewetting of organic soils	4, 5	3, 4, 6	Advanced on the political side, but lacks implementation mechanisms	Important LMT to be considered
Abandoning peat extraction	7	4	This is a measure that should be implemented faster	Important LMT to be considered
Avoided conversion of grassland			GL protection already legally binding, therefore no additional potential, however continuation needed for containing C stock still emissions from GL conversion due to net area approach	Relevant LMT to be considered, need for further exchange/ discussion
Afforestation			Currently not high on political agenda due to anticipated agricultural land demand	Important LMT to be considered, need for further exchange/ discussion
Managing forests incl. HWP	1, 2, 3	1,2,3,7,8	LMT with high potential but intensively debated between stakeholders High potential through large area Trade-offs with wood supply, therefore forest and HWP carbon storage need to be assessed in combination	Important LMT to be considered
Increasing carbon in soil and vegetation on agricultural land		4	Ongoing discussion with BMU	Relevant LMT to be considered

Meeting / Event

1. Workshop, FSC, Sozialkammer-Treffen, 21.01. 2021
2. Conference, Charta für Holz 2.0, Statustagung, 28.04.2021
3. Panel discussion, Familienbetriebe Land und Forst, Rewarding the climate protection performance of the forest, 06.11.2020
4. Bilateral exchange with the BMEL, 04.05. 2021
5. Bilateral exchange with Thünen-Institute and BMU, 07.05.2021
6. Bilateral exchange with BMU and UBA, various meetings in 2020
7. Bilateral exchange with BMU, project meetings in 2021 and e-mail exchange

Stakeholders

1. Certifiers of wood and forests, Forest Stewardship Council (FSC)
2. German Forest Associations (BDF, DFWR)
3. Federal Ministry of Food and Agriculture (BMEL)
4. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
5. German Environment Agency (UBA)
6. Thünen Institute, Institute of Forest Ecosystems
7. Timber and wood associations (German Timber Industry Council (DHWR), Main Association of the German Wood Industry (HDH), Association of the German Wood-Based Panel Industry e.V. (VHI), German sawmill and timber industry (DeSH)), Association of forest owners
8. Representatives of political parties in Germany

ANNEX III

OVERVIEW OF INPUT TABLES FOR SIMULATION MODELLING PER COUNTRY

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1. Germany

1.1. Qualitative storylines by identifying measures and actions from interviews for each LMT scenario

LMT 1: Forest Management

	1. Wishes of the future for the LMT: include timing	2. How to achieve the wishes • Who pays? • Who implements?	3. Target/Actions • Policies, strategies, projects
Scenario 1: "Reference" **Stakeholder representations:** Forest owners, forest administration	• Regenerate damaged forest areas with adapted species (including neophytes)	• Existing support schemes for forest regeneration and forest conversion • Private forest owners	• Continue existing support schemes
	• Maintain managed forest area for wood supply (about 97%)	• Revenues from wood supply • Private and state forest owners	• None
Scenario 2: "Achieve existing targets" **Stakeholder representations:** Forest owners, climate policymakers, government officials, forest administration	• Regenerate damaged forest areas with adapted species (limited share of neophytes)	• Increased funding for natural regeneration and planting of natural species • Private forest owners	• Adapt and extend existing support schemes for forest regeneration and forest conversion
	• Take 10% of national forest area out of production (at least for 20 years) • Implement national and EU targets on protected areas • Increase forest carbon stocks in adapted forest	• Support schemes for extensification of wood harvest, especially in broadleaved forests as al alternative to revenues from wood supply	• New support scheme • Involve voluntary (carbon) markets? • Guarantee of financial resources

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	stands (broadleaved and mixed stands) • Increase biodiversity in forests	• Reduce demand for fire wood • Private and state forest owners	
Scenario 3: "Green supreme" **Stakeholder representations:** NGOs, climate policymakers, government officials	• Regenerate damaged forest areas with adapted species (exclude neophytes)	• Increased funding for natural regeneration and planting of natural species • Private forest owners	• Adapt and extend existing support schemes for forest regeneration and forest conversion
	• Take 10% of national forest area **permanently** out of production • Take additional 10% of national forest area out of production (at least for 20 years) • Increase forest carbon stocks in adapted forest stands (broadleaved and mixed stands) • Increase biodiversity in forests	• Support schemes for extensification of wood harvest, especially in broadleaved forests as al alternative to revenues from wood supply • Reduce demand for fire wood • Private and state forest owners	• New support scheme • Involve voluntary (carbon) markets? • Guarantee of financial resources

LMT 2: Afforestation

	1. What are the wishes of the future for the LMT • include timing	2. How to achieve the wishes • How much does it cost? • Who pays for the cost? • Who implements?	3. Actions • policies, strategies, projects
Scenario 1: "Reference" **Stakeholder representations:** farmers	• Maintain forest area	• Reduce loss of forests due to land conversion • Deforested areas need to be compensated for • Compensation areas bought by state	• None
Scenario 2: "Achieve existing targets" **Stakeholder representations:** climate policymakers	• Increase forest area	• Reduce loss of forest area • Increase revenues from forests compared to agricultural land • Farmers/land owners	• Incentive schemes for establishing forests on grasslands and croplands •
Scenario 3: "Green supreme" **Stakeholder representations:** NGOs, climate policymakers	• Increase forest area substantially	• Reduce loss of forest area • Increase revenues from forests compared to agricultural land • Lower demand for (agricultural) land • Farmers/land owners	• Incentive schemes for establishing forests on grasslands and croplands • Reduce meat /livestock production to free land

LMT 3: Organic soils

	4. What are the wishes of the future for the LMT • include timing	5. How to achieve the wishes • How much does it cost? • Who pays for the cost? • Who implements?	6. Actions • policies, strategies, projects
Scenario 1: "Reference" Stakeholder representations:	• maintain agricultural area on organic soils	• continued management on organic soils	• none •
Scenario 2: "Achieve existing targets" Stakeholder representations:	• Reduce emissions from organic soils under forests, cropland and grassland	• Take organic soils out of production through rewetting • Paludiculture • Farmers/land owners	• Incentive schemes, including voluntary carbon market? • State buying land from farmers
Scenario 3: "Green supreme" Stakeholder representations:	• Reduce emissions from organic soils under forests, cropland and grassland	• Take organic soils out of production through rewetting • Paludiculture • Farmers/land owners	• Incentive schemes, including voluntary carbon market? • State buying land from farmers

1.2. Quantitative storylines: pace of implementation for each LMT

Table 1: Quantitative trends/pace of implementation of LMT options

	Current situation (baseline)	**Scenario 1: "Reference" Stakeholder representations:** Forest owners, forest administration		**Scenario 2: "Achieve existing targets" Stakeholder representations:** Forest owners, climate policymakers, government officials, forest administration		**Scenario 3: "Green supreme" Stakeholder representations:** NGOs, climate policymakers, government officials	
Year	Now	2030	2050	2030	2050	2030	2050

	(provide sources)	(change relative to the current situation) (provide sources)	(change relative to the current situation) (provide sources)	(change relative to the current situation) (provide sources)	(change relative to the current situation) (provide sources)	(change relative to the current situation) (provide sources)	(change relative to the current situation) (provide sources)
LMT 1: Forest management	3 % of forests not available for wood supply (NFI 2012)	3 % of forests not available for wood supply	3 % of forests not available for wood supply	7 % of forests not available for wood supply	10 % of forests not available for wood supply	10 % of forests not available for wood supply	20 % of forests not available for wood supply
LMT 2: Afforestation	Forest area 11,4 Mha in 2012 (NFI 2012)	Maintain forest area (compensate deforestation of ca. 5,000 ha per year, NIR Germany (2022))	Maintain forest area (compensate deforestation of ca. 5,000 ha per year, NIR Germany (2022))	Linear increase to 2050 value	425,000 ha	Linear increase to 2050 value	850,000 ha (BMEL 2016)
LMT 3: Soil carbon	Difficult to assess						
LMT 4: Organic soils	Area of drained organic soils 1,58 Mha (NIR 2022)	No change	No change	Linear increase to 2050 value	325,000 ha	278,000 ha (20% of drained organic soils, Prognos et al. 2020)	650,000 ha (50% of drained organic soils, Prognos et al. 2020)

References

NFI (2012): https://bwi.info/

NIR Germany (2022): https://unfccc.int/documents/461716

BMEL (2016): Klimaschutz in der Land- und Forstwirtschaft sowie den nachgelagerten Bereichen Ernährung und Holzverwendung. Bundesministerium für Ernährung und Landwirtschaft

Prognos; Öko-Institut; Wuppertal-Institut (2020): Klimaneutrales Deutschland. Studie im Auftrag von Agora Energiewende, Agora Verkehrswende und Stiftung Klimaneutralität.