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Options for Strengthening Natural Carbon Sinks and Reducing Land Use Emissions in the EU

Working paper

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List of Abbreviations

AR	Afforestation and reforestation
CAP	Common Agricultural Policy
CDM	Clean Development Mechanism
CRF	Common Reporting Framework
EC	European Commission
EEA	European Environmental Agency
EFA	Ecological Focus Area
EU	European Union
GAEC	Good Agricultural and Environmental Conditions
GHG	Greenhouse gas
HWP	Harvest wood product
IACS	Integrated administration and control system
IPCC	Intergovernmental Panel on Climate Change
LIFE	L'Instrument Financier pour L'Environment
LTE	Long-term experiments
LULUCF	Land use, land use change and forestry
MS	Member State
NDC	Nationally Determined Contribution
NIR	National Inventory Report
PES	Payment of Ecosystem Services
RDP	Rural development programme
SOC	Soil organic carbon
TREES	The REDD+ Environmental Excellence Standard
UBA	Umweltbundesamt
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
VCS	Verified Carbon Standard

Summary

This report assesses seven options for enhancing and maintaining natural sinks and carbon stocks in the EU land use sector until 2050. The options reviewed include forests (increase forest area, restore carbon stocks in forests and increase carbon storage in harvested wood products), agricultural soils under grassland and cropland (expand agroforestry coverage, maintain and enhance carbon in mineral agricultural soils and conserve carbon in organic soils and restore wetlands) and coastal wetlands (protect and restore saltmarshes and seagrass meadows).

The options were selected based on their mitigation potential, ensuring the availability of larger scale assessments in literature and representing options across different land use categories. We have analysed EU and National Inventory Reports (NIRs) and Common Reporting Framework (CRF) tables submitted to UNFCCC, as well as national and international scientific literature. Selective expert interviews were carried out.

Table 0-1 presents the summary of the assessment of all options reviewed. The largest absolute potential is expected from **restoration of carbon stocks in forests**, followed by **afforestation**. Hence, increasing the carbon storage in harvested wood products (HWP) appears to be of limited effectiveness due to trade-offs with forest carbon storage. **Rewetting and protecting organic soils** are effective measures to avoid emissions from land use and shows the highest mitigation potential per area unit. Also, **expanding agroforestry coverage** in all biogeographical regions of the EU has high mitigation potential, especially when involving high tree coverage. The **increase of soil organic carbon (SOC) in mineral soils** is a valuable measure that can also contribute to mitigation but mainly serves other important aspects like increasing soil fertility. Compared to other mitigation options there are uncertainties around estimates of the potential that can be practically achieved, as well as problems of reversibility and difficulty of monitoring.

Ranges of the potential vary widely, indicating that assumptions for the estimation need to be considered. **Integrated scenarios show the net sink potential of the EU in 2050 and provide a realistic range between 400 and 600 Mt CO_2 per year. The individual potential estimates per option are often competing for the same land and such interactive effects are not considered.**

Land-based mitigation options affect how land is managed and/or used. This characteristic determines whether an option entails a direct demand for additional land. Especially an increase of forest area, the expansion of agroforestry coverage and conservation of carbon in organic soils and wetland restoration can be considered options with explicit land use changes and therefore additional demand for land. Also options that require management changes can have an indirect land demand through leakage effects that occur if measures affect agricultural or forestry production levels. A certain risk of leakage is associated with all options. Such leakage effects depend on the degree of management change, the type of commodities affected, market reactions, as well as parallel changes in consumption patterns. Leakage risks need to be considered when options are implemented and can be addressed by option design and by accompanying measures for increasing resource efficiency and reducing overall consumption.

Co-benefits are found to be relevant for a number of aspects, including socio-economic factors, wood production, biodiversity, soil and water. But also trade-offs with biodiversity, food production, nitrogen and other GHG emissions need to be considered. Concretely, it is necessary to consider local circumstances and specific site conditions to adequately assess options. In general, mitigation measures in the land use sector can instigate opportunities for rural development and result in societal benefits that can often not be quantified but are likely to have a positive impact.

Climate change will impact all options considered in the medium to long-term perspective. While effects on plant growth can be positively impacted by higher average temperatures, an increase in decomposition rates can also be expected. Carbon stored in biomass is also likely to be subject to natural disturbances, which are expected to increase with progressing climate impacts. In particular, options involving trees are affected. Climate change risks thus need to be considered for all options, e.g. through the combination of mitigation with adaptation measures to reduce susceptibility of ecosystems to natural disturbances.

Table 0-1: Summary of assessment of options

Assessment variable	**Increase forest area**	**Restore carbon stocks in forests**	**Increase carbon storage in harvested wood products**	**Expand agroforestry coverage**	**Maintain and enhance carbon in mineral agricultural soils**	**Conserve carbon in organic soils and restore wetlands**	**Protect and restore saltmarshes and seagrass meadows**
Range of specific mitigation potential in t CO_2 per ha per year	2.2-7.7	0.9-2.5	0.16-0.28	0.01-7.3	0.5-7	≤ 23.5	Average CO_2 stock at 1 m: 49 – 4,050** Average sequestration rate: 0.11 – 5.5 **
Range of total potential in Mt CO_2 per year	77-210	150-400	25 – 44*	8 - 235	9-58	≤ 48	Unknown***
Type of mitigation	Removal	Removal & Avoided emission	Avoided emission	Removal	Removal & Avoided emission	Avoided emission	Removal & Avoided emission
Land use or management change	Land use change	Management change	Management change	Management change	Management change	Land use change/ Management change	Management change
Land requirement	Additional land	No additional land	No additional land	Additional land	No additional land	Additional land	No additional land
Risk of leakage	Leakage risks to be considered, options need to be accompanied by measures increasing resource efficiency and overall consumption						
Co-benefits	Socio-economic Wood production Biodiversity Water Soil	Biodiversity Water Soil Recreation	Socio-economic Substitution	Biodiversity Water Soil Recreation	Biodiversity Soil fertility	Biodiversity Water Recreation	Biodiversity Water Coastal protection
Trade-offs	Biodiversity Food production	Socio-economic Biodiversity Wood production	Biodiversity Carbon stocks in forests	Food production	Nitrogen	Food production Methane, nitrous oxide	Food production (fishing)
Climate change risks	Climate change risks to be considered, options need to be accompanied by adaptation measures to reduce susceptibility of ecosystems to natural disturbances						
Costs and socio-economic factors	Cost data often limited, depend on site conditions, knowledge and technology						
Monitoring and instruments for implementation	Data available; instruments available	Data available; instruments lacking	Data limited; instruments lacking	Data limited; instruments available	Data limited; instruments available	Data limited; instruments available	Data limited; instruments available

Source: Own compilation

* Values for 2030

** Numbers vary strongly among species and location (IUCN 2021)

*** Because the potential area for restoration of seagrass meadows and saltmarshes is currently unknown, no total potential is given in this summary.

There are no cheap mitigation options in land use according to the analysis. All options are associated with costs, mostly because compensation payments are needed to pay for loss of revenue or up-front investment, but also for rather complex technical challenges for the rewetting of organic soils. Short-term costs can be compensated with medium to longer term benefits, but the transition period still poses a challenge (e.g. agroforestry). Costs are also among the most uncertain aspects of options and not for all options readily available (see, for example, protection of marine ecosystems).

Looking at different options for emission reductions and carbon stock enhancement results in considerable ranges of potentials. Integrated assessments of land-based mitigation potentials are supposed to take interactions between separate options, competition for land and market effects into consideration. Only few studies have assessed the full land use sector, including all land categories and almost none has assessed potential implications for emissions outside the EU. Leakage effects leading to increased emissions from land use change and biomass production outside the EU can be significant but are difficult to assess. Potentials are likely to be overestimated as studies do not include important effects of climate change feedbacks. Also, co-benefits are largely underrepresented in potential assessments but are essential for realising the potential, both in terms of building resilience and economically viable options that encompass environmental integrity.

There is a risk that potentials for strengthening natural carbon sinks and reducing land use emissions are reduced through intensification of land management. Even today land areas in the EU are intensively used and partly degraded. Such pressures can reduce the effectiveness of mitigation options and reduce the ability of managed ecosystems to act as natural sinks. Also, ecosystem degradation has severe consequences for the resilience and stability of ecosystems against natural disturbances like storm, fire and drought as well as pathogens. While disturbances are an integral part of some ecosystems, under climate change they are likely to occur more frequently and with increased intensity, with implications for the mitigation potential and permanence of removals.

Based on this study, some overall messages and required steps can be identified for advancing policies on EU carbon sinks:

1) Protect existing sinks and create opportunities to enhance sinks by reducing pressures on land use and demand for land;
2) Ensure that enhancement of carbon sinks, as a baseline, improves on the current levels of biodiversity and ecosystem resilience and develop context-specific safeguards and criteria to ensure multiple ecosystem services are delivered and ecosystem resilience against future climate risks is enhanced;
3) Improve tools for impact assessment and decision making to support policy development and implementation as well as transparent monitoring, in particular at national and regional scale;
4) Increase coherence of EU policy mix towards enhancing sinks and reducing emissions in the EU and abroad.

1 Background and aim of the report

In September 2020 the European Commission (EC) proposed to increase the 2030 greenhouse gas (GHG) emission reduction target to at least -55 % compared to 1990 levels. While the EU policy framework originally excluded the land use sector, the proposal includes now the full scope of GHG emissions and carbon removals. According to the European Commission, the target forms an interim goal towards a climate-neutral EU and updates its Nationally Determined Contribution (NDC) under the Paris Agreement.

The EC long-term strategy (European Commission 2018) provides for a target of "achieving net greenhouse gas emissions of zero by 2050." The Paris Agreement also sets net zero emissions as a global target, but for the second half of the century. The special report of the IPCC on the 1.5°C target shows that in many scenarios the atmospheric concentration of greenhouse gases will exceed the necessary limits ("overshoot") in order to meet the temperature target, which in consequence will require not only net-zero but net-negative emissions.

It is thus clear that a central issue for medium and long-term climate protection in Europe and globally is the future role of carbon sinks. The land use sector, formally referred to as "Land Use, Land Use Change and Forestry" (LULUCF), is special because land use activities can create both GHG emissions and CO_2 removals. Its contribution to GHG neutrality in the future requires a long-term net negative balance of both terms. In 1990 the net sink in EU27 amounted to 275 Mt CO_2/year (EU 2020). In 2006 net removals of carbon by the sector peaked at 355 Mt CO_2/year and have since then declined to again 280 Mt CO_2/year in 2018. The current sink is dominated by the net uptake of CO_2 by existing and new forests. In contrast, the largest source is land conversion, especially from forests to other land uses (deforestation), and emissions from organic soils under cropland. To achieve a net balance of zero or below, emission sources must be simultaneously reduced, and carbon sinks maintained and significantly expanded.

Maintaining and increasing natural carbon sinks requires a combination of several categories of measures to achieve the required sequestration potential:

- Increase forest area, biomass and soil carbon through reforestation;
- Restore carbon stocks in forests through sustainable forest management and forest protection;
- Increase carbon storage in harvested wood products (HWP) by producing long-lived high quality wood products;
- Expand agroforestry coverage, maintain and increase landscape features (e.g. hedgerows, trees) in agricultural landscapes;
- Maintain and enhance carbon in mineral agricultural soils through sustainable soil management and restoration of degraded agricultural soils;
- Conserve carbon in organic soils and restore wetlands through restoration and rewetting of peatlands;
- Protect and restore saltmarshes and seagrass meadows.

The large heterogeneity of biophysical conditions, climatic conditions, and production systems that play a role in the management of natural sinks are currently a challenge for identifying references and baselines to measure progress and break down targets at the EU level to specific regions and production systems.

Recent studies attest to the great potential of different natural sink options (Griscom et al. 2017; Johnston und Radeloff 2019). However, it is important to keep in mind that any sink potential cannot be realised immediately. Instead, longer time scales are required to sequester carbon through new measures. There is a risk that carbon sinks in 2050 will be overestimated due to gradual sequestration and the uncertain effects of the future climate on these sinks (e.g. from forest fires or changing growth rates). In practice, this means that sequestration activities must ensure the stability and permanence of sequestered carbon, for example, by conducting afforestation in a way that ensures the resilience and sustainability of forest stands. This potentially leads to conflicting goals between measures to increase sink capacities and necessary adaptations to possible climate changes. At the same time, considerable efforts are required before 2030 to achieve long-term sequestration targets. To date, the implementation of measures for natural sinks is still insufficient in the EU (Paquel et al. 2017; Claessens et al. 2019)). In a recent survey on soil carbon sequestration, stakeholders in the EU identified the following main barriers to implementing sustainable land management measures (Claessens et al. 2019): lack of financial incentives, risks associated with changes in production systems, and lack of advisory services and available information on economic and productivity benefits of sink options. Increasing carbon sinks in the EU requires both action at the level of individual policies and integration between policies. In addition to the Common Agricultural Policy (CAP), climate and bioenergy policies, this includes the area of sustainable finance. An ambitious and coordinated package of measures is needed to drastically increase sequestration rates in Europe as early as between 2020 and 2030.

This report provides an overview and assessment of seven options for sink enhancement and reduction of emissions in the EU land use sector and is targeted towards policymakers and EU policy stakeholder groups.

2 Methodology

In order to identify and assess options for strengthening natural carbon sinks and reducing land use emissions in the EU, a screening of documents and data of different sources was performed. We analysed EU and National Inventory Reports (NIRs) and Common Reporting Framework (CRF) tables submitted to UNFCCC as well as national and international scientific literature. Selective expert interviews were carried out. The options were selected by looking at their mitigation potential, ensuring the availability of larger scale assessments in literature and representing options across different land use categories. This included both rather well documented and discussed options such as increasing forest area and restoration of forests and organic soils, and comparatively new options, like protection and restoration of marine ecosystems. The assessment of options based on the collected literature and data included the following criteria:

- Options were assessed by asking which specific (e.g. per unit area) and **overall mitigation potential** they offer, how and how strongly this potential is **constrained**, and how it will develop over time. There is a focus on the potential until 2050, however, estimates for 2030 are presented as well, for comparison purposes. The potential varies across EU Member States and regions as it depends very much on local circumstances and site conditions.
- Options were assessed regarding their **land requirement,** differentiating between land use change and land management change. However, also the latter can have indirect

displacement effects on other areas. **Risk of leakage,** i.e. the risk of options causing activity shifting with associated emissions from land use change to other places was assessed by exploring to what degree the options affect products and services from current land use and how much these products are traded. Also, substitutability of land use products matters for assessing the risk of leakage.

- Often both, **co-benefits and trade-offs** are associated with changes of land use. We reviewed the literature with regard to the impact of options on other ecosystem services and rated those positively where co-benefits outweigh trade-offs.
- **Costs** were considered as implementation costs and taken from literature. Cost estimates can include even more uncertainties than estimates of the effectiveness due to the need to make more assumptions on economic conditions. **Socio-economic factors** were assessed separately from general co-benefits and trade-offs to highlight impacts of options on employment and markets.
- **Climate change risks** arise where mitigation options in the land use sector are negatively affected by changes in temperature and precipitation. This includes secondary impacts of increased disturbances, e.g. through fire or insect outbreaks.
- **Monitoring** constitutes an additional criterion that assesses whether information for monitoring the above-mentioned impacts and the effectiveness of options is readily available. Finally, the assessment looked at **instruments for implementation** to identify existing policies that can be built upon.

3 Options for strengthening natural carbon sinks and reducing land use emissions

3.1 Increase forest area

Afforestation and reforestation (AR) comprise the conversion of non-forested land to forested land for generating carbon removals. Afforestation refers to the conversion of areas that have been without tree cover (mostly due to land use, rarely naturally unforested) for the last 50 years. Reforestation represents the conversion of previously forested areas (past 50 years) that are currently without trees into forests. Reforestation can also include bringing trees back into areas that no longer meet the national definition of forests, e.g. due to strongly reduced tree cover (i.e. less than 10-25 %). It is therefore closely related to forest restoration (see 3.1.7). Through AR, carbon is stored in different pools associated with tree growth and above and below-ground biomass, deadwood, litter and soil.

Afforestation and reforestation can be an effective climate change mitigation option because carbon sequestration in trees is especially high in the age classes between 20 and 60. Additionally, this mitigation option can have multiple co-benefits like the reduction of land degradation and improved water retention potential of the soil (IPCC 2019b). However, AR may also show trade-offs for biodiversity, e.g. on biodiverse grasslands (European Union 2019). Also, afforestation and reforestation need additional land and therefore compete with other land uses such as agriculture. Hence, leakage risks are important to consider and need to be monitored. Furthermore, this option comes along with costs if trees have to be planted and taken care of individually.

3.1.1 Potential

Range of mitigation potential in the EU

The EU mitigation potential in 2050 estimated by the CTI Roadmap tool[1] is 77-210 Mt CO_2 per year or 7.7 to 2.2 t CO_2/ha/year. The underlying two scenarios are the EU reference scenario (EC 2016) and the CTI 2050 roadmap (ECF 2010) which include an increase in forest area between 6 and 59 % (10 to 95 Mha). Another scenario from Griscom et al. (2017) assumes that all grazing land in forested ecoregions is converted into forests, which results in a much higher mitigation potential of 1,140 Mt CO_2/year.

From 1990 to 2018, about 0.4 Mha of land per year were converted to forest land within the EU27+UK. This rate has recently dropped to 0.25 Mha in 2018 because afforestation was comparatively strong during 1990 and 2000, especially in Southern Europe. Usually grassland and cropland were converted into forest land. The carbon sequestered by land converted to forest land was 41 Mt CO_2 (6 t CO_2 /ha) in 2018. This corresponds to an afforested area of 6.8 Mha, which according to UNFCCC definition constitutes the afforested land in the EU over the last 20 years (European Union 2020).

Generally, there was a net gain in forest land in the EU between 1990 (156.5 Mha) and 2018 (164.2 Mha) of 0.28 Mha on average per year. Compared to the average afforestation rate above (0.4 Mha per year) there was also a loss of forests of about 0.12 Mha annually. The majority of the forests were converted into settlements. This comparison emphasizes that options for increasing forest area in the EU need to include measures for reducing deforestation to be effective.

Carbon removals through land conversion to forests were largest in France, Italy, Germany, Spain and Ireland. In these five countries about 26 Mt CO_2 were stored in 2018 (Figure 3-1). EU countries with the largest areas reported under afforestation are France, Italy, Poland, Spain and Sweden which together account for 4.3 Mha. The highest area specific carbon sinks on afforested land are reported by Germany, Luxembourg, Romania, The Netherlands and Austria where CO_2 storage per ha per year was reported to be more than 10 t CO_2/ha. The annual average carbon storage rate in the EU is only at 6.3 t CO_2/ha.

Constraints of the mitigation potential

The assumptions on potential areas for AR vary immensely between the studies. The potential ranges from all grazing land in forested ecoregions (this would result in a forest area increase of about 50 %) to a forest area increase by only 6 % in 2050. There are limitations to the maximum available land for AR due to land competition between agriculture, nature conservation, protection of organic soils, and other land policies. Therefore, cropland area is mainly not assumed to be converted due to food security concerns.

Furthermore, other assumptions are important to explain the range of the mitigation potential in literature: areas considered where trees can realistically or theoretically grow, growth rates and success, tree species selection, planting trees for the afforestation or relying on natural revegetation and assumptions on the management and harvest of the forest.

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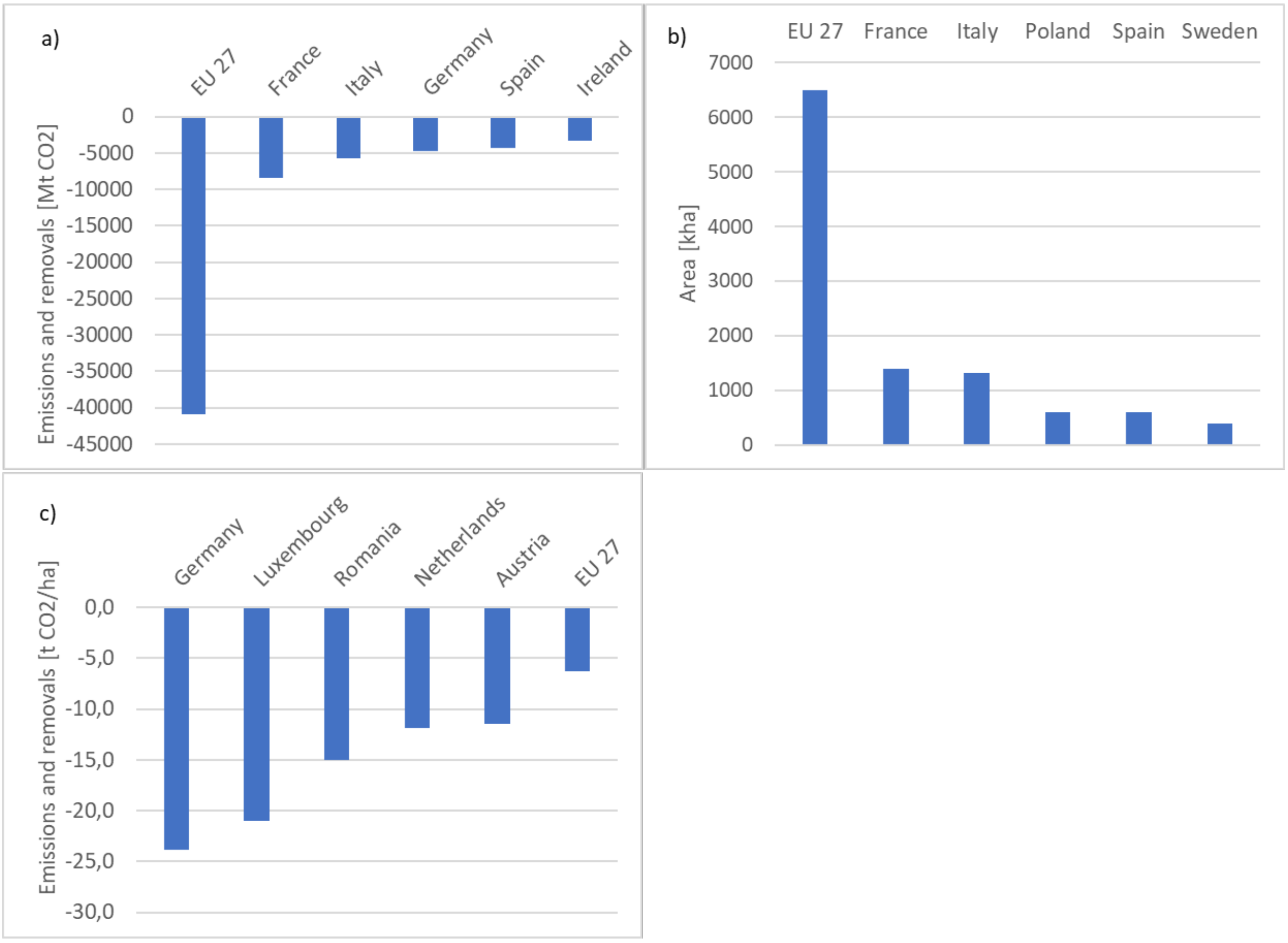
[1] CTI Roadmap tool (visited 11.05.2021)

Land use changes can cause ownership conflicts. Managed grassland is mainly owned and used by farmers who need incentives and knowledge about AR. Moreover, AR cannot be reversed easily, so this narrows down future land management options of farmers.

Figure 3-1: EU countries with largest a) absolute carbon removals through land conversion to forest land b) total area converted and c) implied removals per area in 2018 based on CRF reported data in category "2. Land converted to forest land". Note that a) and b) show cumulated values over 20 years according to reporting rules and not annual rates.



Source: National CRF data submitted to UNFCCC in 2020

As a mitigation option, AR is less effective in boreal areas like in Scandinavia due to the albedo effect (IPCC 2019b and Griscom et al. 2017). Dark coniferous trees absorb more solar radiation compared to open land leading to (local) warming and thus, in regions with slower tree growth, the net climate change mitigation effect of sequestered CO_2 is reduced.

Development of the potential over time

This option depends on tree growth, hence biomass accumulation in the forest. As new trees grow, biomass accumulation tends to be higher in the first decades than later, but absolute biomass is very low in the first decades. The accumulation rate of biomass also depends strongly on site conditions like climate, water availability and soil. Furthermore, after the establishment of new forests, forest management has an important effect on the amount of sequestered carbon (see 3.1.7).

3.1.2 Land requirement and risk of leakage

AR need land to be converted to forest land, and this constitutes the main constraint for this option. The land requirement in the scenarios considered ranges between 10 and 95 Mha until 2050 in the EU. The lower end of this range is approximately the level of AR that happened in the past 28 years in the EU (0.4 Mha per year, see section 3.1.1). Land availability for afforestation and reforestation highly depends on the assumed future land use and land use needs. If e.g. less meat production in the EU is assumed (either due to less meat consumption or more meat imports), less agricultural area is needed for fodder production and is therefore available for options like afforestation and reforestation.

There is the risk of leakage when grassland or cropland is afforested. This is why studies mainly do not consider cropland and grassland for conversion to forest land.

The risk of leakage can be significantly reduced when either abandoned land or land that is unsuitable for commercial purposes is used. A reduction in demand for land use products can also help to free land for afforestation. For example, a dietary shift to less meat and dairy products (from cattle held on grazing land) would reduce the demand for feed and reduce pressure on land in general.

3.1.3 Co-benefits and trade-offs

There are several co-benefits generally associated with AR: water filtration, increased availability of water, drought mitigation, flood control, avoided sedimentation, habitat for wildlife, increase of soil fauna, enhanced soil fertility and air filtration (IPCC 2019b). Possible trade-offs include competition for land and food security when cropland or grazing land is reduced. This might increase food prices. Depending on the actual status of the biodiversity of the area chosen for AR, a loss of biodiversity can occur, e.g. on certain grasslands. In boreal areas, AR is currently not recommended in relation to climate change mitigation due to the higher albedo of (dark) forests (IPCC 2019b and Griscom et al. 2017). Additionally, it is important to take the natural vegetation type into account, to choose the tree species that offer all the mentioned co-benefits. For example, only considering coniferous tree species in temperate regions results in changes of albedo, canopy roughness and evapotranspiration contributing to climate warming (Naudts et al. 2016).

3.1.4 Costs and socio-economic factors

The IPCC states in its special report on land and climate change (2019b) that costs for afforestation and reforestation are at a medium level. In a review paper, Fuss et al. (2018) present a cost range of 1-100 \$/t CO_2 with high agreement on the upper limit and most studies on the lower limit at about 20 \$/t CO_2. These are global average costs and do not necessarily reflect cost levels in the EU.

It must be considered that costs will most likely increase due to climate change and dryer climate, as more intense land management is required to assist adaptation in forests.

The option potentially entails high opportunity costs, depending on where afforestation is done. In less productive areas (for example, replacing extensive low productivity grassland or land in abandonment), afforestation can provide an alternative source of income for landowners. However, it takes decades before timber can be harvested. On the other hand, if afforestation is targeted at critical areas of soil erosion, it may have a positive impact by reducing runoff of water and risk of landslides. Afforestation may overall have limited impacts on local economies, also because labour inputs are small once the forest is established (Elbersen et al. 2014).

3.1.5 Climate change risks

Forests are as yet affected by climate change and young trees are especially vulnerable. While some species in some areas benefit from higher temperatures, elevated CO_2 levels and longer growing seasons, other species face growth limitations and increased mortality. Young trees are especially vulnerable to droughts as the roots are not so well developed.

The net effects on the sequestration potential depend on the future species composition of forests, the ability of species to adapt and also on management decisions (Seidl et al. 2014). The effects can be large for regions and countries, especially where only a few species dominate forest stands (Keenan 2015).

3.1.6 Monitoring and instruments for implementation

Monitoring carbon sequestration through AR requires regular inventories of carbon stocks in different pools. The biomass pool can be assessed with national forest inventories that exist in most countries. Field data can be combined with remote sensing information for a broader spatial and temporal resolution. Soil carbon stock changes are more difficult to monitor due to high spatial variability and are typically assessed through soil surveys and modelling (Boisvenue et al. 2016).

Afforestation has been supported under the CAP Rural Development Programmes, where increasing restrictions were placed in the last period 2014-2020 on tree species composition and targeting of areas where afforestation could take place. The environmental impact of afforestation was criticised due to the location of afforestation on ecologically valuable grasslands (Elbersen et al. 2014). The programming of afforestation measure was high in 2007-2013, whereas in the period of 2014-2020 more countries programmed agroforestry measures. Once a forest is established, national forest policy and legislation applies to the area (i.e. land becomes subject to forest management plans).

Afforestation will also continue to be eligible for payments in the post-2020 CAP under the investment measure in the Rural Development Programmes, under the provision that afforestation activities are consistent with climate and environmental objectives. In addition to public policies, market-based carbon certification schemes can reward landowners via carbon credits. A well-functioning example of such a scheme is Woodland Carbon Code in the UK.

3.1.7 Summary

In summary, AR is a very effective mitigation option that has many positive co-benefits if the area is selected according to ecological criteria which consider geographic location, natural vegetation cover and current biodiversity status of the area before AR. The land requirement for this option is rather high depending on the overall mitigation targets connected to this measure. Also, this measure requires land use change. Hence, potential land-use conflicts as well as risk of leakages if agricultural land is chosen for this option can occur. Therefore, less productive land can offer an opportunity to avoid leakage and offer income alternatives for landowners. Climate change is a potential threat to this measure because young trees are particularly vulnerable towards more frequently occurring weather events like extensive droughts. The future sequestration potential of the newly developing trees will depend on their ability to adapt towards changing climate conditions.

3.2 Restore carbon stocks in forests

Forest management for the restoration of carbon stocks in forests includes measures to create carbon removals by sequestration into biomass and soil on existing forest land but also the avoidance of emissions by preserving carbon stocks. The carbon dynamics in forests can be complex and involves different pools. Growing **living biomass** (above and below ground) takes up carbon from the atmosphere through photosynthesis. Biomass growth depends on site conditions (climate and soil), tree species, tree mortality and forest management. Natural mortality leads to carbon emissions from forests when CO_2 is released from decaying wood, but carbon is also transferred to **litter** or kept in **deadwood** and slowly transferred to **soil carbon**. Harvest of biomass transfers carbon to **harvested wood products** if the wood is not used for energy. The rate of harvest intensity plays an important role in managing carbon stocks (Pilli et al. 2016). Forest biomass will increase and therefore gain carbon when harvest rates are well below the average increment and natural mortality. Also, intensive wood harvest can have negative implications for the stand structure and forest resilience towards disturbances and climate change (Drever et al. 2006). Hence, long-term productivity and carbon sequestration of forests can be negatively affected as well (Ceccherini et al. 2020). There are natural limitations to carbon storage in forest biomass and soil that depend on site conditions, climate, species composition, forest structure and other parameters.

Carbon sequestration in existing forest biomass and soils can be achieved by **biomass growth.** Improving site conditions by fertilisation or drainage can increase biomass growth but also change conditions for biomass decay and soil carbon. Changes in tree species, however, require time, adequate windows of opportunity (e.g. at the end of a harvest cycle) and need to consider other implications of species change (e.g. biodiversity, naturalness of forests etc.).

Managed forests offer also the opportunity to increase carbon stocks in biomass through management decisions regarding **harvest intensity**. As long as natural mortality is lower than the original harvest rate, forest biomass and potentially also soils will gain carbon when harvest rates are reduced. Changes in harvest rates have implications for harvested wood products but also for forest structure. Stand stability and the longer-term productivity are important considerations to achieve long-term storage of carbon. Harvest operations may cause emissions from fossil fuels and other energy use. For achieving net carbon sequestration through forest biomass and soils, different measures exist.

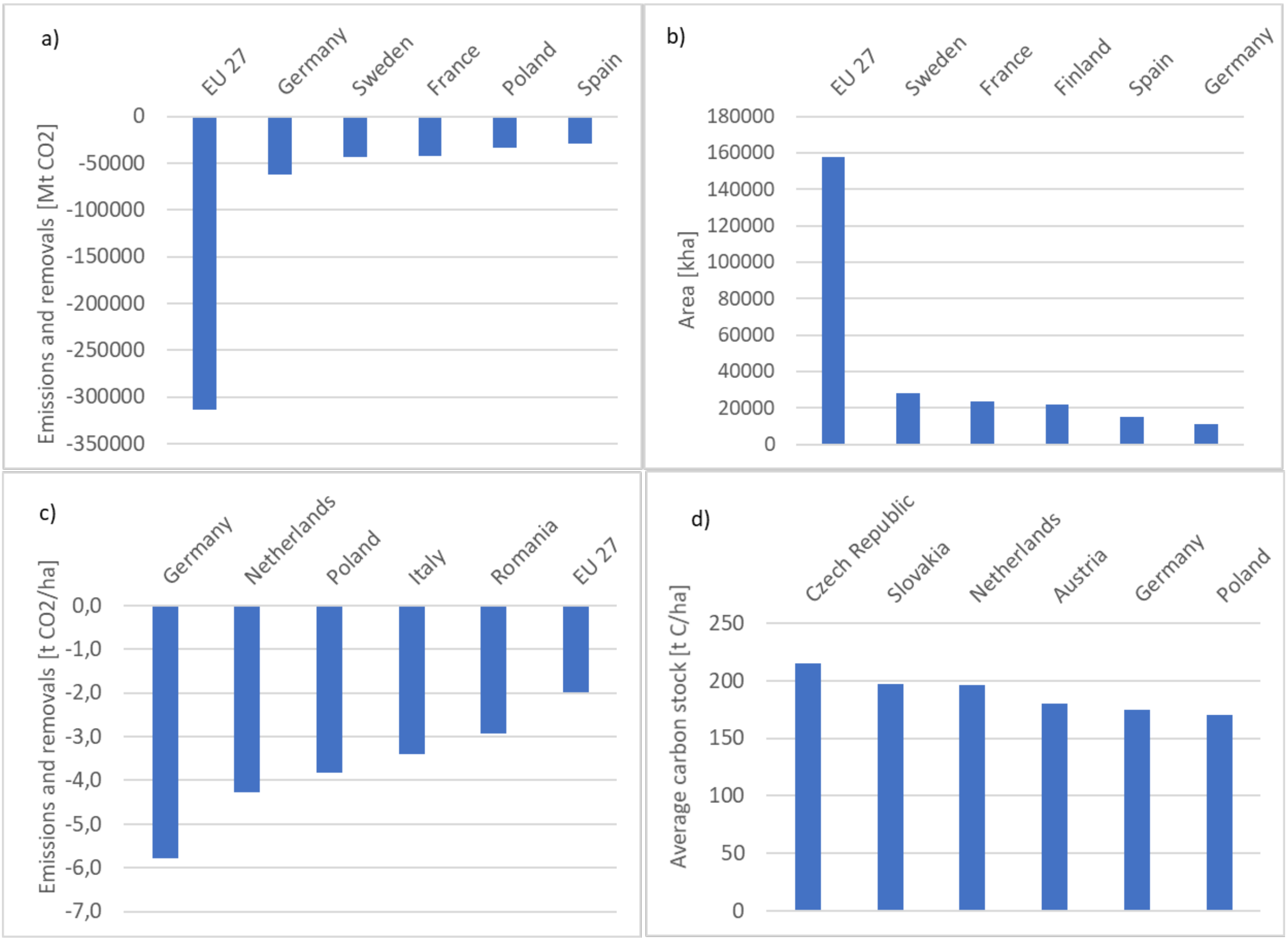
Carbon stocks in forest biomass and soils can be subject to **disturbances**, e.g. through fire and pests. Moreover, forests and their carbon stocks and growth are impacted by climate change, e.g. through drought events. Carbon sequestration in forests needs to consider such disturbances and climate change. The severity of disturbances and the related loss of carbon can be lowered through management, e.g. by reducing fuel load, introducing fire breaks, choice of species, pest control etc. The implementation of **adaptation** measures is also an important measure to ensure long-term storage of carbon. However, they can result in short-term trade-offs with mitigation targets, e.g. when carbon stocks need to be lowered to introduce new species better adapted to climate change.

3.2.1 Potential

Range of mitigation potential in EU

Studies with different ambition levels estimate the development of the forest carbon sink to range between 150 and 400 Mt CO_2 per year in 2050 (e.g. Nabuurs et al. 2017; EC 2016; European Commission 2020). This potential could be realised on the existing 160 Mha of forest land in EU countries, resulting in 0.9 - 2.5 t CO_2 per ha. A recent study by Welle et al. (2020) showed that sustainably managed EU forests could sequester 309 to 488 Mt CO_2 annually until 2050 compared to 245 Mt in 2010, only in biomass pools. The study assumed natural growing conditions in EU forests and alternative use of wood products like abandoning fuel wood use and reducing the use of hardwood for short-lived wood products.

Figure 3-2: EU countries with a) largest annual total sink, b) largest area, c) area specific CO_2 sink as reported in the category Forest land remaining forest land, and d) highest average forest biomass carbon stocks (Avitabile und Camia 2018)



Source: National CRF data submitted to U NFCCC in 2020, Avitabile und Camia 2018

Countries with the largest area are Sweden, France, Finland, Spain and Germany. All five account for almost 100 Mha of forest area (Figure 3-2). Except for Finland they are also among the top five countries regarding total forest sink. The largest absolute carbon sink in the EU can currently be found in German, Dutch and Polish forests. The sink potential is limited by the carrying capacity of forests that can vary considerably with site conditions, species but also management strategies. Currently, a number of countries with high sinks report the highest existing carbon stocks on average, e.g. Germany, Netherlands and Poland.

Constraints for the mitigation potential

The potential for forest management and forest restoration depends on the forest area, the net biomass growth rate and the current state of forest biomass and soil carbon stocks. Biomass growth in EU countries is limited mostly by temperature and water constraints. Also, nutrient availability is considered to be a limiting factor as well as excess of water in forested wetlands. Improving forest biomass growth through fertilisation, drainage, irrigation, etc., however, has considerable trade-offs with regard to GHG emissions from the activities and effects on soil carbon, e.g. higher decomposition rates of organic material.

An important parameter is the future harvest level assumed by studies estimating the forest sink potential. Recently, wood harvest intensity has been reported to be increasing (Ceccherini et al. 2020), with likely implications for the net storage of carbon in EU forests. There is also a scientific debate about the saturation of the sink and the role of forest age for the sink potential (Nabuurs et al. 2013; Luyssaert et al. 2008; Nord-Larsen et al. 2019). Maximum carrying capacities of forests also depend on disturbance regimes and their intensity that has recently increased.

Similarly, forest adaptation measures can be a temporary constraint for sink enhancement. An active forest conversion from less adapted tree species and monocultures to climate resilient mixed forests might require temporary reductions on carbon stocks. The pool of HWP can buffer such increased harvest rates partially if the harvested wood is used for long-lasting products, e.g. construction wood.

There are a number of hurdles for the implementation of mitigation through forest management and forest restoration. Measures that reduce management intensity in forests are usually considered to oppose economic goals in forestry. Another hurdle can be infrastructure to and within the forest. Single tree harvest compared to clear cutting requires a denser road network to transport the wood selectively logged. Motivation of forest owners is a key requirement for the implementation of management changes in EU forests (Nabuurs et al. 2018). There is a lack of alternative sources of income for forest owners other than timber sales that could be addressed by introducing payments for ecosystem services more broadly in forestry.

Development of the potential over time

The potential for forest management and forest restoration has specific time dynamics. Especially in intensively managed forests the age class structure of the existing stands determines the development of the potential over time but also constrains windows of opportunity for management changes. The rate of sequestration is constrained by the maximum tree growth and mortality rates. At which level of carbon stocks the level will be reached, depends on the history of forest stands, site conditions, impacts of climate change and other drivers that can not necessarily directly be influenced by management.

A part of the mitigation potential related to changes in forest management can be realised rather quickly, as in the case of extended rotation and reduced harvest. However, trade-offs with HWP need to be considered. Other options, like forest conversion for better adaptation and increased resilience is a long-term process with impacts on net carbon removals becoming measurable only after decades.

Past practice effects can overlay impacts of recent management changes and make the detection of changes in carbon storage induced by humans challenging. The complex time dynamics of carbon stock changes in forests have led to detailed accounting rules for forests under the Kyoto Protocol and the LULUCF Regulation (Böttcher et al. 2008; Böttcher et al. 2019).

3.2.2 Land requirement and risk of leakage

Restoration of forest carbon stocks does not directly require additional land. However, there can be indirect effects and leakage, due to changes in harvest volumes in the forest. Changes in forest management affect wood production potentials in different ways. The wood available for harvest is reduced while carbon stocks increase. Also changes in wood quality and availability of wood species can be assumed. If wood demand remains unchanged compared to the baseline, wood production might become more intensive in other areas, requiring an extension of the area harvested, potentially covered by increased imports (Rüter et al. 2016). This requires demand side measures as supporting policies but also a consistent and complete coverage of monitoring and accounting including all countries. Forest restoration, however, can also increase the wood available for use in forests, reducing the risk of leakage and leading to net benefits (Kallio et al. 2006). Such indirect land requirement of the option should not be neglected if there are no parallel measures implemented to reduce wood consumption or use wood more efficiently.

3.2.3 Co-benefits and trade-offs

Mitigation options using forest management and forest restoration can have substantial benefits for other ecosystem services, especially where forest biomass and soil stocks have been degraded. However, both benefits and trade-offs are being described in the literature. Especially when measures are only oriented towards sink maximisation, trade-offs with other services and policy goals are likely.

The degree to which co-benefits compensate trade-offs depends on specific characteristics of the forests. Co-benefits listed in the literature include biodiversity, water (filtration, flood control, reduced pollution), air (filtration, reduced pollution), resilience (enhanced adaptation capacity), and livelihoods that are typically improved when forests are restored. There can be trade-offs with nature protection where certain species can be affected negatively by reduced harvest intensity, e.g. if they are light demanding (Roe et al. 2019; Law et al. 2018).

3.2.4 Costs and socio-economic factors

Overall, costs for options to restore carbon stocks in forests through improved forest management and increased forest protection can be considered comparatively low. There can be significant trade-offs with wood markets and opportunity costs for timber production can be high. However, when competing with production of energy wood, cost-effectiveness of the option is likely to be high considering alternative renewable energy sources.

There can be costs related to infrastructure needed for reduced impact logging and also higher costs for harvesting and transporting larger dimensioned timber. But in general costs can be reduced with reduced management intensity by leaving more room for natural forest development. This requires an adequate forest structure and species composition. To achieve this, forest transition is often needed, e.g. by introducing better adapted species that can be associated with high costs. The largest economic effects can be expected from forgone timber sales that should be compensated with payments for ecosystem services, e.g. from environmental funds (Valatin and Price 2014).

The forestry sector is an important economic factor for a number of EU MS. Changes in forest management with implications for timber supply will likely have implications for socio-economic indicators in these countries, like employment, timber prices etc. However, the biophysical basis of the sector is only one influencing factor. Technological innovations and changes in the economic structure in the future offer the opportunity to mitigate expected negative impacts. Climate change mitigation as well as other non-timber management aims need to be addressed more by payments for ecosystem services. This offers opportunities especially for small forest owners to generate revenue independent from timber markets.

Mitigation options through forest protection and restoration can be reduced if national forest legislation is weak and governance structures lacking to implement effective measures. This applies especially for forests under pressure from international timber markets. Primary forests or intact secondary forests are particularly sensitive because despite the fact that they are very important carbon reservoirs and biodiversity assets, their status of protection in some EU MS is low (Mikoláš et al. 2019).

3.2.5 Climate change risks

Forests are already affected by climate change. While some species in some areas benefit from higher temperatures, elevated CO_2 and longer growing seasons, other species face growth limitations and increased mortality. These trends are likely to continue. The net effects on the sequestration potential depend on the future species composition of forests, the ability of species to adapt and also management decisions (Seidl et al. 2014). The effects can be large for regions and countries, especially where only a few species dominate forest stands (Keenan 2015).

There is a scientific debate on how impacts of climate change affect managed and unmanaged forests differently. Reduced wood extraction was reported to increase drought resilience of trees (Mausolf et al. 2018) but also to lower productivity and thus sequestration potential (Bosela et al. 2021).

Due to climate change, especially abiotic disturbances are more likely to increase in frequency and intensity (Seidl et al. 2017; IPCC 2019b). In European forests, wind and drought are major drivers of natural disturbances that facilitate additional biotic disturbances like bark beetle outbreaks (Seidl und Rammer 2017). Seidl et al. (2014) estimated that the carbon storage potential of Europe's forests could be reduced by 180 Mt CO_2 annually in 2021 to 2030 due to disturbances and thus reduce the expected net forest sink by more than 50 %. In 2018 to 2020, mainly spruce trees suffered from storms and droughts followed by bark beetle outbreaks in Germany. The actual extent of the calamities has not been officially documented yet, but estimates show that the disturbances covered an area of approximately 285.000 ha [2]. Hence, emissions of 113 Mt CO_2 from affected spruce forests

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[2] https://www.bmel.de/DE/themen/wald/wald-in-deutschland/wald-trockenheit-klimawandel.html

could occur. Reported data for Portugal and Italy showed a drastic reduction of carbon storage by forests in 2017 when severe wildfires affected both countries (EU 2020). While the net sink in Italy was reduced by 40 % compared to previous years, the sink switched into a source of similar magnitude for Portugal. The net sink reduction in both countries was in total 23 Mt CO_2 for that year.

3.2.6 Monitoring aspects and instruments for implementation

Monitoring carbon sequestration through forest management and forest restoration requires regular inventories of carbon stocks in different pools. The biomass pool can be assessed with national forest inventories that exist in most countries with reasonable accuracy (Cienciala et al. 2008). Ground data can be combined with remote sensing information for a higher spatial and temporal resolution. Soil carbon stock changes are more difficult to monitor due to high spatial variability and typically assessed through soil surveys and modelling (Boisvenue et al. 2016).

Forest production statistics, however, have found to be largely inconsistent, causing problems for accurate estimates of exports and imports of wood and carbon flows between wood product pools (Kallio und Solberg 2018).

The EU does not have a mandate over Member State forest policy. Contrary to agricultural activities, forest management in the EU is less driven by subsidies[3]. Instead, EU policies set incentives for increased wood extraction (EU Renewable Energy Directive, EU Emissions Trading System). If incentive schemes for restoring carbon stocks in forests need to work against such strong inducements, they will not be effective. Similarly, mechanisms for higher product prices (e.g. via labelling) operate at much smaller margins compared to existing subsidies.

Carbon markets are discussed for providing additional funding for implementing management changes in forests. However, there are key risks to environmental integrity associated with carbon markets, regarding additionality, leakage, ensuring permanence or addressing non-permanence, monitoring emission reductions, and crediting issues such as avoiding double counting of reductions. Opportunities and risks of engaging the land use sector differ significantly between different measures. For crediting of afforestation and restoration there is experience with existing standards (TREES, CDM, VCS, etc.), credits for enhancing forest carbon stocks involve significant uncertainty as regards the above-mentioned aspects.

For an effective EU policy on enhancing carbon storage in forests, there is the need to align land use related policies with the policy objectives behind them. This includes removing barriers by amending policies that set wrong incentives but also introducing references between policies for gaining leverage towards more effective forest restoration. The update of the EU Forest Strategy as well as the review of several forest related EU policies in the light of the European Green Deal and the EU 2030 target offer an opportunity for alignment.

3.2.7 Summary of assessment

In summary, the option to restore forest carbon stocks through improved forest management and forest protection can be considered effective, especially because it can be applied in large areas in the EU and does not directly require land conversion from other land uses. Also, costs can be

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[3] Member States can provide funding for forests' environmental and climate services under the CAP Rural Development Programmes, but these are limited compared to the payments focused on agriculture.

considered comparatively low. There can be, however, trade-offs with wood markets and opportunity costs for timber production and risk of leakage if demand for wood products or bioenergy remains high. There are many co-benefits related to forest restoration, namely with biodiversity, water, air, resilience, and livelihoods. As forests are under pressure with progressing climate change, there is the risk for significant reductions of future potentials for carbon storage if adaptation of forests is not considered simultaneously with mitigation.

3.3 Increase carbon storage in harvested wood products

The carbon pools for forest biomass and HWP are very closely connected. Harvesting wood from forests transfers carbon stored in living biomass into different pools of harvested wood products (HWP). From these wood products the stored carbon is released as these products get out of use and are being incinerated or dumped (there is a landfill ban for HWP in the 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. HWP thus cannot remove carbon from the atmosphere but rather avoid emissions from wood and should not be regarded as a carbon sink. They are fed by carbon fluxes from wood harvest. In case the wood is being used for energy generation 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 reduce emissions in other sectors through **substitution**. GHG emission reduction can be achieved by replacing products and uses with higher energy input of fossil fuels compared to those of HWP. Substitution effects depend on assumptions of future energy use and are not accounted for under the LULUCF sector but where the emission reduction is actually achieved, e.g. in the industry sector or building sector. Nevertheless, expected substitution effects can drive the utilisation of wood and lead to imbalances if effects in different sectors are not fully included.

3.3.1 Potential

Range of mitigation potential in EU

Harvested wood products in the EU represented a net carbon storage of -44.6 Mt CO_2 in 2018 (European Union 2020), i.e. the stock of carbon in HWPs was increasing. Most MS reported stock increases of HWP (Cyprus, Greece and Netherlands as an exception). The main contributors to the EU net storage in HWP are currently Poland, Romania, Sweden, Finland and Germany. Assuming a constant harvest scenario, carbon storage in HWP will decrease to -25.2 Mt CO_2 per year in 2030 (Pilli et al. 2015).

Substitution of GHG intensive materials with HWP is among the most popular mitigation measures reported by EU MS to the European Commission, as 11 out of 27 Member States have implemented policies and measures aimed at increasing HWP (Paquel et al. 2017).

The potential for increased carbon storage and additional substitution in EU countries for 2030 was estimated to be about 12 Mt CO_2 annually (Rüter et al. 2016). The scenario assumed that recovery of solid wood products for material and energy purposes is increased. Scenarios that assumed encouraged cascade use by ensuring that wood of sufficient quality and dimensions is first used as raw material and only subsequently as a source of energy, were found to have limited potential. This is because even if carbon stocks in HWP can be increased substantially and substitution effects are assumed, there are negative impacts on forest carbon stocks in forests and reduced energy substitution effects compared to the reference scenario (Rüter et al. 2016). Assuming a reduction of primary use of wood for energy and increased wood products could double the expected storage of CO_2 by HWP from 17 to 40 Mt CO_2 annually until 2030 (Rüter et al. 2016). As the option does not affect harvest levels but simply the allocation of harvested wood to energy and material use, impacts on the forest are negligible

Pilli et al (2017) estimated future HWP removals of -43.8 CO_2 per year in 2030 through increased harvest rates. They conclude that the current HWP storage will be maintained only by further increasing the current harvest and subsequently reducing significantly the sink in forest biomass (Pilli et al. 2017). The future HWP mitigation potential in the EU is thus rather limited and can be reasonably assessed only in conjunction with other mitigation components (e.g. sink in forest biomass).

Constraints of the mitigation potential

There are biophysical and socio-economic constraints to the potential use of HWP such as forest growth rates, forest area, wood production capacities and policies (Verkerk et al. 2011; Mantau et al. 2010). Forest growth and wood production cannot be increased without implications for other environmental aspects. Increased extraction of wood reduces carbon stored in forests and its carbon sink (Hennenberg et al. 2019; Pingoud et al. 2016). Such effects need to be considered when evaluating the net mitigation potential. Whether the extraction of wood results in net benefits for mitigation depends on the state of the forest and its future development, the service life of resulting wood products and their fate as well as potential substitution effects (Hennenberg et al. 2019).

The potential further depends on the overall construction activity, especially residential new construction, but also renovation and extension of existing building stocks. Other important factors are building and product standards that need to be sufficiently favourable for use of wood in products to provide a “level playing field”. An important constraint is also that the awareness of wood product potentials in the EU among stakeholders is limited compared to competing conventional materials (Rüter et al. 2016).

Overall, due to these constraints, the potential can be realised only slowly and requires long-term measures to become effective.

Development of the potential over time

Due to a certain inertia of the HWP carbon pools and long lifetimes of products, changes of the stock are affected by carbon inflows to the pool that can date back decades if not centuries. The potential therefore unfolds only with delay and requires long-term measures. Rüter (2017) presented sensitivity analyses of changes in half-lives for the HWP default commodities and found that a change in half-lives by 10 % would cause a stock change in HWP by only 0.25 %. Such effects depend on the simulation period but also the initial state. The results also show that there is rather limited potential for short-term GHG mitigation through measures that aim to increase the lifetime of wood products.

3.3.2 Land requirement and risk of leakage

This mitigation option does not require additional area as it builds on existing land use systems (managed forests). However, there can be indirect land use implications, e.g. when increased use of solid wood pushes bioenergy use of wood into short rotation plantations or other energy crops. There is also competition for wood residues between energy and material use that need to be considered.

Scenario simulations including a global forestry and a global land use model showed that leakage effects of measures involving HWP can be large (Rüter et al. 2016). Leakage can occur within one country, where carbon stocks in forests are reduced through increased used of HWP. These effects can be larger than the gross mitigation of HWP and substitution, resulting in net emissions of measures. As HWP are intensively traded, there are also potential leakage effects outside the country where mitigation measures are implemented. For example, this applies to the competing use of wood for energy and material. Increased promotion of cascade use of wood could reduce the availability of waste wood for energy production, resulting in increased demand for other energy sources.

Leakage can be avoided by flanking measures addressing the use of HWP with demand side measures, e.g. addressing energy or overall resource use efficiency. Also measures that comprehensively incentivise emission reduction, such as a carbon tax, can help reduce leakage and support efficient use of wood.

3.3.3 Co-benefits and trade-offs

An increase of wood flow into HWP can be realised either through an increased recovery of used wood, a shift from energy wood use to use of HWP or increased harvest levels. The latter is associated with trade-offs regarding biodiversity and nature protection (Verkerk et al. 2014). However, increasing the share of wood products, e.g. in the building sector, can help reduce emissions in that sector through substitution of energy intensive products. Such measures can also contribute to an overall more sustainable building sector where more renewable materials are used, and recycling is intensified. Whether such co-benefits materialise depends also on the question whether increased use of HWP leads to additional consumption and how strongly substitution really takes place.

3.3.4 Costs and socio-economic factors

As the mitigation through HWP involves stakeholders at multiple levels, i.e. in different economic sectors, at the international, national and regional level, as well as in the private and public domain, single measures are difficult to implement and costs difficult to assess. Compared to other mitigation measures costs are therefore probably relatively high. However, it can be assumed that costs are relatively decreasing with higher energy prices as the use of HWP typically reduces energy consumption compared to other products (e.g. due to reduced weight, shorter production chains, regional sourcing, etc.).

Employment and livelihoods in forestry are potentially higher with higher wood harvest rates. However, this assumes constant labour productivity, prices and quality of timber. Effects on the construction sector can be expected as the increased use of HWP requires also specifically skilled personnel. Capacities for the increased production and use of HWP are needed throughout the supply chain from forestry, sawmilling, architecture, construction and maintenance. There are also opportunities for new forms of HWP for different uses as advanced biobased materials, such as glulam, cross-laminated timber, panels, composites, etc.

3.3.5 Climate change risks

Climate change impacts on the potential for HWP related mitigation measures are as high as for forest management and can cause challenges if relying on specific tree species potentially at risk under climate change (e.g. spruce). Wood production of high quality for long-lasting products can be considerably constrained by disruptive events in forests that lead to a reduced wood supply or a reduction of wood quality (e.g. insect outbreaks or wind throws). Resilient and sufficiently adapted forests are therefore an essential basis for realising the mitigation potential that lies within the use of HWP.

3.3.6 Monitoring aspects and instruments of implementation

Forest production statistics have found to be largely inconsistent, causing problems for accurate estimates of exports and imports of wood (Kallio und Solberg 2018; Buongiorno 2018). The LULUCF Regulation requires the accounting of HWP using the so-called “production approach” that includes annual HWP carbon stock changes originating from wood harvested in the reporting country only and thus includes exported but excludes imported wood products. This makes accounting of this pool easier as complex import and export relations between countries are less important. Still, an analysis of the European Commission (Cazzaniga et al. 2019) revealed, by comparing national forest inventory and national wood harvest information, that there can be unaccounted harvests of on average 13 % in the EU, indicating that there is a need for improving the data basis for HWP.

Carbon stock changes of HWP are typically estimated using default decay rates that represent different classes of wood products, e.g. sawn wood, wood-based panels and paper/paperboard (IPCC 2019a). Monitoring information about wood flows between pools of different lifetime and quality is often lacking and difficult to assess as data collection and assessments of the fate of wood products labour-intensive. The availability of estimates of actual carbon storage but also the potential of additional mitigation are therefore limited. This means that mitigation measures might not be well reflected in GHG accounts in countries (Böttcher und Reise 2020).

Rüter et al (2016) identified three types of policy instruments that are relevant for realising the mitigation potential of HWP:

- Measures to stimulate the sustainable use of solid biomass for climate change mitigation. These could include support for innovation and research, promoting energy efficiency, especially in buildings, on a full life cycle basis and carbon taxes.
- Regulations to address the sustainable use of solid biomass for climate change mitigation, including green building codes and green public procurement.
- Funding instruments that allow for supporting measures to stimulate the sustainable use of solid biomass, including the European Agricultural Fund for Rural Development or the European Regional Development fund and research programmes, such as Horizon Europe.

Such instruments need to target the use of wood products in relevant market sectors where they have lower GHG emissions than functionally equivalent alternatives. This requires broadening the knowledge base of relevant agents and collaboration between local authorities and stakeholders.

This could include "cradle-to-cradle" design, improved classification systems for materials, improved market information, and more effective logistics.

To avoid that increased wood use simply substitutes existing HWP and not energy intensive materials, measures to extend the service life of wood products are needed.

3.3.7 Summary of assessment

It needs to be considered that the carbon pools for forest biomass and HWP are very closely connected. HWP cannot sequester carbon themselves and should not be regarded as carbon sinks. Still, wood products hold back emissions and can contribute to mitigation, especially when products are long-lasting and recycling rates are high and high emission products are substituted. It forms a mitigation option that does not require additional land as it builds on existing land use systems. However, there can be indirect land use implications, e.g. when increased use of solid wood pushes bioenergy use of wood into short rotation plantations or other energy crops. Compared to other mitigation measures costs are relatively high and can have large leakage effects.

As measures for increasing carbon stocks in HWP can also contribute to an overall more sustainable building sector where more renewable materials are used, and recycling is intensified, co-benefits can be considered high. There are, however, also trade-offs resulting from intensified wood extraction related to other ecosystem services of forests. Regarding socio-economic aspects, capacities for the increased production and use of HWP are needed throughout the supply chain from forestry, sawmilling, architecture, construction and maintenance that might also form a bottleneck for employing the option at large scale. Climate change impacts on the potential for HWP related mitigation measures is as high as for forest management and can cause challenges if relying on specific tree species potentially at risk under climate change (e.g. spruce).

3.4 Expand Agroforestry coverage

Agroforestry integrates woody vegetation (trees or shrubs) with crop and/or animal systems, creating carbon removals from the atmosphere and its sequestration into biomass and soil. It includes both the integration of trees on farmland and the use of agricultural crops and livestock in woodlands. Two main types of agroforestry in the EU can be distinguished: silvo-pastoral agroforestry (animals grazing, or animal fodder produced under trees) and silvo-arable agroforestry (crops are grown under trees, with row spacing allowing for tractor traffic). The majority of existing agroforestry systems in the EU are silvo-pastoral systems (Burges et al. 2019). Under this broad categorisation, agroforestry can include a wide range of systems with many different practices (Kay et al. 2019). For example, it may include hedgerows along field edges, meadow orchards, alley cropping (short rotation coppice) and wooded grassland. Typical existing agroforestry systems in the EU range from Dehesa in Spain, Montado in Portugal, grazed oak woodlands in Sardinia, alley cropping in Germany, bocage agroforestry in France to wood pasture in Hungary and Romania.

In addition to carbon sequestration, the approach delivers multiple ecosystem services with little to no trade-offs. In the case of intensive short rotation coppicing safeguards need to be put in place to ensure there are no trade-offs for biodiversity. Carbon storage occurs both in above-ground biomass as well as in soil.

3.4.1 Potential

Range of mitigation potential in EU

Estimates of the global potential range from 100 to 5,700 $MtCO_2$/year (Smith et al. 2019). The assessment of the EU potential was conducted in a recent EU Horizon 2020 research project (AgForward[4]), on the basis of which Kay et al. (2019) estimate the carbon storage potential of different agroforestry practices to be between 0.09 and 7.29 t C /ha/year. They calculated the total potential of scaling up agroforestry practices to areas affected by multiple environmental pressures (referred to as priority areas) in the EU-28 (plus Switzerland), taking into account the maximum and minimum potential of various practices and their applicability to different biogeographical regions. Based on this aggregated calculation, the total potential for these priority areas, covering 13.7 Mha or 8.9 % of agricultural land, is estimated to be between 2.1 and 63.9 MtC/year or between 7.7 and 234.8 $MtCO_2$/year. The carbon sequestration potential increases with density of fast-growing tree species and good soil conditions. The higher potential systems are associated with some reduction in production output for food and feed.

The AgForward project also concludes that the umbrella approach of agroforestry is very flexible and adaptable to different biophysical and climatic conditions and has potential to be applied almost everywhere in Europe. In particular, countries with higher shares of arable land and grassland (less forests) have a high potential of areas for new agroforestry. The hotspots of environmental pressures in intensively managed agricultural regions, which are correlated with a high level of production, are areas where the multiple environmental benefits from new agroforestry systems can be expected (Kay et al. 2019).

Constraints of the mitigation potential

Kay et al. (2019) estimate the potential by limiting the area for conversion to those agricultural areas (arable and grassland) where there are multiple environmental pressures (nitrogen leaching, water quality problems, soil erosion, loss of SOC) that agroforestry can address at the same time. They estimate this area to be 8.9 % of the EU agricultural land. Overall, the potential will depend on the type of system, climate, and previous land use (Feliciano et al. 2018).

Since agroforestry involves change in land use and adapted management practices, tenancy agreements are a concern as well as opportunity costs. Moreover, the transition to agroforestry systems is a very knowledge-intensive transition which means that significant investments to develop place-based solutions and peer-to-peer learning / advisory support are needed to scale up this option. At the same time, market opportunities need to be developed in some cases.

Development of the potential over time

The potential development depends on the choice of specific components in the agroforestry system. In systems with fast growing (coppicing) trees, carbon sequestration rates will be faster. The impact of land use change on soil organic carbon (SOC) will depend on the ratio of below-ground (root biomass) compared to above-ground biomass in trees, the species chosen and other management

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[4] https://www.agforward.eu/index.php/de/

assumptions. Ongoing management and any natural disturbances will further affect the development of the potential over time.

3.4.2 Land requirement and risk of leakage

The option requires conversion from pure grassland or arable land use. In a very strict sense, scaling up agroforestry is a land use change. However, the original land use component is maintained (e.g. arable land or grassland) while woody features are added. The systems with the higher potential for carbon sequestration are associated with some reduction in output for food and feed as compared to the previous single land use (Kay et al. 2019). Systems can be optimised so as to reduce competition between crops and tree components and increase synergies between these (Quinkenstein and Kanzler 2018). Agroforestry systems can also improve overall productivity and stability of yields in the arable / grassland components.

Agroforestry entails a significant change to the farming system with initial investment and potential short-term changes in production output. However, it has potential for increased productivity of wood, tree crops and livestock in the medium to long term (Martineau et al. 2016). To reduce leakage effects, agroforestry measures can be targeted at high risk areas for multiple environmental pressures. A planning approach is needed to define good locations for this conversion. The total productivity of the system is potentially greater than for pure arable or grassland systems because solar radiation and water are used more efficiently (Santiago-Freijanes et al. 2018).

Even in the short term, changes in yield outputs are system specific and depend on location/ biophysical conditions. In the UK, for example, one study showed reduced output on growth of arable crops and trees, when these were combined in poplar silvo-arable systems (García de Jalón et al. 2017). On the other hand, in the Mediterranean context, a study indicates that silvo-pastoral systems may improve arable outputs under recurring temperature increases in spring (Arenas-Corraliza et al. 2018).

If wood from agroforestry systems is used for bioenergy (e.g. as in hedgerows, short rotation coppicing), this results in a loss of the sink since carbon is released again with energy use.

3.4.3 Co-benefits and trade-offs

Agroforestry has important co-benefits for wildlife and biodiversity (improved wildlife habitat, more pollinators, insects), improved soil health and protection from erosion, protection from nitrate leaching, and flooding (Kay et al. 2019; Burges et al. 2019; Torralba et al. 2016). Silvo-pastoral systems can also improve animal welfare by providing shelter to livestock and reducing heat stress (Burges et al. 2019). It has positive adaptation benefits by improving the microclimate under rising temperatures, protection against erosion, and improved water balance. Moreover, with diversification of output, farms are less vulnerable to single crop failure.

However, the scale of benefits and also potential trade-offs will depend on the type of agroforestry system and the land use that it replaces. In particular, short rotation coppicing is beneficial when it replaces annual monoculture arable cropping systems, but negative if planted on land with high initial carbon stocks and high biodiversity value (Stauffer et al. 2014).

3.4.4 Costs and socio-economic factors

Transition to agroforestry includes initial investment costs (for trees) and opportunity costs in terms of the land use / production that is replaced. Because of the time needed for wood to mature, there might be short-term income difficulties and a transitional period where costs and income may not be balanced. This provides a barrier and a challenge to establish the system (EIP-AGRI 2017).

Short-term tenancy agreements and the volatility of the tenancy market are a significant barrier for setting up agroforestry because it discourages farmers from making longer-term investments. With structural change in EU agriculture, the share of tenancy of land increases.

Agroforestry is very context specific, which means that specific solutions are needed for different farms and this also means that it is a knowledge-intensive system, which also requires targeted applied research to develop workable solutions. Upscaling of agroforestry requires both financial and knowledge support, such as through advisory services, changes in agricultural education, and innovation networks (participatory research) to foster on-farm innovation and development (Louah et al. 2017).

However, agroforestry can also have beneficial impacts on farm productivity and economics. For example, planting tree species with high added value (such as pear, cherry, maple, walnut, other nuts) can increase farm income (Dupraz und Liagre 2008). Combining multiple crops (e.g. fruit trees with arable crops) or silvo-pastoral systems can increase productivity. In silvo-pastoral systems combining laying hens and trees, for example, can improve laying rates and improve output (Burges et al. 2019).

3.4.5 Climate change risks

Climate change will impact the potential for sequestration primarily through the impact on biomass growth since this is the primary mechanism through which carbon gets incorporated. Yields in general are expected to decrease in the Mediterranean, increase in northern Europe and remain within current values in the temperate zone (Poux und Aubert 2018). Since tree and crop species and varieties will be affected differently, the overall limits on the sink potential are complex and literature that would examine these differential impacts in a comprehensive way is not available.

Climate change also brings higher risk for wildfires. A study observed that agroforestry systems in the Mediterranean may reduce fire risk compared to forests, shrublands or grasslands (Damianidis et al. 2020). This indicates that carbon stocks in agroforestry systems may be less affected by natural disturbances due to climate change.

Under Mediterranean conditions, Arenas-Corraliza et al. (2018) predict that crop production could be reinforced under silvo-arable schemes compared to open fields if the recurrence of warm springs keeps increasing.

Trees affect wind speed and temperature, creating a milder climate by providing shade under the canopies (Moreno et al. 2017). This microclimate can improve pasture productivity and availability (more production in winter and delayed drying in early summer) and reduce livestock energy requirements. Agroforestry systems are therefore also suitable as adaptation measures in agriculture.

3.4.6 Monitoring aspects and instruments for implementation

Monitoring of agroforestry mitigation measures requires comparing changes in carbon stocks, starting with a baseline and continuing with regular intervals. Above-ground biomass can be assessed with remote sensing capabilities and checked with on-the-ground monitoring. The Copernicus Small Woody Features[5] dataset can be potentially used. The 2020 update of the dataset maps linear structures of woody vegetation (including hedgerows and patches of woody features). The European Environment Agency explores the potential to use this dataset for monitoring in the context of the Common Agricultural Policy (CAP). Aerial photographs are used within the CAP IACS system to calculate tree densities and landscape features.

Monitoring of soil organic carbon (SOC) can be either 1) predicted via empirical / process models, or 2) measured via soil sampling. The monitoring of SOC via sampling at field level is costly. However, remote sensing capabilities are being developed as well as sensor technologies that would offer more cost-effective in-situ monitoring. Methodologies to measure and account for carbon stock changes in agroforestry systems are under development in some EU countries (for example in France and Germany).

For both silvo-arable systems and silvo-pastoral systems, the CAP is the main policy area relevant to agroforestry in the EU. Depending on the agroforestry practice in question, agroforestry has been eligible for payments under CAP Pillar 1. Under the CAP rural development programmes (RDP), measures to establish agroforestry systems were available in 2007-2013 (M222) and in 2014-2020 (M8.2). Support under the RDPs has also been available for extensive grazing. As a system that contributes to alleviating multiple environmental pressures, support for agroforestry can also be funded through measures targeting improved nutrient and forest management. The Good Agricultural and Environmental Conditions (GAEC) standards relating to retention of landscape features (GAEC7), and the greening payments related to Ecological Focus Areas (EFAs) have supported elements of agroforestry. Agroforestry can also be supported under the post-2020 CAP, potentially both through eco-scheme payments and under Rural Development Programmes.

For silvo-pastoral systems national forestry legislation applies. Natura 2000 legislation applies to high-nature-value traditional extensive agroforestry systems (e.g. dehesa, meadow orchards). Because of the diversity of agroforestry practices, there is limited knowledge on how much agroforestry is supported under what policies (Mosquera-Losada et al. 2018). Eligibility requirements and conditions under the CAP have limited support for scaling up agroforestry in the EU.

3.4.7 Summary of assessment

Overall, agroforestry potentially offers significant mitigation impacts while also delivering environmental co-benefits, in particular if situated strategically in areas currently facing multiple environmental pressures. However, the diversity of possible systems combined with climatic and biophysical conditions means that specific impacts, costs, risks of leakage and benefits vary as well. For short rotation coppicing, where the mitigation potential is higher due to fast growing trees and their density, safeguards may be needed to ensure overall positive environmental impacts. While agroforestry may result in reduced areas available for arable land / grassland, the overall productivity of the system may increase, and it may also benefit overall yield stability. Agroforestry can improve productivity by improving the microclimate and carbon stocks in agroforestry may also be less

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[5] https://land.copernicus.eu/news/small-woody-features-march-2020-update

affected by climate impacts. Scaling up agroforestry coverage requires addressing several barriers, including short-term tenancy agreements, short-term income losses during the transitional period, and considerable knowledge needs required for setting up the optimal agroforestry systems.

3.5 Maintain and enhance carbon in mineral agricultural soils

Soil carbon sequestration involves increasing the soil organic carbon (SOC) stock by achieving net carbon removals from the atmosphere and carbon sequestration into the soil. Moreover, given the historical losses of existing SOC stocks, preventing further losses from mineral soils is essential as a large share of agricultural soils continues losing SOC without improvements in management (Wiesmeier et al. 2020). In this factsheet, the focus is on SOC maintenance and sequestration on agricultural mineral soils, which involves both croplands and grasslands.

Therefore emissions from mineral soils need to be avoided and carbon sequestration should be supported by the following outcomes (Sykes et al. 2020):

1) Optimised crop primary productivity, especially below-ground biomass growth (roots) and retention of this organic matter in the system;

2) Added C that is produced outside of the cropping system;

3) Integrated additional biomass produced within the cropping system;

4) Minimised CO_2 release from microbial mineralisation by reducing soil disturbance and managing soil physical properties;

5) Minimised deliberate removal of C from the system or lateral transport of C via erosion processes.

The choice of management practices that have the most significant potential for maintenance and sequestration of soil carbon varies according to climate and biophysical conditions (e.g. soil type), as well as the production system involved. The largest potential is associated with: 1) cover cropping; 2) improved crop rotations (e.g. through inclusion of legumes and other nitrogen fixing crops); 3) agroforestry established on cropland or grassland; 4) preventing conversion of grassland to arable land and additional conversion from arable to grassland; 5) organic farming; 6) and management of grazing land and grassland to increase SOC levels (for example, by optimising stocking densities or grassland renovation). Most relevant practices need to be worked out at a more granular scale. Some of these practices have been assessed at regional and national level within the EU (e.g. INRA 2019, Wiesmeier et al. 2020).

3.5.1 Potential

Range of mitigation potential in EU

In agricultural soils, the potential for increasing soil organic carbon is highly variable and ranges between 0.5 and 7 t CO_2 per ha per year (Smith 2016; Roe et al. 2019; Poeplau und Don 2015). However, as the area potentially involved can be very large, measures can still make a significant contribution. Estimates of the global technical SOC sequestration potential vary from 2,000 to 5,000 Gt CO_2 per year (Bossio et al. 2020), where these estimates also include an SOC sequestration component in avoided forest conversion, reforestation, peatland management, and coastal wetland restoration. The global estimate for SOC sequestration focused on cropland and grassland, including cover cropping, avoided grassland conversion, grazing (optimal intensity, legumes in pastures), is 930 Mt CO_2eq/year (Bossio et al. 2020).

The range of estimates at EU level for cropland SOC sequestration is 9 Mt (Frank et al. 2015) to 58 Mt CO_2eq per year (Lugato et al. 2014). While there is overall consensus that the option is a relevant contribution to increasing carbon sinks (Wiesmeier et al. 2020; European Commission 2018), there are uncertainties around the estimates and practically achievable potentials may be more constrained (Batjes 2019).

In terms of emissions savings from maintaining current stocks of SOC, the 2016 UNFCCC inventories for the EU estimate 27 MtCO_2eq emissions from mineral soils under cropland and 41 MtCO_2 eq sequestered on mineral soils under grassland. The emissions per year are expected to decline by 39 % for the total sum of mineral and organic soils even in the absence of management changes (Frank et al. 2015). However, the total current and remaining amount underlines the importance of both reversing the continued losses and additional sequestration of SOC.

Given the uncertainties, there is also agreement that there should not be overemphasis on SOC sequestration compared to other mitigation options and that the adaptation effects of the option may be more important than the overall mitigation impact (Powlson et al. 2011; Amundson und Biardeau 2018).

Table 3-1 presents the potential applicable area within the EU for different land use categories. The option is potentially relevant in all EU Member States since all have cropland and grasslands on mineral soils. It is more relevant in countries and regions where the arable sector and mineral soils dominate, such as France, Germany, Hungary, Romania, Poland. In terms of co-benefits, it is especially important in areas at risk for droughts since SOC plays an important role in water retention capacity. A differentiated detailed SOC sequestration potential mapping is not available per EU Member States (only few assessments are available, for example for France or Bavaria in Germany) (e.g. INRA 2019; Wiesmeier et al. 2020).

Table 3-1: Area of mineral and organic soils under different land uses in EU

Soil type	Land use category	Area (kha) in 1990	Area (kha) in 2018
Mineral soils	Forest land	146,269	153,976
	Cropland	133,443	123,165
	Grassland	89,507	85,899
	Wetlands	6,526	7,623
	Settlements	24,343	30,594
	Other land	12,679	12,423
	Total area	**412,767**	**413,680**
Organic soils	Forest land	12,852	12,661
	Cropland	1,591	1,475
	Grassland	3,146	2,965
	Wetlands	16,791	16,313
	Settlements	130	180
	Other land	16	37

	Total area	**34,528**	**33,631**

Source: EU (2020)

Constraints of the mitigation potential

The saturation level of SOC and the risk of reversal due to changes in management are possible limitations to the mitigation potential. The total realistic mitigation potential is difficult to assess as it is very specific for each region and soil type. Clay soils and soils with lower current SOC content have a higher potential to sequester carbon.

The technical and socio-economic feasibility will also differ depending on the climatic conditions, the cropping system in place and the availability of solutions and advice tailored to specific contexts.

Reversibility concerns are strong; nonetheless the option is seen to have many positive co-benefits for adaptation, contributing to soil health and stability of yields, and it provides an effective short to medium-term mitigation measure.

Development of the potential over time

The soil carbon retention time can be short to long-term, depending on management and climate, as well as biophysical conditions. In some soil types and some climatic conditions, the option can be a relatively short-term option, i.e. changes can be observed after 5 to 10 years.

3.5.2 Land requirement and risk of leakage

The option does not necessarily require complete land use change, it can be implemented on existing cropland or grassland (cover cropping, improved rotations, pasture and grazing intensity management).

However, measures to increase SOC require changes in management and may lead to shifts in outputs – for example, extending the perennial phase of crop rotations (including grassland in rotation) may lead to shifts in outputs (reduced arable outputs, compared to increased perennial crop outputs).

With conversion of arable land to grassland or extending the perennial phase of crop rotations, there is some risk of leakage because it can lead to a reduction in arable land (Thamo und Pannell 2016). However, annual yields may also increase due to improved soil quality and soil health. Soil quality is also a consideration in terms of yield stability. Clear quantitative relationships between SOC levels and yields, however, are not available in literature. Clear estimates of risk of leakage associated with SOC sequestration are not available in literature either.

For some options that increase SOC content (in particular, application of manure or compost) there is not a net removal of CO_2 from the atmosphere, but rather shifting of C within the system (Rumpel et al. 2020). It is important to note that the risk of leakage is a systemic issue that is closely linked to changing consumption patterns.

A central problem with the option is that SOC sequestration can easily be reversed with changes in management (e.g. reversal to simplified crop rotation, not maintaining a positive balance of inputs vs outputs, deep tillage). The permanence of the option requires strict requirements around the time that land managers commit to maintaining improved SOC levels. This, however, can pose a substantial barrier for the uptake of commitments.

3.5.3 Co-benefits and trade-offs

Maintaining and enhancing SOC stocks has important co-benefits by 1) improving the soil structure and soil fertility; 2) increasing the water retention capacity of soils and increasing their resilience to climate change; 3) reducing soil erosion and 4) reducing the soil compaction risk. The benefits related to soil quality and climate change adaptation are even more significant than the overall mitigation effect (Rumpel et al. 2020). Because of uncertainties around the mitigation potential and these significant co-benefits, some argue that the option should be primarily promoted as an adaptation option (e.g. Amundson und Biardeau 2018).

SOC sequestration is seen to have a positive impact on food security, not only through the maintenance of the productive capacity of soils but also because it would mean that agriculture as a whole does not drastically need to reduce production levels, meaning that mitigation does not affect available calories as much (Frank et al. 2017).

There may be trade-offs with N_2O emissions; i.e. increase in SOC may cease to offset N_2O emissions when the system approaches a new SOC storage equilibrium (Lugato et al. 2018). There are also uncertainties about the impact on the water balance of agro-ecosystems, in particular under arid conditions (Rumpel et al. 2020). If cover crops are removed using pesticides, there are potential negative impacts on the water quality.

Moreover, there are concerns about possible unintended impacts on soil health if SOC levels are increased by applying off-farm organic inputs, such as municipal compost or biogas digestate, which contain pollutants (hormones, microplastics, heavy metals). Biochar application also carries potential risks for soil health, while not having a clear positive impact over the whole life cycle. This means that these practices with potential side effects should not be promoted / eligible for support as part of this option.

3.5.4 Costs and socio-economic factors

At a global scale, the implementation costs are estimated to be negative for around 20 % of the potential and below US$ 40 t Ceq-1 for the remainder, making such measures cost-effective compared to other GHG removal technologies (Sykes et al. 2020). However, the cost-effectiveness will vary significantly depending on the regional potential (Alexander et al. 2015). Reduced tillage may have cost-saving benefits for farmers (reduced fuel use), but the overall impact on SOC sequestration has been questioned (Powlson et al. 2014).

In the EU, some measures have higher opportunity costs (in particular, the conversion from arable to grassland has high opportunity costs of changing from productive arable land). For example, the Bavarian RDP offers annual payments of 900 Euro/ha for the conversion of arable land to grassland in high erosion risk areas.

There are substantial regional variations in the financial viability of SOC management measures. When changes to existing land use are considered, several measures are cost-effective. One assessment shows that crop rotations (with legumes) lead to improved farm gross margins in Spain but not in Scotland (Glenk et al. 2017), or cover crops can either improve farm margins although on the whole they would worsen farm margins.

Lack of financial or regulatory incentives, risks associated with changes in production systems, lack of advisory services and available information on economic and productivity benefits of sequestration options are some of the key barriers to the increased uptake of SOC sequestration measures (Claessens et al. 2019). An important economic barrier is also land leasing, where farmers who lease land have little to no financial incentive to invest in maintaining or increasing SOC management (Amundson und Biardeau 2018).

The maintenance and increase in SOC, even though it affects soil fertility, is generally not reflected in market prices, although it may be reflected in land cadaster price categories (e.g. Gebeltová et al. 2020).

3.5.5 Climate change risks

Climate change will impact the potential for SOC sequestration primarily through the impact on biomass growth since this is the primary mechanism through which SOC gets incorporated in soils. This will again be very differentiated in the EU, in the Mediterranean areas there may be more negative impacts due to drought conditions (and water being the limiting factor on root growth) than in the northern parts of Europe where the growing season will be extended.

3.5.6 Monitoring aspects and instruments for implementation

The complexity of climate, biophysical interactions (C and N cycles) and management practices, means that more robust estimates need high spatial resolution tools (Lugato et al. 2014).

Monitoring of the SOC can be either 1) predicted via empirical / process models, or 2) measured via soil sampling. The monitoring of SOC via sampling at field level is very costly due to the inherent heterogeneity at each field. There is also uncertainty associated with modelling / upscaling carbon sequestration rates from long-term agricultural experiments (LTEs) to EU level. Another source of uncertainty are inaccuracies in the assessment of current stock levels, since estimates are based on a comparison to the existing stock and current stocks are not necessarily available with sufficient accuracy. Overall, it can be expected that large shares of the effect of management change will go undetected and invisible in MS' national GHG accounts due to overly coarse reporting methods (Böttcher und Reise 2020).

Depending on the rate of sequestration or loss, changes may only be observed after a minimum of 5 or even 10 years. Soil surveys are typically carried out at maximum every ten years, making it difficult to connect between observed stock changes and management changes that have occurred. For a better detection of management changes, modelling tools can be used. Model estimates as provided by Lugato et al. (2014) are consistent across the EU countries and help to make soil carbon emissions but also the mitigation potentials more comparable.

SOC sequestration gained widespread public attention following the launch of the "4 per 1000" initiative during the COP21 in Paris in 2015 which set out the aim to increase SOC stocks by 0.4 % annually through improved agricultural management. Following a debate around the feasibility of this goal, the initiative has since emphasised that the goal should be seen more as an aspirational goal than a quantitative target. The initiative increases the visibility of the issue, promotes research and aims to demonstrate the role SOC plays in mitigation and adaptation.

Several instruments are available within the CAP, especially the agri-environment-climate measure and organic farming, but also other types of investment measures (non-productive and machinery investments). Most MS have already set up agri-environment-climate measures that support various SOC management measures. The measures can potentially also be funded under the LIFE funding instrument. The CAP post-2020 framework enables funding for SOC measures in a range of instruments, including conditionality (Good Agriculture and Environmental Condition standards), eco-schemes and Rural Development Programmes.

Recently, market-based instruments have drawn more public attention whereby farmers are paid outside of the agricultural policy for carbon sequestered. These initiatives are emerging in the EU but are currently limited in coverage. A study funded by the European Commission (DG Climate Action) is preparing guidance on setting up result-based payments for SOC maintenance and sequestration.

Finally, agri-food companies are increasingly setting up supply chain mechanisms as part of their efforts to reduce the carbon footprint of their products (ranging from dairy cooperatives such as Arla to large international companies such as Nestlé). Finally, another instrument to increase implementation may be the sustainable finance requirements whereby banks and other financial actors set up minimum standards related to loans or other financing mechanisms for agriculture, although this is at the very beginning.

3.5.7 Summary of assessment

The option of maintaining and enhancing soil organic carbon on mineral soils is very relevant because mineral soils continue to lose existing SOC stocks. Therefore, measures should target to avoid further emissions from mineral soils as well as increase carbon sequestration on mineral agricultural soils. However, there are uncertainties around estimates of the practically achievable potential, as well as problems of reversibility and difficulty of monitoring. Moreover, the overall smaller share of the additional sequestration potential make this option less of a mitigation priority compared to forests, peatlands, and agroforestry. Nonetheless, SOC on mineral soils can deliver some mitigation if permanence obligations are robust and, more importantly, SOC has vital functions for productivity, water retention, soil biodiversity and resilience in agricultural systems. The adaptation relevance of the option cannot be overstated because of these many co-benefits.

3.6 Conserve carbon in organic soils and restore wetlands

Conserving carbon in organic soils and restoring wetlands is an option to avoid emissions from soils that occur due to soil management. The definition of organic soils is very complex and includes the thickness of soil layers as well as their organic content, origin, underlying material, clay content and annual period of water saturation (Couwenberg 2011). The IPCC (2006) provides guidelines for the classification of organic soils.

In organic soils the production of organic matter, primarily from plant biomass, exceeds their decomposition, which mainly happens under water saturation. Hence, most organic soils classify as wetlands. They are the most effective carbon storage in the world because they can accumulate carbon stocks over a very long time period. Hence, organic soils store approximately five times more carbon in Europe compared to forests and about half of Europe's total soil organic carbon (Swindles et al. 2019). Avoiding emissions from these soils is therefore a major contribution to mitigate GHG emissions. Restored peatlands also sequester CO_2 from the atmosphere, but at lower rates compared to other ecosystems due to slow peat growth.

Organic soils have been commonly drained for agriculture, forestry and peat extraction. Almost half (30 Mt CO_2, European Union 2020) of the emissions occurring on cropland in the EU27+UK are caused by organic soil drainage in 2018. However, organic soils only represent 1.2 % (1.5 Mha) of the total cropland area (European Union 2020). In 2018, the EU27+UK showed emissions originating from organic soils, mainly under agricultural management, of about 100 Mt CO_2. This corresponds to 74 % of the emissions in the total EU LULUCF sector (European Union 2020). Also, peat extraction is a significant source of GHG emissions in the EU LULUCF sector causing 9.2 Mt CO_2 emissions corresponding to only 292.000 ha of peatland area, mainly in Poland, Germany, Estonia, Ireland and Finland (European Union 2020). On a global scale, the EU is the second largest emitter of GHG from drained peatlands in the world (van Akker et al. 2016). Therefore, reducing GHG emissions from organic soils will be one of the most effective measures to achieve the EU's climate targets (Pérez Domínguez et al. 2020). The most efficient reductions in GHG emissions from drained organic soils can be achieved by raising the water levels near to the surface, e.g. by blocking or regulating drainage systems.

In most cases rewetting will no longer allow previous agricultural usage. Paludicultures can be a profitable solution because these crops (e.g. reed, cattail, reed canary grass, alder, peatmoss) can be cultivated under wet conditions (Wichtmann et al. 2016).

3.6.1 Potential

Range of mitigation potential in EU

A recent study by Pérez Domínguez et al. (2020) shows that fallowing of all organic soils in the EU27+UK could mitigate about 42 Mt CO_2 in 2030. Another study published by UBA (2019) projected emissions and removals for cropland and grassland on organic soils in 2050 assuming that 50 % of the total area of organic soils under management in 2015 (2 Mha) could be rewetted. This measure led to a total mitigation potential of 23.5 t CO_2/ha (48.1 Mt CO_2). Differences in estimations for emissions from degraded peatlands or mitigation effects of peatland restoration can vary substantially, depending on the peatland area assumptions and applied emission factors (Barthelmes 2018). Additionally, abandoning peat extraction could avoid substantial emissions of about 9 Mt CO_2 annually (European Union 2020).

Constraints of the mitigation potential

The mitigation potential for organic soils mainly depends on the ownership as well as the current agricultural usage. Additionally, the surrounding land use (ongoing drainage, fertilisation) and the availability of water resources for rewetting are important to be considered as well.

The mitigation potential can be reduced by methane emissions that occur after rewetting due to anaerobic methanogenic bacteria that are active in the subsoil of peatlands (Parish et al. 2008; Hendriks et al. 2007). The amount of methane production depends on vegetation type, temperature and availability of easily decomposable biomass (Couwenberg und Fritz 2012). To minimise methane emissions after peatland restoration, topsoil removal can be an effective measure, reducing methane emissions up to 99 % (Harpenslager et al. 2015). In the long-term (more than 100 years), the climatic effect of peatland emission fluxes is either slightly positive or negative (Barthelmes et al. 2015).

Development of the potential over time

Rising the water table in drained organic soils prevents demineralisation of organic matter and stops carbon emissions immediately. In the long term, natural peatlands with growing layers of organic matter can be restored, serving as long term carbon sinks. In natural peatlands the carbon balance mainly depends on the processes of photosynthesis and respiration. These processes are influenced by water dynamics, air temperature, nutrients and type of vegetation cover. The highest carbon sequestration rates can be found in young Sphagnum peatlands at the coast (Harenda et al. 2018).

Introducing paludiculture on rewetted organic soils is a very effective measure to reduce emissions from organic soils because it preserves the existing peat body and therefore important carbon stocks (Wichtmann et al. 2016). Already one ha of established paludiculture can be as effective as taking climate mitigation measures on 10 to 100 ha of mineral soils.

3.6.2 Land requirement and risk of leakage

The land required for rewetting 50 % of organic soils under cropland and grassland in the EU as introduced by the study of UBA (2019), will reduce the total area for agricultural usage in the EU by 1 % (2 Mha). However, the implications can vary a lot among Member States depending on how much drained organic soils are currently used for agriculture. For example, a 100 % fallowing of organic soils may result in a loss of 10 % of agricultural land in Finland, whereas in Spain, only about 0.5 % of agricultural land would be affected (Pérez Domínguez et al. 2020). As already mentioned, introducing paludicultures may provide an alternative income for farmers in the future and decrease the loss of agricultural land.

Agricultural feed and food production are important societal and economical services. Rewetting will reduce the production area for agricultural goods and might increase imports of goods, causing GHG emissions abroad (UBA 2019). The risk of leakage can be mitigated through flanking demand-side measures like reducing meat and dairy consumption to lower the demand for agricultural land (UBA 2019).

3.6.3 Co-benefits and trade-offs

Besides their carbon storage potential, peatlands are of great importance for biodiversity conservation because they are essential habitats to many plants and animal species adapted to wet conditions. Often peatlands are among the last undisturbed habitats for rare and threatened species. Peatland catchments are also important for drinking water provision or flood-water regulation (especially in the lowlands or at the coast). Additionally, peat cores provide essential information about the climate history and store paleo-ecological (pollen and macrofossils) materials. Finally, peatlands are of a high recreational value for humans (Bonn et al. 2016).

Cultivating paludiculture increases biodiversity compared to conventional agriculture, and it can reduce nutrients in surface water and flood risks and droughts by acting as temporary water storage (Geurts und van Duinen 2019). As mentioned in the section above (3.6.2), the main trade-off for this option is the possible loss of feed and food production area.

3.6.4 Costs and socio-economic factors

The direct costs for peatland restoration vary between countries in the EU and can be comparatively high if land must be purchased. In Germany, for example, costs range from 3,000 to 5,000 € per ha including land purchase (Förster und Schäfer 2009), whereas in Poland costs vary from 800 to 3,100 € per ha. In the Netherlands these costs range from 10,000 to 30,000 € per ha, including removing the topsoil (Klimkowska et al. 2010). If the owner wants to continue farming, introducing paludiculture can be an opportunity to mitigate the loss of revenue from rewetted agricultural area (Beudert und Leibl 2020). Large-scale implementation of paludiculture, however, requires agricultural policies to set explicit incentives that ensure that it becomes advantageous for landowners to rewet drained agricultural peatlands and subsequently to maintain them as wetlands (O'Brolchain 2020).

For farmers, the rewetting of agricultural land probably makes conventional farming no longer possible, which can lead to loss of revenue and even unemployment. Therefore, it is necessary to introduce measures to support farmers like creating regional markets for carbon credits to finance rewetting of peatlands and compensate the loss of income. To increase the benefit to landowners and increase incentives for restoration, these schemes can be more effective if payments are offered not just for emissions avoided but also for biodiversity and water benefits. Also, paludicultures offer a new potential source of income for farmers who want to continue cultivating their lands but availability of markets for paludiculture outputs can be a barrier.

A study from Scotland about the public view on values of peatland restoration (Martin-Ortega et al. 2017) revealed that people choose peatland restoration over business-as-usual cultivation even if it involves a financial disadvantage because of the peatland’s recreational value and cultural identity besides climate change mitigation benefits.

3.6.5 Climate change risks

Drainage has reduced the water table in European managed and unmanaged peatlands. Due to climate change, less precipitation and higher average air temperatures are likely to increase decomposition in organic soils. The drying of unmanaged peatlands changes their hydrology and is usually followed by a change in vegetation cover, e.g. trees and other vascular plants like sedges can start growing, causing CO_2 and CH_4 emissions. Therefore, it is necessary to decrease human impact on peatlands by restoring their natural hydrology to increase their resilience towards climate change impacts (Swindles et al. 2019).

3.6.6 Monitoring aspects and instruments for implementation

Assessing the success of restoration programmes requires a systematic and standardised long-term monitoring system with appropriate baseline and controls or reference sites. Also, developing remote sensing data and methods linking vegetation cover and GHG fluxes and other proxies is an important prerequisite (Andersen et al. 2017). Standardised and high-quality data on status and development of organic soils in the MS will support national emission reporting and help identify future restoration sites.

Peatland restoration can be funded under the EU LIFE+ programme, as well as through the Common Agricultural Policy (CAP). In the post-2020 CAP, one of the proposed conditionality requirements focuses on the protection of wetlands and peatlands (GAEC 2), and peatland restoration can potentially also be funded under eco-schemes and Rural Development Programmes.

Peatland restoration where productive use of land is ceased requires purchase of land, which makes for high up-front investments. Carbon credit schemes for peatland restoration are not widespread, however, methodologies are available and regional projects implemented (good examples are

MoorFutures in Germany, and Peatland Code in the UK). Land where water level is raised and productive use of land continued through paludiculture is not eligible for the first pillar of CAP payments (because paludiculture crops, e.g. reed canary grass, common reed cattail, peatmoss, etc. do not qualify as agricultural activity), which poses a barrier to paludiculture. Research support for developing paludiculture projects and methodologies for carbon accounting via restoration projects is available through some national and EU research programmes. Also, policy should support building regional markets for paludiculture products.

3.6.7 Summary of assessment

Emissions from organic soils under agricultural management account for a substantial share of the total EU LULUCF sector conservation. Therefore, avoiding these emissions by rewetting and protecting organic soils and wetlands/peatlands is one of the most effective mitigation measures. Besides this measure can also contribute to the restoration of important wetland habitat and serve as water storage as well as help to prevent devastating flood events. The demand for agricultural area is comparatively low on a European scale but affects MS to varying degrees, which can cause problems for the local farmers and agricultural production. Hence, the risk for leakage can be high, especially when animal feed or other agricultural goods have to be imported. Hence, it is essential to additionally lower the demand for agricultural goods like meat and dairy products in the EU.

In the future, the introduction of paludicultures may be an alternative source of income for farmers as well as restoration programmes and carbon crediting systems resulting in positive socio-economic effects. Climate change can have effects on the hydrology of rewetted organic soils leading to emissions from peat decomposition and vegetation change. Therefore, it is very important to decrease human impact on peatlands by restoring their natural hydrology to increase their resilience towards climate change.

3.7 Protection and restoration of saltmarshes and seagrass meadows

Marine coastal ecosystems like mangroves, salt marshes and seagrass meadows sequester carbon from the atmosphere and mainly in their sediments. They are often referred to as “coastal blue carbon ecosystems” (IPCC 2019 Ocean Report). Globally they cover approximately 2 % of the ocean area, but account for about 50 % of the carbon that is sequestered in ocean sediments (IUCN 2017). The top meter of soil has been estimated at 250 t C per ha for salt marshes and about 140 t C per ha for seagrass meadows (Pendleton et al. 2012). However, there is a substantial variability in the sequestration potential of these habitats depending on site conditions. Saltmarshes and seagrass meadows exist along the coastlines of the EU and cover about 3 Mha (Luisetti et al. 2013). Salt marshes are located in the upper coastal intertidal zone between land and sea. The zone is regularly flooded by tides and therefore dominated by salt-tolerant plant species. Their coverage is estimated to be about 0.39 Mha in 2018 and more than half of its coverage can be found in three countries: France (20.3%), Spain (18.3%) and United Kingdom (12.3%) (Maes et al. 2020).

Seagrasses are a group of marine flowering plants that form dense meadows in shallow waters from the lower salt marsh limit to the sublittoral zone. Both ecosystems are endangered by deteriorated water quality, coastal modifications and waste. Also, aerial loss is one of the main disturbances of coastal ecosystems, resulting in loss of carbon storage capacity (Luisetti et al. 2019). Especially fishing by bottom trawling affects sedimentary carbon storage through remineralisation and by impacting the seabed species involved in bioturbation and bio-irrigation (Duplisea et al. 2001). A study in the north-western Mediterranean sea revealed that trawled sediments along the continental slope are characterised by significant decreases in organic matter content of up to 52 % as well as slower organic carbon turnover (ca. 37 %) (Pusceddu et al. 2014). Mitigation can be achieved by restoring these ecosystems and stop their further degradation, e.g. by changing fishing methods.

Saltmarshes and seagrass meadows can be successfully restored if initial threats are eliminated prior to replanting. Main stressors that must be addressed are eutrophication and coastal construction activities. Successful regrowth of seagrass species depends on a minimum threshold of reintroduced individuals.

The potential mitigation contribution of the protection and restoration of saltmarshes and seagrass meadows lies in carbon removals that can be achieved with the restoration. However, their protection also supports GHG mitigation through avoided emissions.

3.7.1 Potential

Range of mitigation potential in EU

The endemic Mediterranean seagrass *Posidonia oceanica* is the most abundant and most efficient species in sequestering CO_2 from the atmosphere. In the Atlantic European sea, *Zostera marina* is the most abundant species. There is only little knowledge about the current carbon stocks and sequestration rate of seagrasses and saltmarshes in Europe (IUCN 2021). Few studies provide information about carbon stocks and sequestration rates among different species and across geographical ranges (Table 3-2).

Table 3-2: CO_2 stock and sequestration rates of different seagrass and salt marsh locations and seagrass species. The data collection is based on IUCN (2021)

Habitat type	Dominant species	Location	Average CO_2 stock (tCO_2/ha) at 1m	Carbon sequestration rate (tCO_2/ha/yr)	References
Seagrasses	*Posidonia oceanica*	Andalusia	814 – 4,051	1.4 – 3.1	Mateo et al. 2018
		Crete Island	187	-	Apostolaki et al. 2019
	Posidonia oceanica death mat	Andalusia	736 – 1,064	0	Mateo et al. 2018
	Zostera marina	Northern Hemisphere	85 – 1,287	-	Röhr et al. 2018
Salt marshes		Andalusia	171 - 573	1.98 – 4.58	Diaz-Almela et al. 2019
		Netherlands	1,200 – 1,438	5.5	Tamis und Foekema 2015
		Denmark	770 – 990	-	Sifleet et al. 2011
		Rhone Delta, France	2,677	-	Sifleet et al. 2011

Source: EU (2020)

The estimates vary a lot among species and different geographical locations. However, average carbon stock is very high compared to terrestrial ecosystems and it is very important to protect these stocks from deterioration. The restoration potential of salt marshes and seagrasses is currently unknown in the EU. According to Marbà et al. (2014) the potential coverage of the endemic Mediterranean seagrass species *Posedonia oceanica* is 5 Mha, which is about twice its current range.

More research on European blue carbon ecosystems is needed to better understand their mitigation potential through restoration.

Constraints of the mitigation potential

Unlike terrestrial soils, soils of coastal blue carbon ecosystems are largely anaerobic. Therefore, decomposition in the soil is very slow and carbon can be stored for hundreds or even thousands of years. Also, the methane production is limited due to the high salinity of blue carbon ecosystems.

The actual distribution of the EU's coastal blue carbon ecosystems is unknown, which makes mitigation estimates very difficult. Also, the current range of carbon sequestration rates in these ecosystems can vary a lot among sites and is not yet fully understood (Duarte 2011; IUCN 2021). Restoration of blue carbon ecosystems is generally possible, but water quality can be a major constraint. Besides eutrophication, water quality is also affected by acidification and plastic pollution.

Development of the potential over time

Compared to other ecosystems like forests, the carbon sequestration rate is not particularly high. However, the long-term storage of carbon can be several centuries, especially in sediments beneath the seagrass meadows of Posedonia (IUCN 2021).

3.7.2 Land requirement and risk of leakage

The potential extent of restoration areas for coastal ecosystems in the EU is currently unknown. There are about 3 Mha of blue carbon ecosystems in the EU (Luisetti et al. 2013). Taking the potential historic aerial estimates of the Mediterranean seagrass species *P. oceanica* of 5 Mha (Marbà et al. 2014) into account, the potential area demand would be at least 2.5 Mha in the EU. Reducing the disturbance of coastal ecosystems by restricting bottom trawling might affect the provision of fish for food consumption (Luisetti et al. 2019) which could potentially increase imports from countries tolerating bottom trawling and endanger coastal ecosystems abroad.

Salt marshes cover only a very small fraction of the total coastal area in the EU (0,39 Mha) and have undergone severe area reductions in the past 50 years of about 26 % in the Atlantic and about 13 % in the Mediterranean region (IUCN 2021). Also, according to the latest EC Science to policy report on mapping and assessing ecosystems and their services in the EU (Maes et al. 2020) the condition of these coastal ecosystems is mainly poor to bad and at least one third is further deteriorating. Improving the condition of the existing salt marshes in the EU does not require additional coastal area but most likely can contribute to protecting their carbon stocks.

3.7.3 Co-benefits and trade-offs

Coastal ecosystems filter nutrients and sediments and accumulate and recycle organic and inorganic materials. They also provide protection from storms through sediment stabilisation as well as oxygenation of the water column and sediments. Additionally, seagrass meadows and salt marshes are an essential habitat for many marine organisms and therefore are also important for the fisheries sector (IUCN 2021).

Protecting coastal ecosystems like seagrass meadows excludes certain fishery methods like bottom trawling. Hence, reduction in EU fishing grounds is an important trade-off that has to be considered. Also, the protection of salt marshes could involve management changes such as lowering mowing intensity and excluding cattle grazing on salt marshes as well as preventing nutrient leaching into the salt marshes to avoid plant community conversion.

3.7.4 Costs and socio-economic factors

Costs involve transplantation of seedlings grown in aquaria or mature donor plants from undamaged seabeds. Also, prior to this measure it is crucial to evaluate and eliminate causes of habitat degradation like eutrophication and increased water turbation (e.g. close to harbours), which probably involves deconstruction of infrastructure like drainage systems into the sea (van Katwijk et al. 2009; Bekkby et al. 2020).

The reconstruction of coastal ecosystems in the EU negatively affects coastal infrastructure and usage. But the conservation of blue carbon ecosystems could also be economically sustainable by monetising avoided emissions, e.g. in voluntary markets.

3.7.5 Climate change risks

Globally, the composition and biomass of co-occurring seagrass species could be negatively affected by the compounding effects of heat waves, hypersaline conditions and increased turbidity and nutrient levels associated with floods. The seagrass species *P. oceanica* could suffer severe habitat losses of 70 % by 2050 with the potential for functional extinction by 2100 under RCP8.5 climate scenario (Bindoff et al. 2019). *P. oceanica* was shown to be very sensitive to more frequently occurring heatwaves, especially in its early germination stages (Guerrero-Meseguer et al. 2017).

In all projected scenarios, salt marshes tend to increase their carbon stocks by decreasing their carbon emissions with temperature increase (Duarte et al. 2014). However, salt marshes are expected to generally decrease their occurrence because of the loss of pioneer species. Also, the productivity of native species like *S. maritima* is probably lowered by increased temperatures, and non-native species might invade the ecosystems affecting their biochemistry and biodiversity (Duarte et al. 2016).

3.7.6 Monitoring aspects and instruments for implementation

Coastal ecosystems can be monitored by trajectories or remote sensing applications. Since carbon sequestration rates of seagrass meadows and saltmarshes vary significantly over time and space, it would be necessary to fully understand the dynamics to apply correct monitoring intervals. Monitoring of coastal ecosystems is urgently needed but so far there is no common data on their status and development.

The Habitats Directive offers an important international legislative instrument to protect and restore seagrasses and salt marshes. However, the actual coverage of these ecosystems in the EU and their climate mitigation potential is still not fully understood and more research will be necessary, also to implement payment schemes for ecosystem services.

So far coastal ecosystems are not completely covered by the EU GHG reporting under the IPCC. However, the IPCC wetland supplement (IPCC 2014) provides guidance on estimating and reporting of GHG emissions and removals from managed coastal wetlands including seagrass meadows and salt marshes. Only few EU countries actually include some coastal ecosystems in their LULUCF wetland definition: Portugal (coastal wetlands, salt marshes), Croatia (salt marshes, salines, intertidal flats, coastal lagoons), Cyprus (salt marshes) and Bulgaria (coastal lagoons) (European Union 2020). Hence, the absolute majority of GHG originating from managed seagrass meadows and salt marshes is not yet monitored or reported in the EU.

3.7.7 Summary of assessment

Salt marshes and seagrass meadows are important carbon rich ecosystems, which provide habitat to many marine species and ecosystem services like protection of the coast from storm events and nutrient filtration. Emissions from these ecosystems can be effectively avoided by abandoning sediment destruction from commercial bottom trawling and water pollution. This may lead to risks of leakage by relocating the fishing industry outside the EU, additionally causing negative socio-economic effects for local fishermen. Therefore, it is essential to introduce alternative sustainable fishing methods alongside with coastal restoration programmes. Additionally, coastal ecosystem emissions and removals need to get more visibility in national emission reporting. Currently, data on the status and development of saltmarshes and seagrass meadows in the EU is very limited and information on costs of restoration measures is missing. Climate change most likely increases heat waves that may constitute a potential threat to carbon sequestration potentials of coastal ecosystems.

3.8 Summary assessment of options

There are different land use and management options to efficiently avoid emissions and enhance the natural carbon sink function of ecosystems in the EU. Table 3-3 presents the summary of the assessment of all seven options against the criteria: Restoring carbon in forests by extensive management or protection as well as afforestation are well proven mitigation measures with many ecological and social co-benefits. In particular, the restoration of carbon stocks in forests provides the largest absolute potential of 150 to 400 Mt CO_2 per year. Also, expanding agroforestry coverage is a promising mitigation measure in almost all biogeographical regions of the EU and has a wide range of co-benefits like soil and biodiversity protection. Its potential is estimated to be between 8 to 235 Mt CO_2 per year, depending on the amount of tree biomass involved in the agroforestry system. The most effective option to immediately reduce emissions is the rewetting and conservation of organic soils, which shows the highest mitigation potential per unit area of ≤ 23.5 t CO_2 per ha per year. Because the area of organic soils is comparatively small, the absolute mitigation potential for the EU is at the lower range compared to other options. All other options show similar ranges of area specific mitigation potentials, with measures related to HWP being exceptionally low (0.16 to 0.28 t CO_2 per ha). An option that has not yet often been discussed is the protection and restoration of saltmarshes and seagrass meadows that has great potential to protect high carbon stocks in the sediments but probably holds limited sequestration potential. However, there is a huge lack of data for realistic estimates of the overall mitigation potential of coastal ecosystems. Furthermore, research is needed to complete further data needs like detailed data on drained soils and the state of degradation of forests in the EU.

However, ranges found in literature are very wide, indicating that assumptions in the studies analysed vary considerably. The main reasons are the differences in the underlying assumptions of the studies, e.g. the area potential, emission factors applied and reference year to calculate the mitigation effect. Additionally, the assumptions behind the presented mitigation potentials often do not consider land competition between options. Hence, they cannot be simply added to a total mitigation potential over all options but need to be assessed using an integrated modelling approach which is shortly introduced in chapter 4.1.

Land-based mitigation options affect how land is managed and/or used. This characteristic determines whether an option causes a direct demand for additional land. Especially an increase of forest area, the expansion of agroforestry coverage and conservation of carbon in organic soils and wetland restoration can be considered options with explicit land use changes and therefore additional land requirements. However, options that target management changes only can likewise cause indirect land requirements through leakage effects that occur if measures affect agricultural or forestry production levels. A certain risk of leakage is associated with all options. Such leakage effects depend on the degree of management change, the type of commodities affected, market reactions, and parallel changes in consumption patterns. Leakage risks need to be considered when options are implemented and can be addressed by option design and by accompanying measures for increasing resource efficiency and reducing overall consumption.

Co-benefits are found to be relevant for a number of aspects, including socio-economic factors, wood production, biodiversity, soil and water. But also, trade-offs with biodiversity, food production, nitrogen and other GHG emissions need to be considered. More specifically, it will be necessary to consider local circumstances and specific site conditions to adequately assess options. In general, mitigation measures in the land use sector can establish opportunities for rural development and result in societal benefits that can often not be quantified but are likely to have a positive impact.

Climate change will impact all options considered in the medium to long-term perspective. While effects on plant growth can be positively impacted by higher average temperatures, an increase in decomposition rates can also be expected. Carbon stored in biomass is also likely to be subject to natural disturbances, which are expected to increase with progressing climate impacts. In particular, options involving trees are affected. Climate change risks thus need to be considered for all options, e.g. through the combination of mitigation with adaptation measures to reduce susceptibility of ecosystems to natural disturbances.

All options are likely associated with high or medium costs, mostly because compensation payments are needed to pay for loss of revenue or up-front investment, but also for rather complex technical challenges for the rewetting of organic soils. Short-term costs can be compensated with medium to longer term benefits, but the transition period still poses a challenge (e.g. agroforestry). Costs are also among the most uncertain aspects of options and not for all options readily available (see, for example, protection of marine ecosystems).

Table 3-3: Summary assessment of options

Assessment variable	Increase forest area	Restore carbon stocks in forests	Increase carbon storage in harvested wood products	Expand agroforestry coverage	Maintain and enhance carbon in mineral agricultural soils	Conserve carbon in organic soils and restore wetlands	Protect and restore saltmarshes and seagrass meadows
Range of specific mitigation potential in t CO_2 per ha per year	2.2-7.7	0.9-2.5	0.16-0.28	0.01-7.3	0.5-7	≤ 23.5	Average CO_2 stock at 1 m: 49 – 4,050** Average sequestration rate: 0.11 – 5.5 **
Range of total potential in Mt CO_2 per year	77-210	150-400	25 – 44*	8 - 235	9-58	≤ 48	Unknown***
Type of mitigation	Removal	Removal & Avoided emission	Avoided emission	Removal	Removal & Avoided emission	Avoided emission	Removal & Avoided emission
Land use or management change	Land use change	Management change	Management change	Management change	Management change	Land use change/ Management change	Management change
Land requirement	Additional land	No additional land	No additional land	Additional land	No additional land	Additional land	No additional land
Risk of leakage	Leakage risks to be considered, options need to be accompanied by measures increasing resource efficiency and overall consumption						
Co-benefits	Socio-economic Wood production Biodiversity Water Soil	Biodiversity Water Soil Recreation	Socio-economic Substitution	Biodiversity Water Soil Recreation	Biodiversity Soil fertility	Biodiversity Water Recreation	Biodiversity Water Coastal protection
Trade-offs	Biodiversity Food production	Socio-economic Biodiversity Wood production	Biodiversity Carbon stocks in forests	Food production	Nitrogen	Food production Methane, nitrous oxide	Food production (fishing)
Climate change risks	Climate change risks to be considered, options need to be accompanied by adaptation measures to reduce susceptibility of ecosystems to natural disturbances						
Costs and socio-economic factors	Cost data often limited, depend on site conditions, knowledge and technology						
Monitoring and instruments for implementation	Data available; instruments available	Data available; instruments lacking	Data limited; instruments lacking	Data limited; instruments available	Data limited; instruments available	Data limited; instruments available	Data limited; instruments available

Source: Own compilation

* Values for 2030

** Numbers vary strongly among species and location (IUCN 2021)

*** Because the potential area for restoration of seagrass meadows and saltmarshes is currently unknown, no total potential is given in this summary.

4 Integrated potential for strengthening natural carbon sinks and reducing land use emissions: challenges and risks

4.1 Overview of integrated potential

Looking at different options for emission reductions and carbon stock enhancement results in considerable ranges of potentials (see 3.8 above). Integrated assessments of land-based mitigation potentials are supposed to take interactions between separate options, competition for land and market effects into consideration.

Table 4-1 compares integrated estimates for land-based mitigation. The considerable range of estimates expresses different scopes of activities but also assumptions on the intensity of measures. The potential for the EU net sink in 2050 ranges between 244 Mt CO_2 (the EU Reference scenario forming the baseline of the development of the sector) and 787 Mt CO_2 per year in an ambitious policy scenario. Most estimates consider a net sink of 400 to 600 Mt CO_2 per year as feasible for 2050 and a similar range for 2030.

Table 4-1: Comparison of selected studies assessing net sink potentials of managed land in the EU

Study author and name	Main mitigation categories	Time horizon	Potential Mt CO_2/ year	Main assumptions
EC (2016) EU Reference scenario [6]	LULUCF	2030 2050	-288 -244	Business-as-usual management of EU lands.
Oeko-Institut: GHG-neutral EU 2050 [7]	Afforestation, forest restoration, harvested wood products, peatland restoration, grassland protection	2050	-518	Increase forest area by 16 Mha; stabilise forest harvest rate at 70% of increment; increase the share of longer-living wood products; convert 50 % of cropland on organic soils to wetlands, forests and grasslands; reduce grassland conversion on organic soils to zero, on mineral soils to 50 %; no net land take of infrastructure and settlements by 2050.
CTI 2050 Roadmap Tool (2019) [8]	Afforestation, forest restoration, reduced cropland and grassland management intensity	2050	-584	Reduced land degradation: 24 % less land required to produce food (multi-cropping, etc.); 76 % of surplus land is afforested, 20 % converted to grasslands; forest harvest intensity lowered by 25 %.
EU CALC project (2020), Ambitious scenario [9]	Afforestation, bioenergy, area protection, forest restoration	2030 2050	-570 -787	Afforestation of 114 Mha grassland and cropland, increasing bioenergy capacities, improved diets and alternative protein sources, improved forestry practices and land management, improved hierarchy for biomass end-uses, and set aside 50 % of area for protection.
EC 2030 Climate Target Plan Impact Assessment, LULUCF+ scenario [10]	Afforestation, forest restoration, restoration of peatlands	2030 2050	-340 -425	Optimisation of forest management, afforestation projects and improving soil management including through rewetting and restoration.

Source: Own compilation based on cited literature

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[6] https://ec.europa.eu/energy/data-analysis/energy-modelling/eu-reference-scenario-2016_en

[7] https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-11-26_cc_40-2019_ghg_neutral_eu2050-technical-annex.pdf

[8] https://www.buildup.eu/en/learn/tools/cti-2050-roadmap-tool

[9] https://www.european-calculator.eu/transition-pathways-explorer/

[10] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020SC0176

4.2 Challenges for implementation

Only few studies have assessed the full land use sector, including all land categories, and almost none has assessed potential implications for emissions outside the EU (an exception in this list is the EC 2030 Climate Target Plan Impact Assessment). Leakage effects leading to increased emissions from land use change and biomass production outside the EU can be significant but are difficult to assess. General equilibrium models that simulate changes to markets and trade flows are highly uncertain and can only be interpreted within the modelling assumptions. Those studies ignoring market effects outside the EU assume flanking measures on the demand side that address expected changes in production levels and land availability.

Table 4-1 also lists the main assumptions of the studies reviewed that are essential to understand differences between the results. However, there are also common assumptions associated with modelling approaches that are often less well documented. Typically, large scale assessments of mitigation potentials assume perfect policy implementation. Important details that might constrain the potential in the realisation phase such as ownership structure, capacities of technologies, training of land managers and landowners, efficiency of funding instruments, effectiveness of carbon markets, change in consumption patterns, etc. are ignored. This can constitute a strong bias towards an overestimation of the effectiveness of measures. This is especially true for potentials estimated for the short-term perspective of 2030.

Similarly, potentials are likely to be overestimated as none of the studies includes effects of climate change affecting ecosystems. Such effects are not only relevant for longer-term potentials but can kick in also in the short term. Measures enhancing the net sink might also lead to higher resilience of ecosystems and climate change adapted conditions. However, this depends very much on the details of how the measures are implemented, e.g. tree species chosen for afforestation. In general, it can be expected that integrated studies cannot provide such details that are needed to realistically assess climate change related impacts.

Also, co-benefits are largely underrepresented in potential assessments but are essential for realising the potential, both in terms of building resilience and economically viable options that encompass environmental integrity. The main assumption made is that establishing natural carbon sinks will deliver on multiple ecosystem services. However, most models are unable to make such co-benefits visible. It should be considered that cost-effectiveness of options depends to a large degree on the integration of options for achieving multiple policy objectives. This requires integrated studies to go beyond single-dimensioned assessments by improving the visibility of co-benefits.

4.3 Risks for natural carbon sink potentials

There is a risk that potentials for strengthening natural carbon sinks and reducing land use emissions are reduced through intensification of land management. Even today land areas in the EU are intensively used and partly degraded. The latest report by the European Environmental Agency EEA (2020) about the state of nature in the EU shows that most carbon rich ecosystem types in Europe are under pressure by intensive management practices, habitat conversion (e.g. expansion of settlements and drainage of wetlands) and even destruction. Only 15 % of habitats are in a good conservation status, while about 45 % show a poor and 36 % a bad conservation status. Especially coastal habitats are degraded as well as peatlands (more than 50 %) and grasslands (49 %). Also forests are of poor to bad (total 80 %) conservation status in 2018 (EEA 2020). Ceccherini et al. (2020) recently reported an increase in the forest harvest rate for Europe, which is an important driver of decreasing carbon stocks in forest biomass. Such pressures can reduce the effectiveness of mitigation options and reduce the ability of managed ecosystems to act as natural sinks. In addition, ecosystem degradation has severe consequences for the resilience and stability of ecosystems against natural disturbances like storm, fire and drought as well as pathogens.

In 2018 to 2020, forests, especially spruce, in most of the EU suffered from storms and drought followed by bark beetle outbreaks. For example, in Germany the actual area affected by these calamities is estimated to cover about 285,000 ha[11]. These disturbances are an integral part of ecosystems but due to climate change they are more likely to occur more frequently and with increased intensity (Seidl und Rammer 2017; IPCC 2019b). Hence, the expected European net forest sink could be reduced by 50 % in 2030 due to a decreased carbon storage potential by 180 Mt CO_2 annually in 2021 to 2030 (Seidl et al. 2014).

Also, global warming due to climate change can increase microbial activity leading to faster decomposition (Davidson und Janssens 2006) which could negatively affect the ability of e.g. wetland ecosystems for long-term carbon sequestration. In peatlands, decreasing water tables can occur during dry summers followed by a change in vegetation cover, e.g. towards sedges. This increases methane emissions and further changes the hydrology of the peatland leading to peat decomposition and CO_2 emissions (Swindles et al. 2019).

5 Conclusions and next steps: From potentials to policy framing

5.1 Conclusions on options and potentials

The largest absolute potential is expected from **restoration of carbon stocks in forests**, followed by **afforestation**. Hence, increasing the carbon storage in HWP appears to be of limited effectiveness due to trade-offs with forest carbon storage. **Rewetting and protecting organic soils** are an effective measure to avoid emissions from land use and shows the highest mitigation potential per unit area. Also, **expanding agroforestry coverage** in all biogeographical regions of the EU has a high mitigation potential, especially when involving high tree coverage. The **increase of soil organic carbon in mineral soils** is a valuable measure that can also contribute to mitigation but mainly serves other important aspects like increasing soil fertility. Compared to other mitigation options there are uncertainties around estimates of the potential that can be practically achieved, as well as problems of reversibility and difficulty of monitoring.

Besides these land mitigation options, there is more potential for emission avoidance by **restoring and protecting marine coastal ecosystems** like seagrass meadows and saltmarshes. However, there is a lack of data for realistic estimates of the overall mitigation potential of coastal ecosystems and they are only marginally reflected in current GHG inventories

All mitigation measures will to some degree require substantial management changes, and they are in direct or indirect conflict with each other or different land uses such as expanding settlements in terms of demand for land. Especially when mitigation measures affect agricultural or forestry production, leakage effects will have to be addressed, e.g. accompanying measures like cattle stock reduction and changing consumption patterns. The need for financial investment for e.g. compensation payments will depend on many different factors. In general, mitigation measures in

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[11] https://www.bmel.de/DE/themen/wald/wald-in-deutschland/wald-trockenheit-klimawandel.html

the land use sector can instigate opportunities for rural development and result in societal benefits that can often not be quantified but are likely to have a positive impact. Climate change will impact all options considered in the medium to long-term perspective. While effects on plant growth can be positively impacted by higher average temperatures, an increase in decomposition rates may lead to temporal net emissions especially in wetland ecosystems. Increasing natural disturbances due to progressing climate change are also expected to negatively impact carbon stored mainly in trees.

In summary, the mitigation options explored represent the wide range of opportunities that exist to mitigate climate change and generate benefit for other ecological and societal targets. The prioritisation of the measures above may be very different for some MS depending on their biogeography, natural vegetation cover, biodiversity protection priorities, social structure, and land use needs.

5.2 From potentials to policy framing

The study shows that the EU land use sector offers mitigation options that can at the same time deliver significant mitigation and a range of environmental and socio-economic co-benefits. Nonetheless, the assessments of the scale of this potential vary widely, in large part due to different types of assumptions made. Carbon sink options are also associated with uncertainty on how their potential will materialise under climate impacts, which includes the risk that they will not deliver the expected mitigation impact. The future sequestration potential depends heavily on the ability to withstand climate risks. Moreover, since cumulative assessments that consider interactive effects of implementing different options on the same area, entailing potential land competition, are very limited or not available, the potential estimates are not conclusive. Therefore, policies on maintaining and enhancing sinks should proceed cautiously to ensure that mitigation potential of carbon sinks is not overestimated and to avoid overreliance on carbon sinks as a climate mitigation strategy.

Environmental and socio-economic co-benefits of carbon sink options are largely underrepresented in available assessments. They are closely linked to the ability to realise mitigation potential because they enable resilience to lower climate risks, realise long-term sequestration and maintain sinks in the future. They are also central for adaptation effects, but do not occur automatically. Whether both mitigation and adaptation potentials are realised depends largely on how the options are designed and where they are implemented. Achieving both mitigation and adaptation may require some short-term trade-offs between these objectives (for example, by introducing new tree species that are better adapted to future risks but may lower short-term stocks). Singular or dominant short-term focus on maximising carbon leads to the risk of overlooking other co-benefits and undermining resilience of ecosystems, and ultimately long-term sinks. Therefore, criteria and safeguards are needed to ensure that climate and environmental and biodiversity benefits are achieved together. This requires that ecosystem services and ecosystem resilience are at the heart of the policy response for carbon sinks.

The study demonstrates the complexity involved in assessing and managing mitigation potential of carbon sinks in the land use sector in the EU. This complexity also means that many different policy areas and instruments have a direct bearing on the state and future development of carbon sinks. In order to devise an approach that realises mitigation potentials of current and future sinks and optimises the co-benefits and reduces leakage effects, a strategy on carbon sinks is needed that is coherent with other policy areas directly affecting the sinks, in particular agriculture, food, biodiversity, adaptation, bio-economy, and forest policies.

Based on this study, some overall messages and required steps can be identified for advancing EU policies on natural carbon sinks:

1) Protect existing natural carbon sinks and create opportunities to enhance sinks by reducing pressures on land use and demand for land:

- Enforce implementation of existing measures to **prevent conversion of forests and agricultural land** to settlements or infrastructure by reducing the rates of soil sealing and enforcing environmental legislation (EU Water Framework Directive, Habitat and Birds Directive under Natura 2000);
- Manage and reduce pressure from consumption on **managed forests and agricultural land** (including meat consumption, reducing food waste, demand for timber, bioenergy, bio-economy) in order to reduce intensity of land use and biomass extraction;
- Ensure true and fair pricing for agricultural products to reduce pressure to intensify **agricultural land** management;
- Reduce conflicts in the demand for land and risk of leakage when **increasing forest area and expanding agroforestry coverage** by strategic placement of options in areas currently facing multiple environmental pressures and on less productive land;
- Establish legally binding national restoration targets to **increase forest area, support restoration of forest carbon stocks, and conserve carbon in organic soils** under the EU Biodiversity Strategy.

2) Ensure that enhancement of carbon sinks, as a baseline, improves on the current levels of biodiversity and ecosystem resilience. Develop context specific safeguards and criteria to ensure multiple ecosystem services are delivered and ecosystem resilience against future climate risks is enhanced by e.g.:

- Choice of native tree species adapted to site conditions for **afforestation, reforestation and restoration of forest carbon stocks**;
- Consider biodiversity before land use conversion, e.g. there should be no **afforestation and reforestation** of biodiversity-rich grasslands;
- Eliminate pressures from resource and land use before ecosystem restoration, e.g. water usage in the area of **rewetting and wetland restoration** activities or pollution drivers before **restoring and protecting coastal ecosystems**;
- Install management strategies to control fire risk, e.g. fire breaks.

3) Improve tools for impact assessment and decision making to support policy development and implementation, as well as transparent monitoring, in particular at national and regional scale, including:

- Robust estimates of current and future sinks, **interactions, synergies and trade-offs between different options** and their combined impacts on mitigation potential, demand for land, delivery of co-benefits, ecosystem resilience;
- Estimates on which **realistic targets for natural sinks** can be set in the short term and long term at different scales;
- Assessment of **implications of enhancing sinks in the EU on leakage** outside the EU;

- **Barriers to implementation constraining the mitigation potential** and how to address these, such as lack of incentives to change land use, ownership and tenancy arrangements, market outlets.

4) Increase coherence of the EU policy mix towards enhancing sinks and reducing emissions in the EU and abroad by e.g.:

- **Eliminate countervailing subsidies for unsustainable practices** and land uses to increase the effectiveness of policies for maintaining and enhancing natural carbon sinks;
- Strengthen **sustainability criteria**, as under the Renewable Energy Directive and extend them to other biomass uses;
- Implement and strengthen the EU initiative for **deforestation-free supply chains**.

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