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Management options for increasing the mitigation potential in LULUCF sector

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Summary

This report is aimed at identifying a small descriptive number of land management options relevant to increase the mitigation potential of the LULUCF sector throughout Europe, synergic with climate change adaptation objectives and without having a negative impact on biodiversity (Task 2.2.2.1 - Subtask 2 of ETC/CA 2022).

A scoping search of information was carried out to provide a list of mitigation options in the land sector. This list is not extensive but more illustrative to support the methodological development on creating a geospatial map on carbon sequestration potential, starting from published existing EEA work.

The definition of mitigation measures in the land sector (focus of Task 2.2.2.1 - Subtask 2) is key to understanding the relevance of the various existing datasets (part of the catalogue developed in Task 2.2.2.1 - Subtask 1), for the development of the methodology on how these existing datasets can be combined (Task 2.2.2.1 - Subtask 1), and to create a carbon sequestration potential map compatible with the LULUCF Regulation (Task 2.2.2.1 - Subtask 3).

The activities of the team were performed in close cooperation with the EEA and the ETC/DI teams. The teams worked collaboratively using shared files (docs and excels).

1. Introduction

Increasing the mitigation potential of the LULUCF sector is a crucial action for achieving the climate neutrality target by 2050 set by the European Union in the framework of the EU Green Deal. In the pathway towards this objective, the EU has set an intermediate target to reduce emissions by at least 55% by 2030, compared to 1990 levels.

In the context of the Fit-for-55 package and the proposed amendment of the LULUCF Regulation, the achievement of the intermediate target by 2030 would require EU LULUCF sector increase the sink up to 310MtCO2eq yr-1 (currently 256 MtCO2eq yr-1, EU-27 average for 2017–2019) while in the long term, for the achievement of the EU climate neutrality, the sink from LULUCF will need to be nearly doubled up to 425 Mt CO2 /year (EC, 2019), thus posing a significant challenge to the land-based sectors.

Therefore, under this framework, the LULUCF sector in the EU needs to efficiently maximize its mitigation potential while simultaneously addressing the critical environmental, economic and social functions of the land, and also considering the interactions with other sectors.

In addressing this challenge, a clear understanding of the land management options and their potential for climate change mitigation represents a powerful tool for the EU Member States (MSs) to plan and prioritize their mitigation activities in the LULUCF sector. In support of MSs, EEA has mandated the ETC CA/LULUCF to provide a scoping study – starting from published existing EEA work, to explore and identify specific land management options that would increase the mitigation potential of the LULUCF sector in Europe, without having a negative impact on biodiversity and being potentially synergic with climate change adaptation. Given the scoping nature of this work, the list of mitigation options in the land sector is not extensive but illustrative to support the methodological development of creating a geospatial map on carbon sequestration potential, aligned with the LULUCF Regulation in terms of categories and possible effects in net emissions and removals in the accounting.

The LULUCF Regulation covers managed lands as defined in the IPCC land categories (see Box 1, a-f). All land categories are considered in two different ways, both having an effect on the mitigation potential: either land remains unchanged (e.g. forest remains forest) or land is converted to (e.g. land converted to forest). Since nearly the whole land in the EU is considered managed, the whole territory will be subject to accounting under Regulation 841/2018.

Box 1: Scope of the LULUCF regulation 841/2018 for the period 2026-2030 according to the EC review proposal (COM(2021) 554 final)

"Article 2, par 2: This Regulation also applies to emissions and removals of the greenhouse gases listed in Section A of Annex I, reported pursuant to Article 26(4) of Regulation (EU) 2018/1999 and occurring on the territories of Member States in the period from 2026 to 2030, in any of the following land reporting categories and/or sectors:

(a) forest land;
(b) cropland;
(c) grassland;
(d) wetlands;
(e) settlements;
(f) other land;
(g) harvested wood products;
(h) other;
(i) atmospheric deposition;
(j) nitrogen leaching and run-off."

According to IPCC, the main categories and sectors may be further stratified in more detailed classes.

2. Potential mitigation of land management options

Many human activities directly and indirectly affect the mitigation potential of the LULUCF sector by causing changes in carbon stocks for the different carbon pools of the terrestrial ecosystem (e.g. above- and below-ground biomass, soil,– litter and dead wood) and in terms of changes in fluxes of greenhouse gases (GHG) between the terrestrial ecosystem and the atmosphere.

Mitigation options that can be implemented on land can be sorted into two main categories:

- increase carbon sequestration: activities that increase the carbon removals from the atmosphere;
- reduce GHG emissions, including avoided emissions: decrease emissions by halting the loss of carbon stocks or reducing the anthropogenic emissions of climate altering gases such as carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O)

Table 1 reports the description of the main mitigation options in the LULUCF sector, for which anthropogenic greenhouse gas emissions and removals by sinks are defined as all those occurring on 'managed land.' Managed land is where human interventions and practices have been applied to perform production, ecological or social functions.

Three types of mitigation categories can be considered:

- Land use change (transition to land uses with higher carbon stock, like cropland to forest);
- Land management (management of certain land use that improves the sink or reduces the sources e.g. cover crops, use of residue, sustainable forest management etc.);
- Restoration or protection of existing stock resulting in avoided emissions (ecosystem restoration, avoided deforestation)

Mitigation options can include also an increased production of bio-based products that can support GHG emission reduction by replacing energy intensive materials and fossil-based sources of carbon, products and chemical feedstocks and that can increase carbon sequestration in long-term storage harvested wood products.

Forests represent a significant global carbon stock accumulated through growth of trees and an increase in soil carbon. Forest-based climate mitigation may occur through conserving and enhancing the carbon sink and through reducing greenhouse gas emissions from deforestation and forest degradation (Grassi et al., 2017). Unsustainable practices such as illegal logging and forest degradation result in GHG emissions due to the loss of carbon stock accumulated over time and can have additional physical effects on the regional climate including those arising from albedo shifts. Forests' carbon sequestration potential depends on many factors (age distribution, species, climatic conditions etc) including the forest cycles. Therefore the **time dimension** is a crucial factor to properly account for forest-based mitigation. Through sustainable forest management it is possible to take into account multiple management objectives, including mitigation and biodiversity, for example in areas of degraded forests, sustainable forest management can increase carbon stocks and biodiversity. Generally, a sustainable forest management which balances the maintenance or the increase forest carbon stocks, with the wood provision contribute to mitigation objectives, e.g. storing carbon in long-lived wood products, substituting for emissions-intensive materials, using bioenergy instead of fossil-based energy (Verkerk et al 2022).

Other terrestrial systems also play an important role. Most of the carbon stocks of croplands and grasslands are found in the below-ground plant organic matter and soil. Consequently, sustainable farming practices aimed at increasing soil carbon sequestration in croplands and grasslands have a great mitigation potential.

A main **drawback of LULUCF activities is their potential reversibility and non-permanence** of carbon stocks because of human activities, natural disturbances or a combination of the two with loss of carbon stocks and release of GHG into the atmosphere as a result. Therefore, practices aimed at reducing or halting the ecosystems' degradation play a key role in mitigation.

Table 1 – Categorization of main mitigation options in the LULUCF sector

Mitigation category	Mitigation option	Type of mitigation
Land use change **(Conversion to land uses with higher carbon stocks)**	Cropland to Grassland	Carbon removal/emission reduction
	Afforestation/Reforestation (Cropland or Grassland to forest)	Carbon removal/emission reduction
Land management (Management of a certain land use that improves the carbon sink or reduces the sources e.g. cover crops, use of residue, forest management et.)	Reduction of soil disturbances (minimum/zero tillage)	Carbon removal/emission reduction
	Annual crops to perennial crops/agroforestry (including recreation/restoration of hedgerows)	Carbon removal/emission reduction
	Management of agricultural residues	Carbon removal/emission reduction
	Biochar application	Carbon removal/emission reduction (from the energy sector)
	Cover crops	Carbon removal/emission reduction
	Improved forest management	Carbon removal/emission reduction
Avoided degradation/restoration	Restoration of degraded forests	Carbon removal/emission reduction
	Protection of existing stocks (Ecosystem conservation, forest protection, avoided deforestation)	Emission reduction
	Restoring environmental conditions like rewetting drained peatlands/wetlands	Carbon removal/emission reduction

3. Methodological approach

The Intergovernmental Panel on Climate Change (IPCC) in its Special Report on Climate Change and Land (IPCC, 2019a) identifies many land-related climate change mitigation options that have also co-benefits for climate change adaptation and in terms of biodiversity protection. At the same time the report also recognizes that some activities can have adverse side-effect on other ecosystem services such as through increased competition for land and water if not implemented with due consideration to the local conditions including current land use.

Relevant EEA work already exists helping on the selection of main mitigation options. For example, a detailed list and description of good practice, challenges, and future perspectives regarding agricultural climate mitigation practices is reported in a 2021 EEA Report "Agricultural climate mitigation policies and measures" from German et al. (2021).

The 2019 EEA paper "Land and soil in Europe" provides useful insights on the importance to preserve and correctly manage the land sector paying particular attention to maintain healthy land and soils which produce most of our food and host all animals and plants species.

The 2022 EEA briefing "Carbon stocks and sequestration in terrestrial and marine ecosystems: a lever for nature restoration?" reports a scoping analysis linking habitat types with carbon storage and sequestration capacities to support nature restoration and conservation, as well as climate mitigation policies.

Starting from the options proposed in the IPCC report (IPCC, 2019a) and considering the published existing EEA work a subset of land management options has been selected from Table 1, representative for each type of mitigation category, identified as the following:

- Afforestation/reforestation
- Agricultural soil management
- Peatland rewetting and protection

For this subset of land management options, the methods to calculate spatialized mitigation potential, based on the available information has been described (section 4) considering the methodologies for accounting carbon removals and emissions reduction presented by the IPCC Guideline for National Greenhouse gases inventory (IPCC, 2006; IPCC, 2019b).

However, it must be said that mitigation options can have trade-offs and synergies with other management objectives, and therefore the design and implementation of those should be part of a comprehensive approach to land use and management at landscape level. Also, the complexity of the ecosystems, socio-economic considerations and site-specific features should be well considered in designing and implementing mitigation options. Still, a better quantification of spatialized mitigation potential can provide policy makers with more information on the potential impacts of specific options.

4. Examples of mitigation options

4.1 Afforestation and reforestation

Context and definition

Afforestation and reforestation are defined as the establishment of a forest land cover through planting trees and/or deliberate seeding on a land that currently has no tree cover and that in the past was (reforestation) or was not (afforestation) forest.

A new forest area can be classified as:

- main forest category:
  - broad-leaved forest,
  - coniferous forest, and
  - mixed forest,

and can be further detailed into:

- one of the 14 existing European Forest Categories (EFC), and
- one of the 75 European Forest Types (EFT)

The main forest category can be retrieved by the III level of classification of the Corinne Land Cover maps (CLC 2018 — Copernicus Land Monitoring Service); while the EFC and the EFT as described in the EEA report "European forest types. Categories and types for sustainable forest management and reporting" (2006) correspond to the IV and V level of classification of the CLC 2018, respectively (Giannetti et al., 2018). Moreover, Mauri et al. (2022) produced current and future suitable area for 67 forest species in Europe.

When an afforestation/reforestation activity is carried out, the most appropriate main forest category or EFC or EFT should be chosen - preferring mixed species composition to, for example, enhance biodiversity - according to specific suitability criteria defined by analysing in which conditions each forest type was observed in the past (e.g. 30 years). To this aim, the range of a main forest category or EFC or EFT – i.e. the geographical area within which that species can be found – should be defined.

The range of forest species can be defined according to different suitability criteria which usually refer to bioclimatic variables[1], which for example can represent annual trends (e.g., mean annual temperature, annual precipitation), seasonality (e.g., annual range in temperature and precipitation) and extreme or limiting environmental factors (e.g., temperature of the coldest and warmest month, and precipitation of the wet and dry quarters), altitude, slope, soil type.

Then, according to the bioclimatic variables expected in the future climate scenarios, the potential future range of the forest species is detected, depending on the time horizon of interest (e.g. 2050 or 2100).

Potential data source

Many modelling processes exist which directly provide as result the range of forest species based on bioclimatic variables. However, the following source of information would be useful:

- Map of land cover
- Map of current and future climate scenarios (with main indicators: temperature, precipitation, etc.)
- Digital elevation model
- Map of soil types

Mitigation mechanism

The mitigation mechanism of this management option is increase of carbon sequestration in all C pools.

Baseline scenario

The afforestation/reforestation option can be carried out on various land uses and the potential for carbon sequestration will change accordingly. The most likely baseline land uses on which the afforestation/reforestation option can be applied are *grasslands* or *croplands*, since it is very unlikely that a settlement land use is re-converted to a such natural ecosystem as the forest one. The conversion

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[1] Bioclimatic variables are derived from the monthly temperature and rainfall values in order to generate more biologically meaningful variables. https://www.worldclim.org/data/bioclim.html

of wetlands into forests should be avoided given the high amount of GHG emissions that this would generate and for biodiversity protection as these ecosystems are often in protected areas hosting relevant habitats for numerous animal and plant species.

Protected areas in general should be also carefully considered and usually not included among the suitable areas for afforestation/reforestation, unless specific target includes this option, since for example many grasslands included in protected areas could be at high conservation value therefore cannot be converted to forest.

In case of afforestation/reforestation on grassland or croplands, the potential carbon loss due to the conversion from the previous land use should be deducted from the potential carbon sequestration (IPCC, 2019). This includes the potential carbon loss both from the soil organic carbon (SOC) pool (e.g. the carbon stored in the mineral soil of a grassland or a cropland must be deducted from the potential carbon sequestration from the afforestation/reforestation) and from the living biomass pool (e.g. in the case of afforestation/reforestation on a perennial cropland the carbon stored in the woody biomass of the tree crop that will be uprooted must be deducted from the potential carbon sequestration from the afforestation/reforestation).

Potential data source:

- Map of land cover
- Map of protected areas
- Map of current soil carbon content
- Map of current living biomass and/or statistical data of living biomass from national forest inventories

Vulnerability to risks

Information on the risks which can threaten the permanence over time of the new forest must be considered, thus allowing also for climate change adaptation.

Risk maps can be useful to plan for afforestation/reforestation, for example areas at high risk of fire in the future scenarios should be considered as not appropriate to apply afforestation/reforestation activities being forest wildfires among the most common disturbances in European forests - wildfires, pests and diseases (bark beetle), and windstorms (Seidl et al., 2014). Also the changes in distribution of the species due to changes of climate conditions should be considered to guarantee the success of the new established forests in the long term. The datasets of the EU4Tree developed by Mauri et al. (2022) can provide an comprehensive datasets on current and future suitable area for 67 forest species in Europe to assess which species can guarantee long term success in each European site.

Potential data source:

- Map of areas at risk of fires
- Map of future distribution of species

Regarding the risk of pests and diseases (bark beetle), the areas at higher risk to be considered unsuitable for afforestation/reforestation can be defined by identifying suitable ranges, i.e. the geographical area within which the pathogen can be found.

Potential data source:

- Map of distribution of plant pathogens/diseases
- Map of current and future climate scenarios (with main indicators: temperature, precipitation, etc.)
- Map of species distribution according to climate scenarios (EU-Trees4F)
- Map of future fire risk scenarios

Carbon pools involved

The afforestation/reforestation option entails a potential for carbon sequestration in all five carbon pools: Living biomass - above/belowground, soil organic carbon (SOC) and Dead organic matter (DOM) - litter and dead wood. In addition, the harvested wood can also result in long living products thus prolonging the carbon storage beyond the life spam of the tree.

However, the Living biomass - above/belowground and the soil organic carbon (SOC) represent the most relevant pools in terms of the amount of carbon stock and, consequently, the most investigated, with available spatialized information, maps and data.

Potential data source:

- Map of soil carbon content
- Map of current living biomass and/or statistical data of living biomass from national forest inventories

Time frame

The afforestation/reforestation option aims to increase carbon sequestration in all the relevant carbon pools. However, carbon can be accumulated up to a maximum level of carbon stock in each pool (steady state or saturation effect).

In the SOC pool, the time needed to reach the maximum carbon stock depends on the amount of carbon effectively contained in the soil in the initial state before the afforestation/reforestation and on its capacity to reach a steady level after the afforestation/reforestation which, in turn, depends on many factors including the type of soil, soil depth considered and climate conditions. As general assumption, the IPCC GL establish that, when more detailed data is not available, the time needed to reach a steady state after a management change can be assumed to be equal to 20 years.

In the living biomass pools the maximum carbon stock is reached with a growth that follows a logistic equation, with increasing increments in its first half and then, after an inflection point, with decreasing increments in its second half which remain asymptotic towards its maximum carbon stock. The time needed to approach the maximum carbon stock in living biomass depends on the way the forest is managed and its forest cycle[2].

Biodiversity considerations

The operational application of the option will follow the "Guidelines on biodiversity-friendly afforestation and reforestation and closer to-nature-forestry practices" under the EU Biodiversity Strategy for 2030 (EC2020).

Trade offs

Large scale afforestation on agricultural areas can reduce cultivated surface and induce indirect land cover transitions elsewhere.

Afforested/reforested lands generally need management and monitoring. Therefore, appropriate resources and skills should be in place to avoid land abandonment.

Methods to calculate mitigation potential

The potential carbon sequestration in all the relevant carbon pools can be derived with different approaches. Indeed, modeling approaches can be applied for the simulation of carbon sequestration at local level on the basis of species and local characteristics. The approach is anyhow data intensive and

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[2] Forest can be managed according to two main systems. High forests originated from seed or from planted seedlings which took 80-100 years to reach maturity. In contrast to a coppice forests regenerated from shoots formed at the stumps of the previous crop trees, root suckers, or both, i.e., by vegetative means. Normally grown on a short rotation of generally 15-20 years.

can be implemented in a second phase of the development of the scenarios, moving towards a tier 3 approach. We hereafter focus on more empirical methods based on tier 1-2 approaches.
One method is to consider the maximum observed carbon content both in the soil and in the biomass, at present, for each main stratum of forest type, climate condition and soil type, and assuming that it is the maximum achievable for each stratum. The annual increment is provided using the Stock difference Method of the IPCC (Eq. 2.8), where the final biomass/soil C content status is subtracted to the initial C content of land before conversion to forest land, divided by the time that it is assumed to be needed to the C pool to achieve the equilibrium (Eq.1). The time changes depending to the pool and local conditions.

Eq (1)
$$\Delta C_{AR} = \frac{C_{AR} - C_{OL}}{T}$$

Where:

ΔC_{AR} = annual change in carbon stocks in the pool

C_{AR}= carbon stock in the pool of the afforested/reforested land at the steady state

C_{OL}=carbon stock in the pool before conversion (other land use)

T= time needed to the pool to achieve the maximum C content (or steady state)

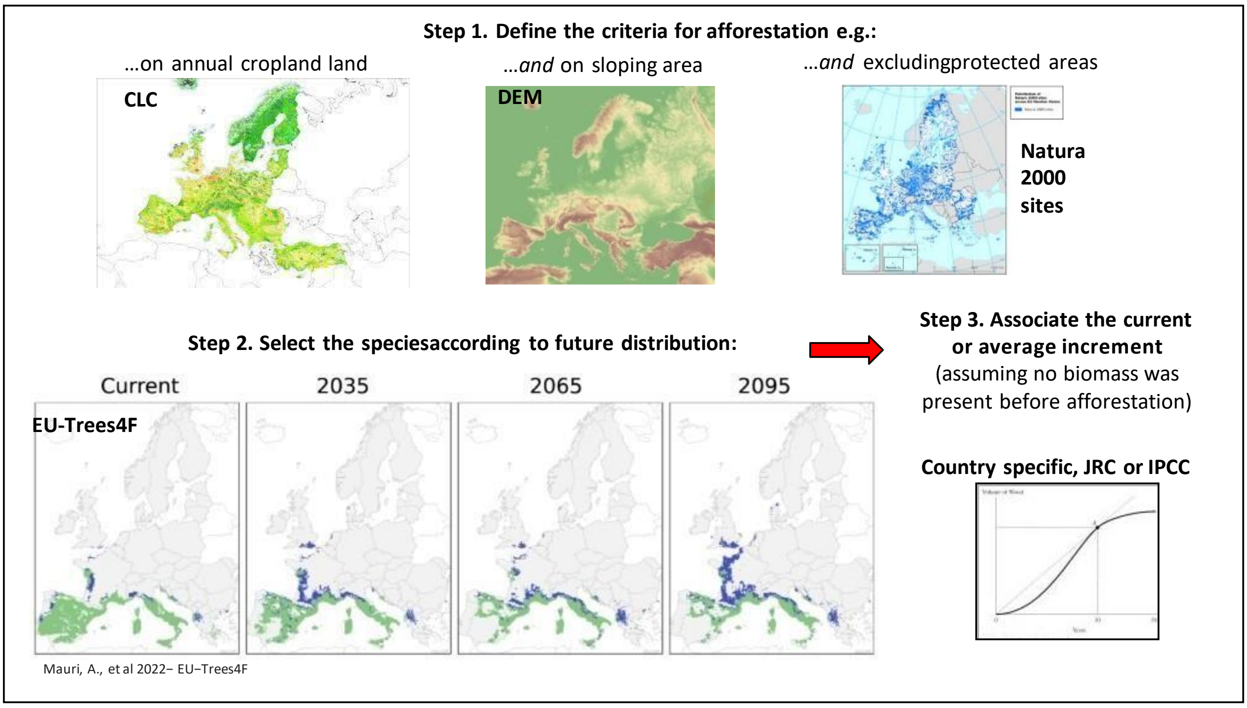

Figure 1 – Initial criteria for the selection of reforestation area help the spatialization of potential sites that need to be overlayed with the maps of potential future distribution of forest typesto identify suitable species. The sink can be estimated using trees current or average increments from different data sources

The attribution of soil C content for each strata for both forest categories and cropland and grassland where the afforestation/reforestation can be implemented, can be done through LUCAS data, following the following logical steps:

Step 1- Stratify the EU into land cover types belonging to environmental zones (as the EU env. Zones already include soil types and climate, it is not needed to use soil type as further information here)
Step 2 – Convert the LUCAS C concentration data on soil into C SOC stock via pedotransfer equations
Step 3 – Overlay the CSOC measurements on the strata obtained in step 1 and average them so to attribute a C SOC stock to each land use on a specific environmental zone.
The effect of soil carbon of the land use change can then be computed in each strata using equation 2.25 of the IPCC GL.

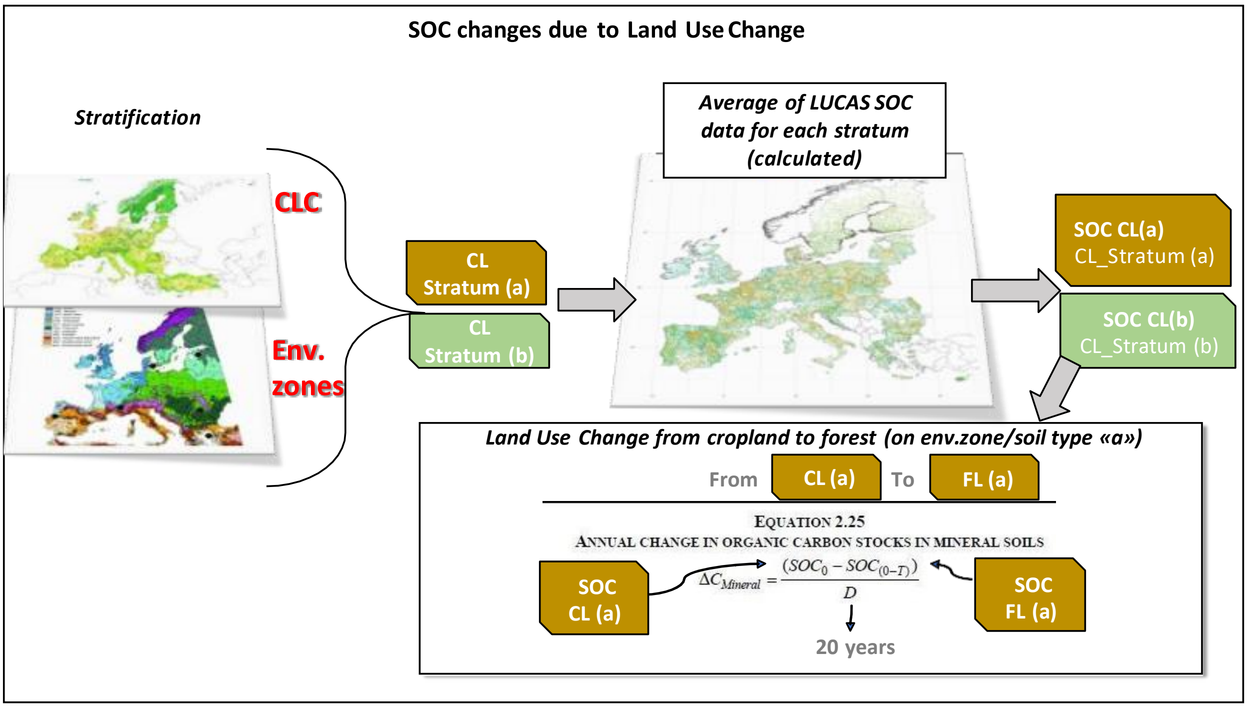

Figure 2 - Steps for the computation of SOC stock variations due to land use change using LUCAS data

Potential data source:

- Map of land cover
- Biomass map
- Map of environmental zones
- Map of current soil carbon content
- LUCAS dataset
- Map of current living biomass and/or statistical data of living biomass from national forest

Other approaches (which follow the IPCC Tier 2 and 3) can include the reference to values of soil carbon and carbon in living biomass derived by literature and specific for geographical regions or the modeling applications. Specifically, in the case of living biomass, values of annual woody increment can be derived by yield tables developed per species and fertility level, then species-specific biomass expansion factors (BEF) and root to shot ratios (R) can be applied to derive the actual carbon content in above and below ground forest biomass pool.
A large database of growth curves collected at the European level can be used to retrieve the net annual increment attributable to young forests (less than 40 years old) (Somogyi et al., 2008; Pilli et al., 2016). The resulting total annual increment can be further converted to annual carbon removals by assuming an average wood density equal to 0.50 t m^{-3}, an average biomass expansion factor equal to 1.2 and an average carbon content equal to 0.5. The resulting values do not account for carbon stock change on dead wood, litter and soil, since these pools are directly affected by the land use preceding the afforestation.

Potential data source:

Literature, expert judgment
Yields tables, biomass expansion factors (BEF), root to shot ratios (R)

Key parameters to calculate mitigation potential

Land Use
Soil Carbon
Soil type
Ecological zones (climate)
Biomass data
DEM
Fires
Fire Risk map
Land management
Future scenarios

4.2 SOC increase from cropland management

Context and definition

Cropland management modifies soil carbon stocks to varying degrees depending on how farming practices influence carbon input and output from the soil system (Paustian et al., 1997; Bruce et al., 1999; Ogle et al., 2005). The main management practices that affect soil C stocks in croplands are the type of residue management, tillage management, fertilizer management (both mineral fertilizers and organic amendments), choice of crop and intensity of cropping management (e.g., continuous cropping versus cropping rotations with periods of bare fallow), irrigation management, and mixed systems with cropping and pasture or hay in rotating sequences. In addition, drainage and cultivation of organic soils reduce soil C stocks (Armentano and Menges, 1986).

Soils are complex systems where chemical processes interact with biological processes. These are facilitated or impeded by several factors such as soil granulometry, water content, pH, type of solute products. The SOC and the associated bricks of living organisms (N, P, K) also play a key role, being at the same time factors and outcomes of the biological processes.
Soil carbon stocks are the product of:

- Soil Carbon content (kg C/kg soil) in the different soil layers (horizons)
- Soil bulk density (m3/kg soil) in each layer
- Area (m2) considered, generally one hectare
- Soil depth considered (m)

Often soil carbon stock is only estimated in the upper part of the soil (20 to 30 upper cm). Long-term sequestration however tends to be more significant in the deeper layers. The median age of carbon is reported to be greater than 100 years below 30cm and it reaches 1000 years at 1m depth (Ballesdent et al. 2018 in Pellerin et al, p. 19).
Soil carbon stocks of mineral soils (with SOC less than 12%) vary significantly from a few t/ha to 300 t/ha. They are rather low in soils having been cropped for a long period of time. They are significantly higher in grassland and forested land. The soil history influences the carbon dynamics for several decades after land use change. Soils previously occupied by permanent grasslands have higher carbon stocks even several years after they have been transformed into cropland. Forested soils once used for crop production store more carbon than those afforested for a long time (Pellerin & Bamière, 2019).

The soil carbon balance is to a large extent the result of two opposed processes: (i) the carbon absorption by crop photosynthesis and the transfer of part of that carbon to the below-ground biomass and (ii) the degradation and mineralisation of the organic matter of the soil (from below and above ground biomass). The rate of these processes is influenced by several factors of the local edaphic and land use conditions (Figure 3).

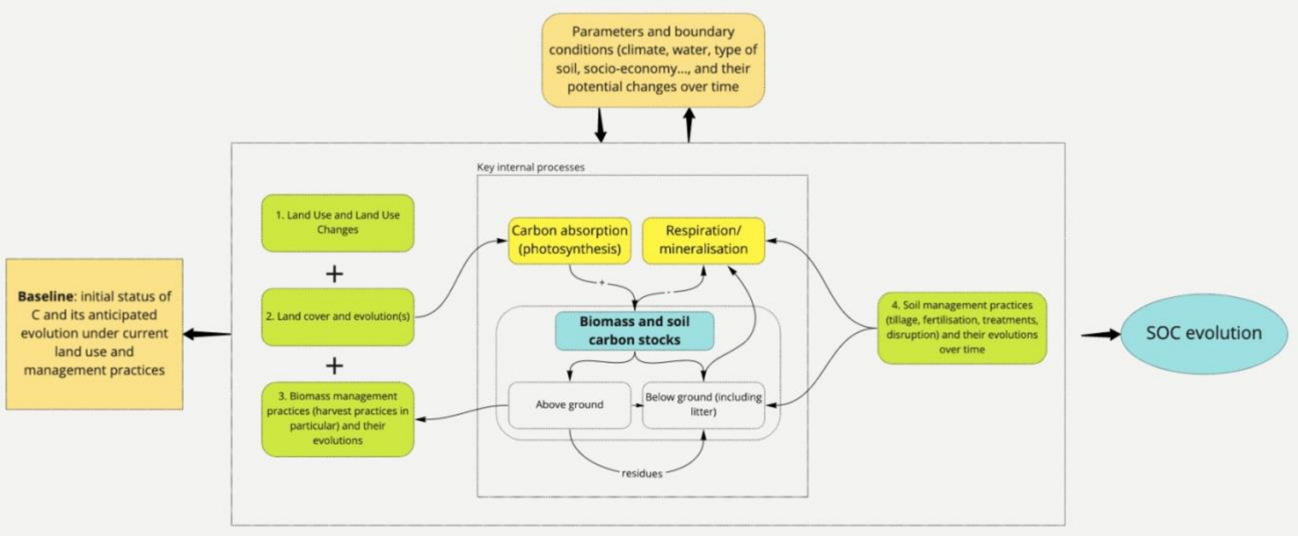

Figure 3. Key factors and processes of the soil organic carbon evolution

Organic matter mineralisation is the primary process of carbon loss from soil. Mineralisation results from various biochemical processes of the micro and macro-organisms of the soil ecosystem. These processes are key to the creation of stable organic matter. One essential parameter of mineralisation is the ratio between carbon and nitrogen (C/N) of the organic matter, initially quite high in living vegetal biomass. In the mineralisation process, the N content of the remaining products increases and the C/N ratio decreases. Therefore, nitrogen is the main factor that accelerates or inhibits the mineralisation processes.

According to Pellerin et al (2019), four critical factors influence *carbon sequestration in cropland*:

- The types and amounts of organic matter added to the soil by the plants or through fertilisation practices, which in general induce higher carbon sequestration
- Temperature accelerates the mineralisation process; a 10° increase typically multiplies the mineralisation rate by 2 to 3
- Oxygen availability in the soil: the most important effect is when anaerobic conditions prevail for long periods in the soil, which reduces the mineralisation rate
- Water content effect is not straightforward, at medium level, water accelerates the processes and the mineralisation. But when the soil becomes saturated, the oxygen availability is reduced and the effects of anaerobic conditions predominate.

Two other critical processes of carbon loss need to be accounted for. The first one is soil erosion. Because organic matter is located mostly in the upper part of the soil, water or wind erosion have an impact on soil carbon stocks. This is particularly the case in cropland that remains bare during autumn and winter. Carbon losses due to erosion are above 2tC/ha/year in 24% of the soils in the EU and 5.2% of the soils suffer from severe erosion (>10t/ha/year, which represents 1 mm of soil each year) (Panagos et al 2015). In addition, the more organic matter is depleted from the soil, the more sensitive the soil is to erosion. The impacts of erosion are also dependent on the local topography particularly in case of water erosion. The second one is the leaching of dissolved organic molecules which impact carbon stocks in certain areas, influenced by excess irrigation or soil water transfers in humid periods.

The overall result of these factors is a general decline of soil carbon content in the soil from the North-West to the South-East of Europe. For the same reasons, in a country the carbon stocks for a given land use and type of soil tend to increase with altitude given the decrease in average temperature.

Climate change is changing the above factors in two major and opposed ways: (i) the increase of CO2 in the atmosphere has a fertilising effect, particularly when combined with additional nitrogen fallout, and (ii) the temperature increase. Projections indicate that in the future, the second factor will become predominant (Pellerin et al, 2019).

While SOC contents tend to decrease in cropland across Europe, several practices can be implemented to increase the SOC content of cropped soils. They range broadly into four categories as shown in the table 2.

Table 2 – Main farming practices with potential positive effect on soil carbon sequestration

Type of practice	Specific practices
Land use or land use change	Permanent grassland, perennials and change to such crops, agroforestry, hedgerow implementation or restoration
Crop and biomass management	Mulching, cover or catch-crops, improved crop rotation, crop residue management, grass management, erosion control measures
Tillage practices	No-till, conservation (minimum, reduced) tillage
Fertilisers and amendments	Manure application, compost, biofertilizers, sewage sludge, liming, biochar and combination thereof

The most critical practices are those that add carbon to the soil through either (additional) plant cover or addition of external carbon although, in the latter case, the overall mitigation potential should be carefully considered verifying the occurrence of an actual additional benefit where carbon is effectively removed from atmosphere and not simply moved from one place to the other. Other practices (such as conservation tillage) need to be implemented to ensure that the carbon incorporated is not quickly released back into the atmosphere through organic matter degradation. In this respect nitrogen may play an important role: too little nitrogen may impede the biological processes that produce stable organic matter. At the same time, over-fertilisation may accelerate organic matter degradation and losses of carbon to the atmosphere.

Accordingly, the mitigation potential of different cropland management practices must be stratified according to climate regions and major soil types, which can either be based on default or country-specific classifications. This can be accomplished with overlays of land use on suitable climate and soil maps.

Potential data source:

Soil carbon stocks of EU topsoils (Jones et al, 2005)
https://esdac.jrc.ec.europa.eu/content/octop-topsoil-organic-carbon-content-europe
Available data: organic carbon in the topsoil:
https://esdac.jrc.ec.europa.eu/ESDB_Archive/ptrdb/oc_topa3.pdf
ESDAC Topsoil Soil Organic Carbon (LUCAS) for EU25

Mitigation mechanism

The mitigation mechanism of this management option is the increased soil organic carbon sequestration. A tentative overview of the approach required to assess the carbon sequestration and net mitigation potential is synthesized in Figure 4.

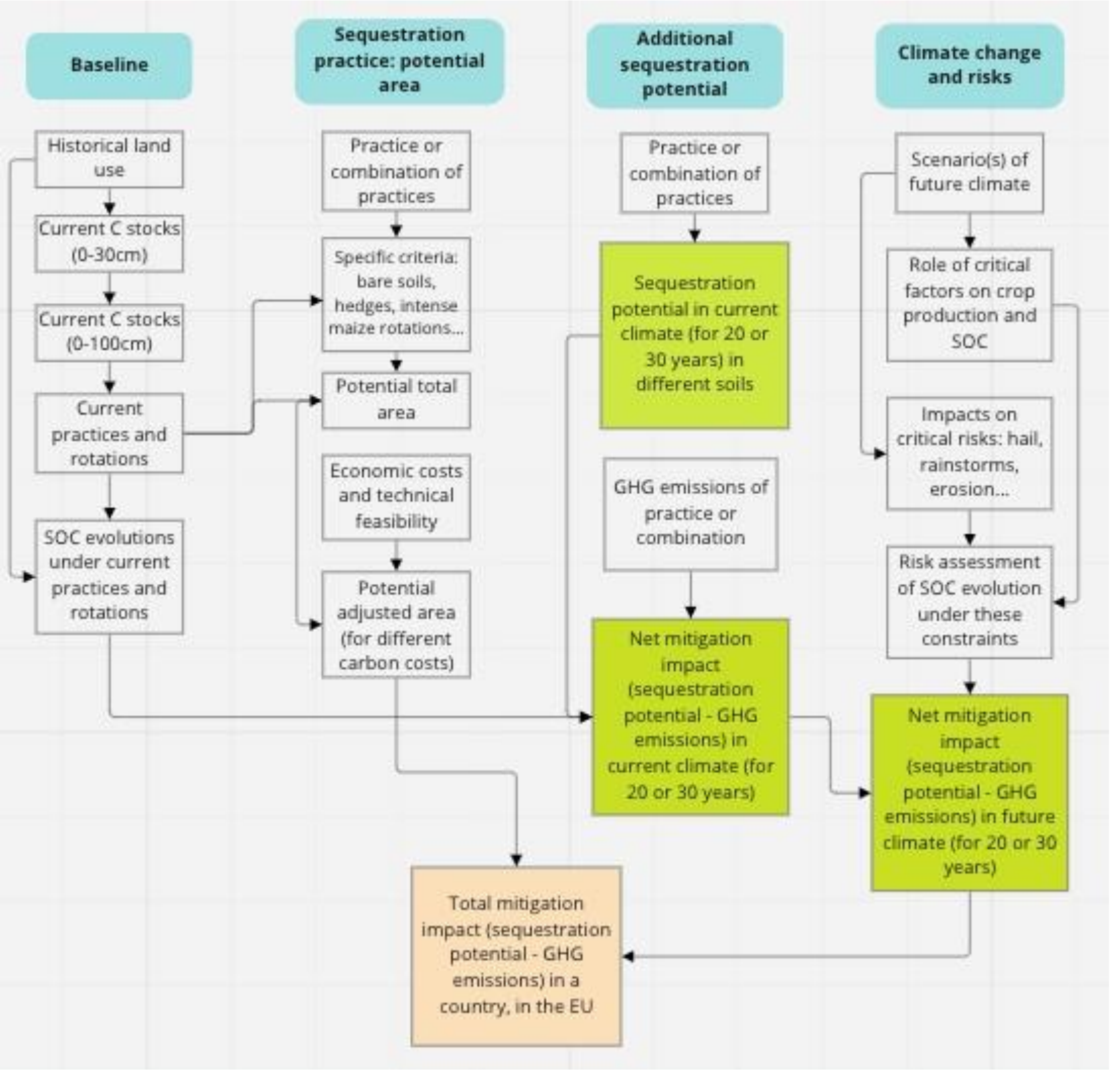

Figure 4. A proposed approach for the determination of a total mitigation impact of soil carbon sequestration practices in the EU

Baseline scenario

In general, for a given set of practices, soil carbon sequestration will increase progressively until a new balance between carbon inputs and organic matter mineralisation is reached. It is not an indefinite process. If the set of practices changes or if the climate conditions change (e.g. if dry weather sequences become more frequent) a new balance will be reached.

Determining the baseline is challenging given the historical "memory" of the soils and the long-lasting evolutions of carbon stocks (Figure 5). In most cropland soils, a long-term decrease is observed, that is particularly important in the case of grassland conversion.

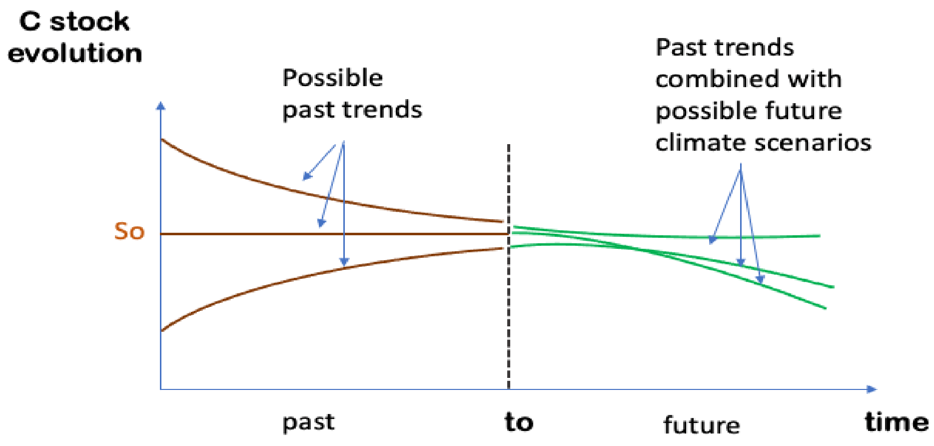

Figure 5. Assessing a dynamic baseline for soil carbon sequestration. The past trends depend on farming practices and on the history of the land. The future direction depends on the future climate scenario in addition. So is the measured carbon stock at a given reference time (adapted from Pellerin & Bamière, 2019).

Some important choices are therefore required to select the most appropriate baseline (Figure 6). The measured carbon stock at a given reference time will not be enough. Its probable evolution in a steady climate context should be at least considered.

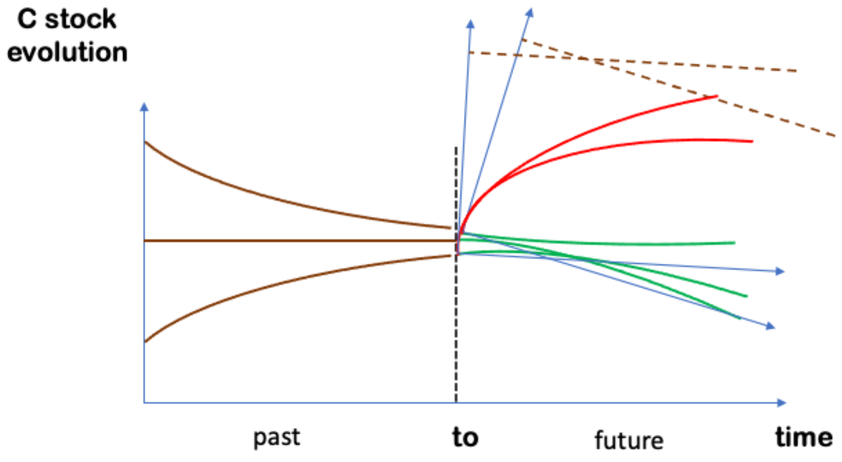

Figure 6. Carbon sequestration assessment from new practices taking account of a dynamic baseline. The actual sequestration is the difference between the red curve and the selected baseline (green curve)

Vulnerability to risks

Soil carbon is particularly sensitive to warm conditions and more generally to all mechanisms that enhance the mineralisation process or reduce the uptake of CO2 of the plants from the atmosphere. Warm and dry spring or summer seasons affecting crop yields can affect the soil carbon stock significantly. Such dry conditions can also prevent the proper and timely implementation of cover crops.

Carbon pools involved

The carbon pool involved in cropland management is mostly the soil carbon pool, to be assessed at least in the top30cm, but preferably up to 1m of the soil, and not only in the top 30 cm. Living biomass is relevant when perennial crops are considered.

Time frame

Given the dynamics of soil carbon processes and the climatic variability, at least a 20yr scenario needs to be considered at least, following the IPCC default time frame.

Biodiversity considerations

In general, increased soil carbon sequestration goes hand in hand with increased soil health and enhanced soil biodiversity. In addition, many sequestration practices (e.g. cover crops or agroforestry) have positive effects on biodiversity in general.

Trade offs

The most critical trade-off to be anticipated relates to leakage effects. Some practices involve mobilizing organic matter produced outside the farm. In that case, assessing the consolidated carbon sequestration balance is essential i.e. assesing whether the carbon simply transferred from one place to the other and if there is a real added climate value of this transfer.

Methods to calculate mitigation potential

As a first approximation, changes in carbon stocks in mineral soils of both annual and perennial croplands can be calculated by applying equation 2.25 of the IPCC, 2006 (vol. 4, chapter 2). The change of C stock following a management change, is computed in relation to the carbon stock in a reference condition (i.e., native vegetation that is not degraded or improved), called the" SOCref", which is multiplied by stock change factors (F_{LU}, F_{MG}, F_I) specific for each management option - derived by the default values provided in table 5.5 of the 2019 IPCC refinement. The following assumptions are made: (i) Over time, soil organic C in agricultural soils reaches a spatially-averaged, stable value - specific to the soil, climate, land-use and management practices - after a transition period, i.e. 20 years, is considered as IPCC default; and (ii) Soil organic C stock changes during the transition to a new equilibrium SOC occur in a linear fashion.

The SOCref classification of the soils is based on the default reference SOC stocks for mineral soils (tC/ha in 0-30 cm) provided in table 2.3 of IPCC 2006 (see annex II). The identification of country specific SOCref can be performed using a combination of the following map layers:

- IPCC climate zones (JRC) - http://eusoils.jrc.ec.europa.eu/projects/RenewableEnergy/
- Corine Land cover for identification of initial land use
- Soil map of Europe (reclassified according to the main groups of soil types as in table 2.3 of IPCC 2006 GL and provided by the JRC)
- Map of Europe with administrative boundaries.

Overlapping the above mentioned layers, the EU soils can be classified according to the IPCC soil classes (table 2.3, vol. 4, chapter 2 of the 2019 IPCC refinement) and their related climate zones. According to the thereby defined distribution of the soil types and climate zones it is possible to spatialize the SOCref. The stock change factors (F_{LU}, F_{MG}, F_I) specific for each land use and management option can also be spatialized according to the climate zones and uses, allowing the user to define the initial and final use, derived by the default values provided in the table 5.5 of the 2019 IPCC refinement (vol.4, chapter 5).

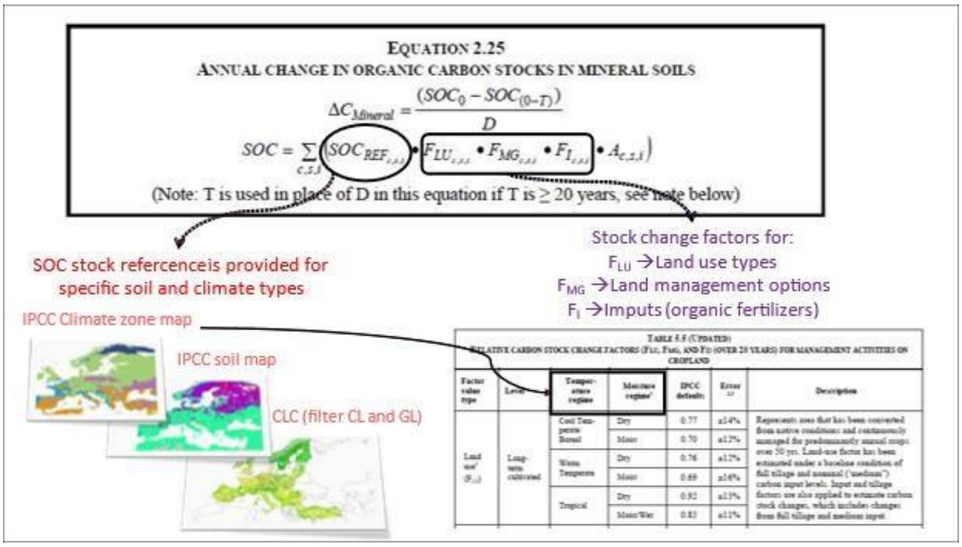

Figure 7 – The overlay of climate zones and soil type allows the attribution of specific values of reference SOC and factors for land use, management and inputs.

As there are no spatialized information on the management types over Europe, the simulation performed using the default method above should be performed by the user through a web interface, that can select the inputs, management and land use factors over a specific cropland area at two different points in time (present and future). The system should map the resulting fluxes applied over the current cropland area. The same approach can be used to simulate the changes between annual to perennial cropland, using the harvesting cycles indicated in IPCC.

Potential data source:

- Map of current and future climate scenarios (with main indicators: temperature, precipitation, etc.)
- Map of current soil type

Potential data source:
Models, literature, expert judgment

Key parameters to calculate mitigation potential

Land Use
Soil Carbon
Soil type
Ecological zones (climate)
Biomass data
DEM
Fires
Fire Risk map
Land management
Future scenarios

4.3 Peatland restoration through rewetting

Context and definition

Peatlands are defined as “areas with a naturally accumulated layer of peat at the surface” where “peat is a sedentarily accumulated material of which at least 30% (on a dry mass basis) is dead organic matter” (Tanneberger et al, 2021). They are classified as “mires” when they are actively producing peat. Mires themselves can be categorized into bogs and fens. Bogs receive most of their water and nutrients from precipitations; they are nutrient poor and acidic; their vegetation is made to a large extent of sphagnum moss. By contrast, fens receive a significant amount of their water from mineral-rich groundwater or surface water; they are less acidic and their vegetation predominantly consists of graminoids and shrubs.

Peatlands are sources of significant GHG emissions when drained or degraded by farming practices or peat mining for biofuel production[3]. Emissions are due to peat organic matter oxidation allowed by air - and thus oxygen- entry into a drained soil. By contrast, the low oxygen content in water prevents organic matter degradation when the soil is saturated throughout the year. Lowering the average water table in a peatland to a depth of 40cm below the soil surface induces CO2 emissions of around 20tCO2e/ha/year (Jurasinski et al., 2016). The lower the average water table, the higher the emissions, every 0.5 m lowering yielding roughly another 20t of CO2e emissions (Figure 8).

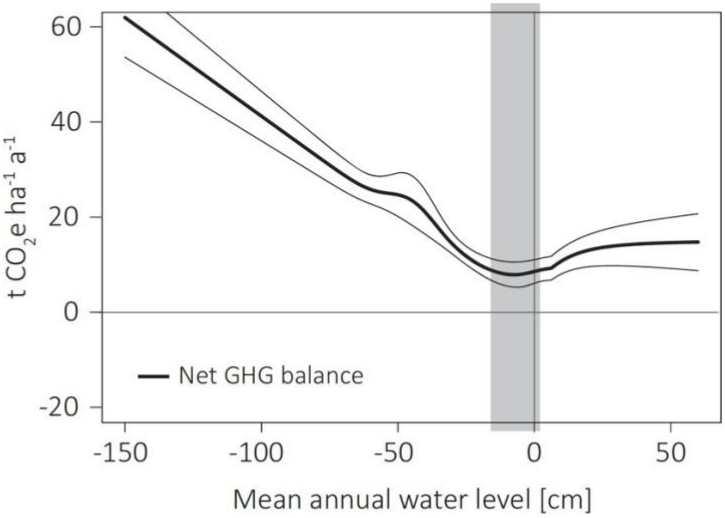

Figure 8. Relationship between peatland emissions and average water table level. From Jurasinski et al (2016). Similar results were obtained in various countries across Europe. Note that the increase in emissions observed when peatland is submerged is due to methane emissions.

Methane emissions are also important particularly in submerged[4] peatlands, which, given the global warming potential of this gas (28 times higher than CO2 when considering a 100-year time scale), needs to be taken care of. Therefore, the trade-off between CO2 and methane emissions is one of the key aspects to consider when restoring peatlands. Recent studies show that despite the risk of methane emissions, rewetting of peatlands has positive overall impacts (Günther et al, 2020). The risk of methane emissions seems to be higher only during a few years after rewetting.

Accordingly, it is critical that peatland water levels be controlled very precisely to reduce GHG emissions to a minimum: fluctuations of the water table should be avoided and the water table should be close to the soil surface without submerging it. The effect of peatland rewetting is immediate in terms of emission reduction. Carbon sequestration in the soil may also start but its impact on carbon can be neglected since sequestration is a slow process. In the case of paludiculture (i.e. the production of

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[3] IUCN list the following degradation causes: drainage, forestry, extraction, grazing, burning, pollution, construction. See details in https://www.iucn-uk-peatlandprogramme.org/sites/default/files/Review%20Peatland%20Biodiversity%2C%20June%202011%20Final_1.pdf

[4] Nitrous oxide emissions may also occur but in rather small quantities. In case of rewetting, these N2O emissions, like those of CO2, are dramatically reduced

valuable crops on rewetted peatlands), carbon absorption in the above-ground biomass can be significant (see if any carbon balance on this).

Box 2 – Organic soil in the IPCC

While this document focuses on peatlands, the broader issue of "organic soils" should be kept in mind since the boundary between organic soils and peatlands is not straightforward when dealing with GHG emissions. IPCC guidelines do not refer to peatlands specifically due to the definition differences across regions. They refer to organic soils, I.e. soils containing at least 12-18% of organic carbon on a dry weight basis. Peatlands are specific organic soils with a layer of peat, made of deadly and locally produced plants. In their pristine conditions, they are also wetlands i.e. lands with a permanent water table generally close to the soil surface. Typically, pure peat layers contain a high percentage of carbon, above 50% on a dry weight basis.

In terms of carbon emissions, a problem arises from the fact that using a percentage of the weight hides the fact that on a volumetric basis, which is more important for the organic matter degradation and the GHG emissions, the amount of carbon looks rather different because the soil bulk density decreases at high carbon content. A typical curve (in Barthelmes, 2018) looks as presented below and indicates that peat with 50% of organic carbon on a dry weight basis has a similar volumetric carbon content (0.06 gC/cm3 of soil) as a mineral soil containing 5% of C on a dry weight basis.

While we focus here mainly on peatlands, it seems that a broader approach including other organic soils, at least those taken into account by IPCC, should be used to better estimate the emissions and potential to cut them. Only a few countries implement such an approach in the EU (Barthelmes, 2018).

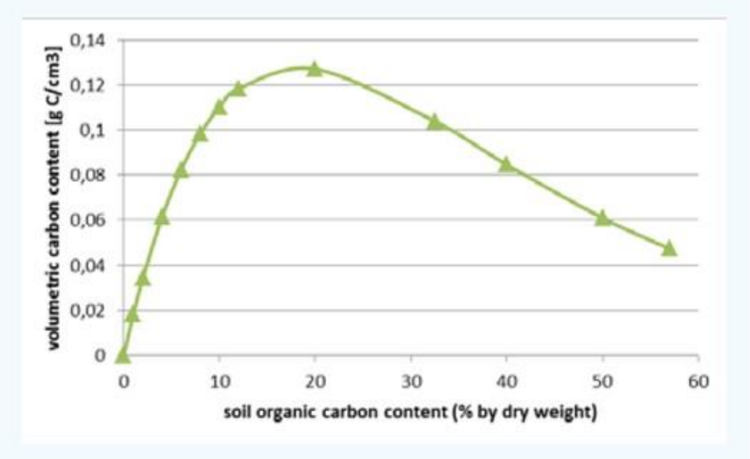

Figure 9. Volumetric carbon content vs carbon content on a dry weight basis (from Barthelmes, 2018)

Degraded peatlands that need restoration can be split in two main categories:

- Peatlands not drained for agricultural production, but where infrastructure transformation is required to rewet (possibly in addition to removal of physical degradation);
- Peatlands drained for agricultural production either for cattle grazing or grassland production, or for crop production.

To assess peatland degradation, a detailed methodology has been developed by the Greifswald Mire Centre (Tanneberger et al. 2021) which combines the use of:

- The peatland map of Europe (Tanneberger et al. 2017)

- The Copernicus Land Monitoring Service mainly based on PROBA-V satellite observations from which a number of land cover classes indicating peatland degradation were extracted; these land cover classes were intersected with the peatland map of Europe
- Complementary information from Tanneberger et al 2017 on the forested peatland areas (since afforestation of the peatlands also induces their degradation)
- Protection of peatland areas extracted from the map of the World Data Base on Protected Areas.

Potential data source:

- Map of land cover
- Maps of peatlands in Europe
- Map of soil types
- Map of Organic Carbon in Topsoils of Europe (also pr data on soils with SOC content >20% and >25%)
- Global database on peatlands (https://greifswaldmoor.de/global-peatland-database-en.html)
- Map of protected areas

Mitigation mechanism

The mitigation mechanism of this management option is to avoid emissions due to the rewetting of these systems.

Peatlands can be managed for climate protection in two ways: (1) by keeping undrained peatlands wet to protect existing carbon stores and sinks and (2) by rewetting and/or restoring previously drained peatlands. Wet peatlands (both undrained and rewetted) can be managed for nature conservation (increasing biodiversity benefits), to avoid GHG emissions and to sequester carbon (GWM 2022).

Baseline scenario

The baseline is an estimate of the current emissions of the peatland against which any improvement measure will be compared in the future. This requires assessing the mean annual water table depth, which is the parameter controlling emissions.

Since the mean annual water table depth is not easily accessible, a series of proxies need to be used to determine it, which revolve around the following:

- the soil type and its peat/soil carbon content
- the type of vegetation
- hydrogeological indicators
- level of infrastructure of the peatlands (drains, roads, buildings…)

Carbon pools involved

The main carbon pool involved is soil carbon, which oxidation rate needs to be assessed to estimate the related CO2 or CH4 emissions.

In the case of forested peatlands or paludiculture, the carbon pool of the above- and below-ground biomass should be considered too. In fact, a specific case relates to forested peatlands, which are less precisely known at the moment (Tanneberger et al, 2021), and where the current water table level needs to completed with the dynamics of the forestry growth and its implications for the consolidated carbon balance between emissions (due to peat and litter degradation) and CO2 absorption by the trees. Over time this balance is influenced by the carbon absorption rate of the trees which, in their intense growing phase, may at the same time speed-up the recession of the water table and the CO2 uptake from the atmosphere. Still, consideration on adaptation aspects should be taken into account.

Potential data source:

- Map of land cover
- Map of forest cover

- Map of soil carbon content
- Map of current living biomass and/or statistical data of living biomass from national forest inventories

Methods to calculate mitigation potential

The IPCC have produced comprehensive guidelines to assess the potential mitigation potential of peatland rewetting (IPCC, 2013). These guidelines do not apply strictly to peatlands but to drained or rewetted organic soils. We present here some key results of the approach proposed in these guidelines.

The general approach (Figure 10) requires to compute the difference between the baseline assessed as an average level of emissions of the drained peatland and the level of emissions after rewetting. It is assumed that the changes occur right after the rewetting despite of the transitions in CO2 and CH4 emissions observed for a few years in certain cases.

Emissions of the drained peatlands are assessed using a multi-factorial approach which provides detailed guidance that can be used for Tier 1, 2 and 3 approaches. Some simplification rules are then provided for the Tier 1 approach which relies mostly on published average emission factors (EFs), generally formulated as annual emissions (or removals) per ha and per year. These EFs (Table 4) are then multiplied by the area subject to these emissions.

A detailed series of pools and factors need to be considered (Figure 10): the climatic zone, the land use category, the different carbon pools involved, the GHG involved (CO2, CH4 and N2O), the origin of these emissions (organic matter dynamics, exports of dissolved carbon, wildfires). The guidelines provide several rules that can help select the most relevant factors in different climatic and land use contexts. A summary of the main EFs for temperate areas (Table 3) indicates that only part of these factors is taken into account in Tier 1 approaches (although useful for the other Tiers). It should also be noticed that the average CO2 EFs of the drained peatlands are not very high, which is the result of the sample utilised by IPCC which includes organic soils in general and not strictly peatlands.

Table 4 – IPCC emission factors of drained peatlands in temperate climate (from IPCC 2013).

GHG type	Land Use Category	Climatic zone	Emission Factor	Unit
CO2	Forest land, drained	temperate	9,5	tCO2e/ha/yr
CO2	Cropland, drained	temperate, boreal	29,0	tCO2e/ha/yr
CO2	Grassland, drained, nutrient poor	temperate	19,4	tCO2e/ha/yr
CO2	Grassland, deep drained, nutrient rich	temperate	22,4	tCO2e/ha/yr
CO2	Grassland, shallow drained*, nutrient rich	temperate	13,2	tCO2e/ha/yr
CO2	Peatland managed for extraction	temperate, boreal	10,3	tCO2e/ha/yr
CO2	Dissolved organic carbon	temperate	1,1	tCO2e/ha/yr
CH4	Forest land, drained	temperate	2,5	kg CH4/ha/yr
CH4	Cropland, drained	temperate, boreal	0,0	kg CH4/ha/yr
CH4	Grassland, drained, nutrient poor	temperate	1,8	kg CH4/ha/yr
CH4	Grassland, shallow drained, nutrient rich	temperate	16,0	kg CH4/ha/yr
CH4	Grassland, deep drained, nutrient rich	temperate	39,0	kg CH4/ha/yr

CH4	Forest land, drained, ditch	temperate, boreal	217,0	kg CH4/ha/yr
CH4	Grassland, shallow drained, ditch	temperate, boreal	527,0	kg CH4/ha/yr
CH4	Grassland, cropland, deep drained, ditch	temperate, boreal	1165,0	kg CH4/ha/yr
N2O	Forest land, drained	temperate	2,8	kg N2O-N/ha/yr
N2O	Cropland, drained	temperate, boreal	13,0	kg N2O-N/ha/yr
N2O	Grassland, drained, nutrient poor	temperate	4,3	kg N2O-N/ha/yr
N2O	Grassland deep drained, nutrient rich	temperate	8,2	kg N2O-N/ha/yr
N2O	Grassland shallow drained, nutrient rich	temperate	1,6	kg N2O-N/ha/yr
CO2	Wildfire losses in organic soils	temperate, boreal	1323,7	kg CO2/T of dry matter burnt
CH4	Wildfire losses in organic soils	temperate, boreal	9,0	kg CH4/T of dry matter burnt

* “Shallow drained” and “deep drained” refer to peatlands where the average depth to water table is respectively less or greater than 30 cms during the year.

In the case of rewetted peatlands, the approach is similar and the different factors referred to in the case of drained peatlands should also be considered. The authors however stress that after rewetting the land use is likely to change, which might require to reconsider the carbon pools. They also indicate that in several cases, the CO2 and CH4 emissions changed abruptly but continued to evolve in a few years after rewetting. They however recommend to use the recommended EFs (Table 5) immediately after rewetting.

For Tier 1 assessments, only a few EFs are available, which shows that very little experience has been gained on peatland rewetting so far. EFs clearly show the dramatic decrease in CO2 emissions and the relative increase of CH4 emissions.

Table 5 – IPCC emission factors of rewetted peatlands in temperate climate (source IPCC 2013).

GHG type	Land Use Category	Climatic zone	Emission Factor	Unit
CO2	Rewetted wetland with poor nutrient status	temperate	-0,8	tCO2e/ha/yr
CO2	Rewetted wetland with rich nutrient status	temperate	1,8	tCO2e/ha/yr
CO2	Dissolved organic carbon	temperate	1,0	tCO2e/ha/yr
CH4	Nutrient poor peatland	temperate	92	kg CH4/ha/yr
CH4	Nutrient rich peatland	temperate	216	kg CH4/ha/yr

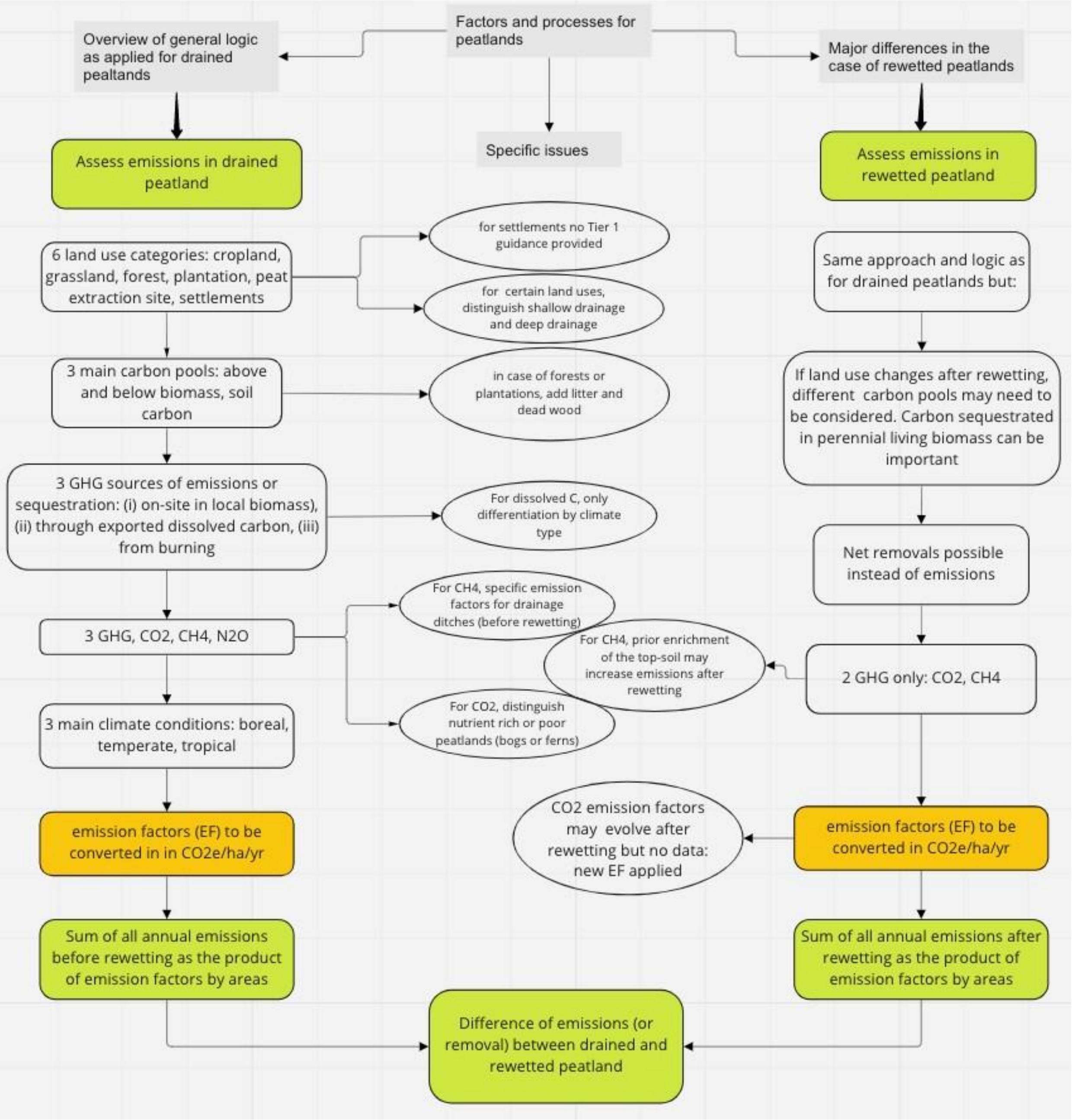

Figure 10. The IPCC approach to peatland emissions assessment before and after rewetting. This approach can be used for Tier 1 and Tier 2 assessments.

The complete assessment is obtained by the difference between the pre- and post-rewetting emission assessments, expressed in CO2e.

Time frame

In the case of peatland degradation, an annual time frame is sufficient in theory since the mean annual water table elevation is the critical controlling factor. After rewetting it is necessary to verify that the annual water table depth remains stable or properly controlled.

Biodiversity considerations

In most cases rewetting will have positive effects on biodiversity. The typical peatland vegetation will regenerate and biodiversity will be increased. In the case of paludiculture, chemical pesticide control and fertilization should be avoided to avoid the classical detrimental effects of agriculture on biodiversity.

Trade offs

The main trade-off to be considered is the related methane emissions associated with submerged land. It seems however (Barthelmes et al, 2018) that this risk is mostly important in nutrient rich sites in the first years after rewetting. Avoiding complete land submersion just after rewetting may hence be recommended.

Another aspect to consider relates to food production in the case of drained peatlands converted to agriculture. In several northern European countries, drained peatlands converted to agriculture represent more than 10% of the agricultural area. Removing such large areas from food production would need to be compensated and would have leakage consequences (i.e. emissions due to the conversion of other lands, such as forests or grasslands). The current paludiculture solutions would indeed not replace the food production in these peatlands since paludiculture crops are used for fiber or fuel production in most cases.

Key parameters to calculate mitigation potential

The critical parameter is the current mean water table level which in not directly accessible with remote sensing techniques. Therefore, a combination of tools is likely to be needed:

- topographic data combined with maps of the drainage system;
- land cover, vegetation status: in particular, if some parts of the peatland remain without crops, vegetation indicators (particularly in grassland) could be used as proxies; the types of crops grown, the presence of forested areas would be other indicators;
- modelling tools could be added to simulate the annual fluctuation of the water table and derive its average depth.

In the specific case of a forested peatland the carbon absorption rate of the trees which compensate partly the peat degradation should be included. To this aim, the forest carbon sink should be assessed based on the type and age of the trees. Similarly in the case of rewetting for paludiculture, the potential for emission reduction should be complemented by an assessment of the carbon uptake by the vegetation grown. In all these cases, the general IPCC approach presented in Figure 10 can help specify which key parameters need to be taken into account.

Information/datasets needed:

Map of land cover
Map of peatlands, assessment of their status
Water related information: catchment delineation and features, indicators of water levels
Map of current and future climate (which indicators?)
Vegetation indicators
Map of protected areas (to assess natural status of the peatlands)

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