STUDY

Requested by the AGRI Committee

European Parliament

Agricultural potential in carbon sequestration

Humus content of land used for agriculture and CO_2 storage

Policy Department for Structural and Cohesion Policies
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RESEARCH FOR AGRI COMMITTEE

Agricultural potential in carbon sequestration

Humus content of land used for agriculture and CO_2 storage

Abstract

To reach the climate neutrality envisaged in the Green Deal by 2050, reducing agricultural GHG emissions is not enough, and efforts to implement large scale carbon sequestration in European agricultural soils will be necessary. The renewed CAP includes improvements in environmental conditionality and foresees eco-schemes and agri-environmental measures that can help achieve this goal. Carbon sequestration in soil is cost-effective, but improvements in methodology are still required, as well as the cooperation between the public and private sectors.

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DISCLAIMER

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LIST OF ABBREVIATIONS

AECM	Agri-Environment-Climate Measure
AFOLU	Agriculture, Forestry and Other Land Use
AKIS	Agricultural Knowledge and Innovation Systems
C	Carbon
CAP	Common Agricultural Policy
CEC	Cation Exchange Capacity
CH_4	Methane
CMP	Cumulative Methane Production
CO_2	Carbon dioxide
CSP	CAP Strategic Plan
EAFRD	European Agricultural Fund for Rural Development
EAGF	European Agricultural Guarantee Fund
ESR	Effort Sharing Regulation
ETS	Emissions Trading Scheme
EU-KP	EU territory as well as Iceland and the United Kingdom's Overseas Territories and Crown Dependencies which have ratified the Kyoto Protocol
FAS	Farm Advisory Services
GAEC	Good Agricultural and Environmental Conditions
GHG	Greenhouse Gas
Gt CO_2-eq	Gigatonnes (1Gt = 10^9 tonnes) of carbon dioxide equivalent
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land Use Change and Forestry

MAOM	Mineral-associated organic matter
MRV	Monitoring, Reporting and Verification
MS	Member State
Mt CO_2-eq	Megatons (1Mt = 10^6 tons) of carbon dioxide equivalent
Mtoe	Megatons (1Mt = 10^6 tons) oil equivalent
N	Nitrogen
N_2O	Nitrous oxide
NxOx	Nitrogen oxides
NH_3	Ammonia
POM	Particulate Organic Matter
RDP	Rural Development Programme
SDG	Sustainable Development Goals
SMR	Statutory Management Requirements
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
t CO_{2}-eq	Tonnes of carbon dioxide equivalent
VCS	Verified Carbon Standard

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GLOSSARY

Action-based carbon farming: a scheme where a farmer or landowner receives a payment for implementing defined management actions, independently of the resulting impact of those actions.

Agroforestry: the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or livestock production systems to benefit from the resulting ecological and economic interaction.

Archaea: one of the two domains of prokaryotes (single-celled organisms whose cells lack a defined nucleus), with distinct molecular characteristics separating them from bacteria, the other domain.

Carbon leakage: refers to the situation that may occur if the displaced agricultural production is transferred to other land, where there is a consequent rise in net GHG emissions as a result of the transfer.

Carbon sequestration: net change in the total C stock of an ecosystem, relative to a previous situation. It may be positive (net gain of carbon) or negative (net loss of carbon). It includes net changes in the aerial parts (biomass) and soil (roots + soil organic matter). See also 'SOC sequestration' below.

Farm carbon audit tool (audit tool): a computer model that calculates a farm's Greenhouse Gas (GHG) emissions and/or carbon sequestration based on input data that summarise the farm's management outputs. They can also calculate other outputs, including sustainability indicators such as nutrient runoff or emissions intensity.

Global change refers to the causes and impacts produced by human activity on the Earth system. "Global" change includes climate change and land use change that together result in destruction, fragmentation and overexploitation of ecosystems, invasive species, disruption of biogeochemical cycles, and general pollution of soil and water caused by nitrogen and phosphorus.

Humus refers to highly decomposed soil organic matter, in which original plant and animal debris cannot be identified. Humus comprises the most stable and complex form of organic matter, produced by partial decomposition of organic debris.

Hybrid approach/model: a scheme that uses a combination of result-based and action-based payments on the same parcel of land.

Hydraulic conductivity of the soil refers to the ability of a soil to permit water movement through its pore space

Leaching: when applied to soil nutrients, leaching refers to the downward movement of dissolved nutrients in the soil profile with percolating water.

Labile organic matter: part of the total organic matter (OM) that is easily decomposable. Depending on the quantification procedure, it may refer (i) to the particulate OM, (ii) to the OM extracted by mild procedures, (iii) to the acid-hydrolyzable OM, or (iv) the OM lost (as CO_2) upon incubation of the soil under standard conditions, with the latter being the most realistic estimation.

Lighthouses are places for demonstration of solutions, training and communication. In the area of agriculture for instance, lighthouses will showcase practices that are exemplary in terms of providing sustainably produced, healthy food, feed or fibre, as well as ecosystem services, while linking rural and urban communities

Living labs: The living lab is a participatory approach involving farmers, scientists, and other interested partners in the co-creation, monitoring and evaluation of new and existing agricultural practices

Mineral soil: Any soil consisting primarily of mineral (sand, silt and clay) material, containing little organic carbon (less than 20 % w/w).

Mineral-associated organic matter (MAOM): Organic matter bound to the mineral components of soil, strongly enough to not be detached by strong agitation (or ultrasonic dispersion) with water. In practice, it usually refers to the organic matter bound to fine soil particles (< 50 µm or < 20 µm).

Mires are lands where peat is actively being formed and accumulating due to incomplete decomposition of remains of plant and animal materials under water saturated conditions

Organic C residence time in soil: Often named as 'Turnover', is a measure of the speed of renovation of soil organic carbon (SOC), or to the OC of a given fraction (POM, MAOM, etc.), in the soil. Turnover = 1/r, with 'r' being the fraction (0 to 1) of total OC lost in one year, and assumed to be replaced by new OC.

Occlusion: physical protection by encapsulation within soil aggregates. This encapsulation may affect both particulate organic matter and mineral-associated organic matter. The occluded organic matter is meant to be less prone to being lost by microbial decomposition.

Organic soil: a soil composed primarily of decomposed or partly decomposed plant and animal materials. As such, it contains more than 20% organic matter by dry weight.

Paludification: refers to the accumulation of peat directly on top of mineral soils

Particulate organic matter (POM): labile fraction of soil organic matter constituted by organic fragments between 2 mm and 50 or 20 µm, not or very loosely bound to mineral particles. POM is assumed to be the main source of carbon and energy for microorganisms.

Peatland: land that contains peat in the sense of a histic horizon (e.g. mires, moors, meadows). A histic horizon is a soil layer near the surface which, when not subject to drainage, consists of poorly aerated organic material which is water saturated (or would be in the absence of drainage) for 30 consecutive days or more in most years.

Stable organic matter: as opposed to labile organic matter, stable organic matter has residence time of several decades to centuries. High residence time can be explained by the chemical composition of the organic matter (e.g. charred carbon, highly humified compounds, lignin- or suberin-derived) or by its protection from decomposition due to soil minerals.

Result-based carbon farming: a scheme where a farmer or landowner receives a payment for reducing net GHG fluxes from their land, whether that is by reducing their GHG emissions or by sequestering and storing carbon. A result-based approach requires a direct and explicit link between the results delivered (e.g. GHG emissions avoided or carbon sequestered) and the payments that the land manager receives. It differs from the more familiar action-based schemes, where the farmer is paid for complying with very specific farming practices or technologies, which have been selected by the managing authority for the assumed climate mitigation benefits.

Rhizosphere: the part of the soil affected by root activity, in particular by the release of organic materials (exudates and tissue fragments) affecting its chemistry, microbiology, nutrient and CO_2 release.

Soil carbon and Soil Organic carbon (SOC) : soil carbon is the carbon stored in soils. This includes both soil organic carbon (SOC), present in soil organic matter, and inorganic carbon in carbonate minerals.

SOC sequestration: net change in SOC storage. It may be positive (SOC sequestration) or negative (SOC losses). Usually, the term is applied only for the former case.

SOC storage: total organic carbon in soil, as amount per unit surface area down to a given depth. In the literature, it is often given as kg OC m^{-2} or as Mg OC ha^{-1}, either down to 25-30 cm (the 'plough layer', more common in studies about agricultural soils) or to 1 m depth.

Soil aggregates: arrangement of primary soil particles (sand, silt and clay) through smooth chemical bonds, particle associations and around soil organic matter (which is often named 'occluded'). Aggregates are a crucial part of soils, for their generation and stability ensure good retention of water and good aeration of soil, and therefore soil fertility.

Soil biota: refers to all permanent soil inhabitants. Soil biota includes an enormous diversity of organisms, including microorganisms (i.e., bacteria, fungi, archaea, viruses) and microscopic and macroscopic animals (i.e. protozoans, nematodes, microarthropods, earthworms, etc.)

Soil texture: the proportion of mineral particles of different size (sand, silt and clay) in a given soil. Soil texture has a major influence on soil porosity, which in turn regulates soil water holding capacity, gaseous diffusion and water movement and determines soil health.

Symbiotic N fixation: mutualistic relationship in which plants provide a niche and a source of C to N-fixing bacteria in exchange for fixed N. The most widely known of these is that of Rhizobium-type microorganisms with legumes, which are thus recommended as part of most crop rotations.

EXECUTIVE SUMMARY

KEY FINDINGS

- Estimates of carbon stocks in the EU-27 soils range from 34 Gt (Gigaton) in the 20 top cm to 75 Gt in the top 30 cm, with uneven geographical distribution (soils of Nordic and Northeastern countries are carbon rich while those of the southern countries are generally carbon depleted). All simulations predict overall increases of the EU soil carbon stocks, as the result of decreasing soil organic carbon (SOC) stocks in Mediterranean countries compensated by SOC accumulation in others, notably Ireland, France and Germany.
- 31,7% of total SOC stocks in the EU are found in agricultural soils (9,3% in grassland and 21,4% in cropland).
- 20 to 25% of European SOC is stored in peatlands, even if they cover only 6 % of the EU-27's land area
- Agricultural greenhouse gase (GHG) emissions decreased by 108 Mt CO_2-equivalent from 1990 to 2018, but this reduction occurred until 2005 and the emission rate has remained stable since then. Achieving further substantial GHG emission reductions in the agricultural sector will require significant changes in farming practices and agricultural policies. Emission intensity of agricultural production can be further reduced if we are able to overcome the barriers that have limited adoption of GHG mitigation measures and innovations.
- More than 55% of the climate mitigation potential in the EU-27 agricultural sector lies with agricultural soils and manure management. Stimulating carbon sequestration in soil is necessary to attain the Green Deal's objectives. To achieve agriculture related mitigation targets, together with stimulating SOC sequestration, reducing CO_2 emissions from drained peatlands and rewetting and restoring them is crucial.
- Some sustainable agricultural practices are particularly favourable to carbon sequestration in soil (cover crops and catch crops, reduction in tillage, plant diversity). The rewetting and restoration of peatlands, agroforestry and grasslands are key to preserving and enhancing SOC stocks.
- The new CAP provides tools for farmers to engage in sustainable practices for carbon sequestration in soil, although efforts in research and knowledge construction and transfer are still needed. A reliable evaluation of the effects of management on soil Carbon stocks is essential to settle fair payments for results or to certify carbon credits for markets. Due to significant gaps in the European network of soil data, soil sampling for Carbon analysis is still necessary.
- Result-based schemes should be accompanied by reliable indicators and monitoring, and capacity building including Farm Advisory Services and certified public labs. To reduce Measurement Reporting and Verification (MRV) costs in organic C sequestration in soils, a reliable integrated soil survey system is required in the EU. Increasing the number of long-term experiment sites and the variety of tested management options (e.g. by reinforcing the European living-lab network) is essential.
- If a significant increase in carbon sequestration is to be achieved, large agricultural areas will have to be managed accordingly and the related compensations to farmers may prove unaffordable for public bodies. Complementary actions by private actors, or public private partnerships can help set up carbon markets which could play an important role for carbon sequestration, as exemplified by pilot projects in Europe and abroad.

The EU should reduce its net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels, as agreed in the EU Climate Law. On 14 July 2021, the Commission presented proposals to deliver these targets and make the European Green Deal a reality. In the context of the "Fit for 55" package, the Commission will now engage with sectors to prepare specific roadmaps charting their path to climate neutrality.

To this end, the Commission shall proceed with the quantification of the mitigation potential in agriculture up to 2030, which will include reductions in greenhouse gases (GHG) emissions, effects of land use changes and carbon storage in agricultural soils. An integrated policy framework covering agriculture, forestry, and land use (AFOLU) is proposed from 2030 with the view of achieving carbon neutrality in these sectors by 2035.

The agricultural sector emitted about 429 Mt CO_2-equivalent in 2019, which accounts for about 11% of total European GHG emissions. Methane emissions, mainly from enteric fermentation contribute about 54% of the total, followed by nitrous oxide emissions (about 44%) mostly related to soil fertilisation. Agricultural CO_2 (with a share of almost 3% of total GHG emissions from the agricultural sector) is attributable to soil management and land use change.

Achieving the Green Deal neutrality targets will require reshaping our food system and reducing agricultural emissions but also promoting carbon sequestration in agricultural soils.

Carbon sequestration potential in European agricultural soils

Agricultural GHG emissions decreased by 108 Mt CO_2-eq from 1990 to 2018, but this reduction occurred until 2005 and the emission rate has remained stable since then. Achieving further substantial GHG emission reductions in the agricultural sector will require significant changes in farming practices and agricultural policies.

More than 55% of the technical mitigation potential in the EU-27 agricultural sector lies with agricultural soils and manure management. There is great variability in the estimates of the realistic capacity of our agricultural soils to sequester carbon, due to the uncertain evolution of climate, policy, economic and technical scenarios. The most reliable values range from 9 to 24 Mt (Megaton[1]) C y^{-1}.

Estimates of carbon stocks in the EU-27 soils range from 34 Gt (Gigaton[2]) in the 20 top cm to 75 Gt in the top 30 cm, with uneven geographical distribution, depending on rainfall and temperature patterns and geological and topographic characteristics. Soils of Nordic and Northeastern countries are carbon rich while those of the southern countries are generally carbon depleted.

Under the business-as-usual management scenario, from 2010 to 2050 total soil organic carbon stocks in the European agricultural soils could increase from the initial 12.8 to 13.9-14.1 Gt in cropland, and from 6.7 Gt to 8.9 -9.4 Gt in pastures, depending on the severity of the climate scenarios.

The potential for carbon sequestration is highest in the semiarid and arid regions of central and meridional Europe, since soils are here carbon depleted. The very rich soil carbon stocks of the northern zones must be preserved to reverse current CO_2 emissions to the atmosphere, very often due to peatland desiccation for cropping and grazing.

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[1] 1 Megatonne = 1.000.000 tons.

[2] 1 Gigatonne = 1.000.000.000 tons.

Sustainable agricultural practices adequate for carbon sequestration, and warnings

Some sustainable agricultural practices are particularly favourable to carbon sequestration in soil. **Cover crops and catch crops** increase carbon stocks in almost all types of soils and climate conditions, and their repeated use for decades can result in soils with greatly increased SOC stocks and total nitrogen reserves. **Reduction in tillage** results in increased carbon stocks in soil but can lead to reduced yield. Efficient combinations of reduced tillage with other practices such as cover and catch crops and adequate fertilization can reduce this problem, and has proven positive effects, including reductions in energy costs and soil erosion, improvement in the soil health and reduction of GHC emissions. **Augmenting plant diversity** (as in multicropping and mixed cropping systems) is a suitable option to increase both plant production and soil carbon stocks. **Fertilisation with organic materials**, in particular manures, is widely seen as mandatory to increase SOC locally, usually combined with mineral nutrition. In several ways, manure is more beneficial to carbon sequestration and to soil health when applied as compost. However, not any kind of compost is adequate for application to soil. Urban-waste compost, for example, is made of the organic fraction of urban garbage combined with pruning residues. Its use must be restrained to countries where it is obtained under quality controls that are strict enough to guarantee the absence of harmful components (heavy metals and other pollutants) and plastics or microplastics.

The rewetting and restoration of peatlands, agroforestry and grasslands are key to preserving and enhancing SOC stocks.

Biochar is being promoted as the most effective method to increase SOC content. However, its effects on plant production and soil health are highly dependent on its precise structure and composition, in turn dependent on the type of original biomass and the characteristics of the production process. Without a system of biochar labelling and qualification, a generic recommendation about using biochar in European crops as a method of increasing SOC stocks would be very risky.

Carbon sequestration in soil in the new Common Agricultural Policy

The renewed structure of the Common Agricultural Policy, due to come into effect in 2023, includes important tools to progress towards sustainable management of agricultural soils to combine increased carbon sequestration with enhancement of global soil health.

First, increased conditionality requires farmers to adopt environmental and climate-friendly practices to be eligible for direct support. Among these practices, the protection of permanent grasslands is of key importance for carbon sequestration.

Second, several eco-schemes are offered to farmers for voluntary implementation under Pillar I, together with rural development measures under Pillar II. In addition to a specific package of practices specifically dedicated to carbon farming, agroforestry and agroecology systems and improved nutrient management have proven positive effects on carbon sequestration in soil and soil biodiversity and health. In peatlands, paludiculture is a win-win option to combine agricultural exploitation with protection of carbon stocks and reduction of GHG emissions.

Making carbon sequestration in soil possible and climate-significant at the European scale

To achieve the Green Deal carbon neutrality's goals, the challenge of carbon sequestration in the agricultural soils of Europe must be widely accepted by farmers, and the effectiveness of the practices and strategies they adopt must be verifiable in terms of quantifiable changes in soil carbon stocks and permanence in soil of the sequestered carbon.

Measurement, reporting and verification (MRV) of these effects is often evoked as a constraint to fairly compensate farmers for results, due to lack of precision of measurement methods, high demand of field and laboratory work effort and high costs. However, rapid progress is being made in alternative approaches to soil carbon measurement and prediction, including proximal and remote sensing as well as in machine learning techniques. Increased research in these fields is required to make these new technologies available in practice.

To improve our knowledge on the response of soil carbon to agricultural practices, and then to improve the accuracy of soil carbon models, there is an urgent need to reinforce the European soil monitoring network and to increase the number of long-term agricultural research stations and agricultural lighthouses under different soil and climate conditions.

Farmers also need technical support and advice, integrated strategies and knowledge transfer, integrating all sectors involved in climate-smart agriculture.

If a significant increase in carbon sequestration is to be achieved, large agricultural areas will have to be managed accordingly, and the related compensations to farmers may prove unaffordable for public bodies. Complementary actions by private actors, or public private partnerships can help set up carbon markets which could play an important role for carbon sequestration, as exemplified by pilot projects in Europe and abroad.

INTRODUCTION

On December 2021, an agreement on the reform of the Common Agricultural Policy (CAP) was reached and formally adopted, and the new legislation will come into force in 2023.

During this new period, the Member States shall benefit from a greater flexibility to adapt CAP directives to local conditions. Much of the potential benefits of the new environmental framework for achieving the climate goals of the EU Green Deal will depend on how the MSs include CAP tools for carbon sequestration in soil in their National Strategic Plans.

The main objective of this analysis is to provide information for decision-making on carbon sequestration and preservation of carbon stocks in European agricultural soils. First, we highlight the importance of proper management of soil carbon stocks for regulating climate and soil fertility and, therefore, for guaranteeing food provision. Then, we review the tools offered by the renewed Common Agricultural Policy to make carbon sequestration in agricultural soils viable and preserve of the current soil carbon stocks. We analyse strong points and weaknesses at different levels, including the total and achievable capacity for carbon sequestration of our soils, considering environmental, technical, social, and economic limitations and opportunities. Finally, we highlight promising technical and market options to make carbon sequestration in soil possible at the scale required in order for the Green Deal Goals to be reached. These options are based on current progress and inspiring pioneer experiences from Europe and abroad.

It must be pointed out that even the if the term “humus” is now dropped by some soil scientists to describe soil organic matter, it was kept in the study’s title since it was used in the project’s terms of reference.

The study has been carried out by experts on soil carbon management in agricultural soils, based on an exhaustive review of academic documentation ordered after their personal experience on this field of knowledge. The data base of the European Soil Data Centre (ESDAC) of the Joint Research Centre (JRC) of the EC, together with technical and scientific publications derived from it have been of key value to prepare maps and to explain the current distribution of soil carbon stocks. Data from the Annual European Union Greenhouse Gas Inventories, available from the European Environment Agency, have been used to analyse the mitigation potential from the agricultural sector.

For policy, market, and economic opportunities to make carbon sequestration cost-effective and affordable, we have analysed previous documentation available from the EC and from technical and administrative bodies of different countries, as well as the opinions of agricultural organizations published in newsletter of the sector. When appropriate, farmers’ opinion has been directly required.

The study is organized into seven chapters.

Chapter 1 introduces basic concepts to understand the functioning of the terrestrial carbon cycle and, specifically, the main aspects of carbon sequestration in soils, including elements that influence soil capacity to stock carbon or to release it back to the atmosphere.

Chapter 2 provides an analysis of the effects of climate change and land use change on soil carbon stocks and on carbon fluxes between the atmosphere, the hydrosphere and the soil.

Chapter 3 reviews what is known about current soil carbon stocks in the agricultural soils of Europe, making a difference between mineral soils and organic soils (peatlands), since the consequences of their degradation for climate are contrasting. We discuss different simulated scenarios for their evolution.

Chapter 4 informs about the possibilities of achieving the climate goal of the Green Deal through increasing reduction of GHG emissions, and about the vital importance of combining this reduction with carbon sequestration in agricultural soils for this purpose.

Chapter 5 describes agricultural practices that favour carbon sequestration in soil while contributing to soil health and biodiversity and crop productivity, and the most adequate combination of practices are also proposed. We also alert about the risks involved in applying some types of new biomass materials to soil before adequate quality controls and labelling are implemented.

Chapter 6 summarises the EU climate framework and, in particular the trajectory of the Common Agricultural Policy towards integrating environmental issues. We highlight the main advances for the 2023-2027 period and the most promising tools to incentivize carbon sequestration. We also provide a review of how the Member States incorporate GAEC and eco-schemes related to Carbon Farming into their National CAP Strategic Plans.

Chapter 7 summarizes successful schemes for carbon sequestration in soil available from Europe and abroad. It builds on innovative approaches aimed at reducing the cost of monitoring and verification of carbon sequestration in soil, improving mechanisms to encourage farmers to engage in carbon sequestration, and developing safe ways of cooperation between the public and the private sectors to make carbon sequestration in soil affordable at the European scale.

1. THE TERRESTRIAL CARBON CYCLE. MAIN DRIVERS OF CARBON SEQUESTRATION IN SOIL

KEY FINDINGS

- Soils are an important compartment of the global carbon (C) cycle. There is more carbon stored in soils than in the whole biosphere.
- The role of soils as a sink for carbon may be enhanced through proper management of the terrestrial ecosystems.
- The carbon stored in each soil is not of a fixed magnitude: it is the result of an equilibrium between gains and losses. For a given set of conditions there is an equilibrium state, at which the soil becomes carbon neutral.
- Soil organic matter includes both labile (i.e. which can be decomposed easily) and stable compounds: if properly managed, the stability of carbon in soil may be enhanced.

1.1. Basic concepts

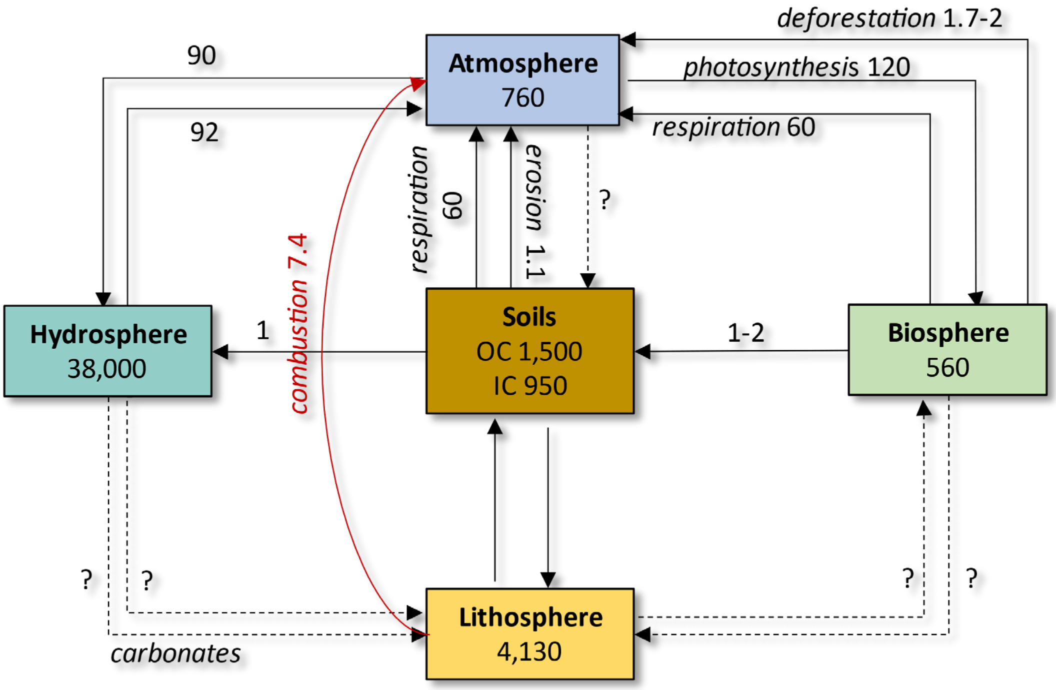
Total carbon (C) in terrestrial ecosystems amounts to about 2860 Gt (gigatonnes), of which 560 Gt are found in living plants and animals, and 2300 Gt in soil (1,550 Gt of organic carbon -OC-, and 750 Gt of inorganic carbon) (Lal, 2008). The soil carbon pool is about 2.9 times larger than the atmospheric C pool (about 800 Gt).

The carbon cycle in soil can be explained using four main concepts: (1) soils are a compartment of the global carbon cycle, (2) carbon in soil is in an unstable equilibrium, (3) carbon in soil includes 'labile' and 'stable' forms, and (4) carbon in soil include 'free' and 'protected' forms.

1.1.1. Soils are a compartment of the global carbon cycle

Figure 1 summarizes the compartments of the carbon cycle. The hydrosphere, and particularly the oceans, is the main compartment. All compartments are interconnected by fluxes. The C flux from the lithosphere to the atmosphere, caused by combustion of fossil carbon sources, is particularly relevant and, as it is widely known, in the last two centuries has provoked a total shift in the ancient biogeochemical equilibrium. To enhance carbon sequestration in soil, two key fluxes must be enhanced: photosynthesis (plant growth and plant production) and release of dead organic matter from plants (in the biosphere) to soil. On the other hand, soils also release carbon to the atmosphere, either by respiration (as CO_2) or by methanogenesis (as methane -CH_4). This last flux should be kept as low as possible.

Figure 1: The carbon cycle. Carbon pools in boxes and fluxes in lines. Numbers indicate the size of carbon pools (in Gt) and fluxes (in Gt y^{-1}). IC: inorganic carbon; OC: organic carbon.

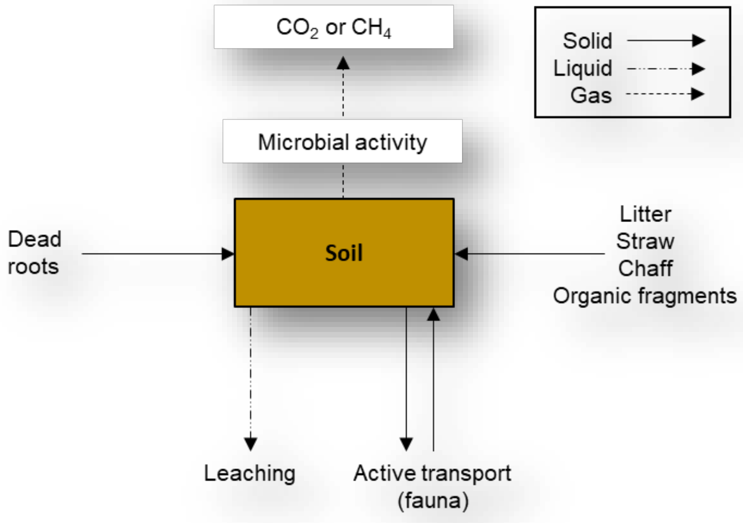


Source: Modified from Lal (2001). Some numbers have been updated from Lal et al. (2007) and Lal and Follett (2009).

1.1.2. Carbon in soil is in an unstable equilibrium

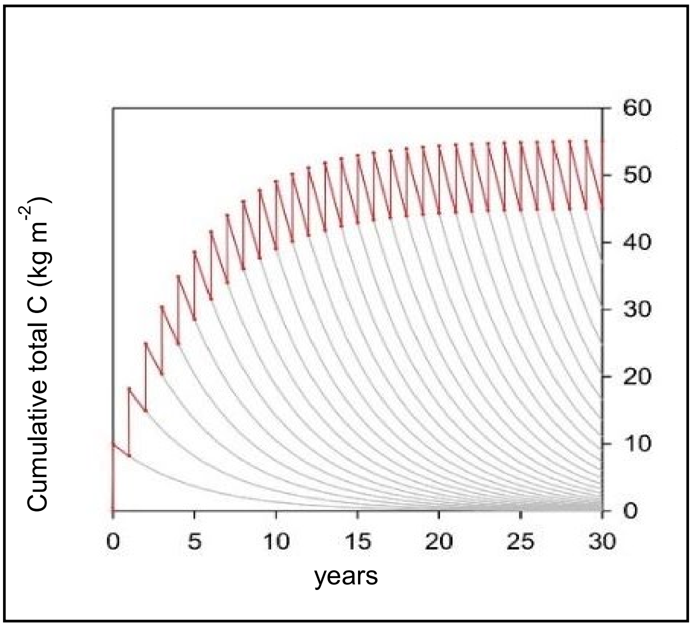
Figure 2 illustrates a second basic concept in C cycling: the soil as a system that receives, stores and releases carbon. The main carbon inputs are plant-derived dead fragments (dead roots, litter, chaff, straw and so on) often introduced deeper into soil by ploughing. As for carbon outputs, the main one is the loss of C as carbon dioxide (CO_2) or methane (CH_4) (in waterlogged areas) because of microbial activity. Also, part of the organic matter may be lost to the underlying soil by leaching. Soil fauna, in particular earthworms, may transport (upwards and downwards) relevant amounts of material, both organic and mineral. In soils found on slopes, lateral transport by gravity is also to be considered.

Figure 2: Carbon inputs and outputs in a soil layer.



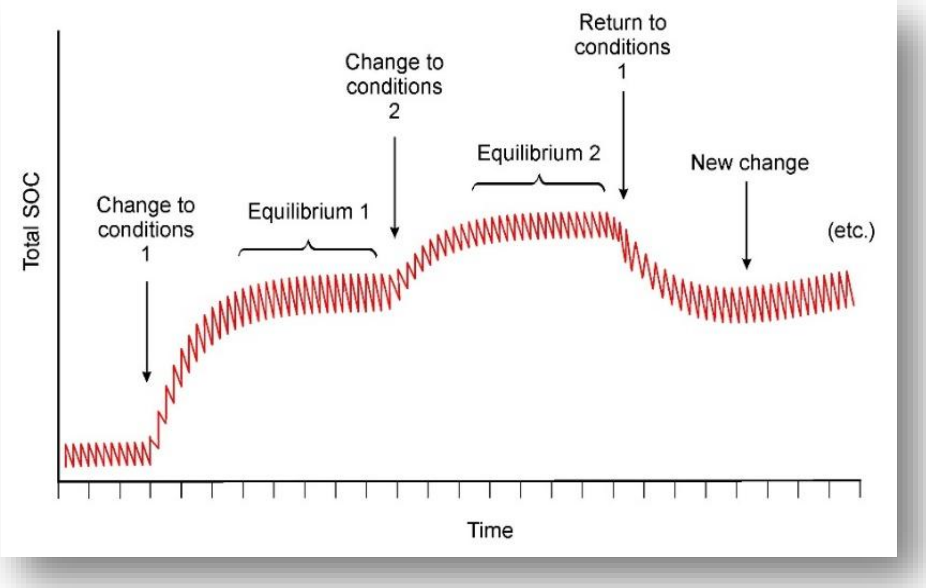
Soil accumulates C when outputs are lower than inputs. If such higher inputs occur repeatedly, soil will accumulate carbon. For a given set of conditions, there will be an equilibrium state, at which soil carbon stock does not change anymore (***Figure 3***). By 'set of conditions' we mean total organic inputs, the quality of these inputs (which will determine the decomposition rate), the soil type, and the climatic conditions. If they are all kept constant, the equilibrium state is maintained, and soil becomes carbon neutral. In contrast, if one or more of these conditions (e.g., the annual inputs or their quality or climate) changes, the equilibrium state changes too.

Figure 3: Arrival of an input of plant material and its decomposition. Accumulation of new inputs, year after year, results in C accumulation in the soil layer, but this accumulation always tends to an equilibrium.



The soil may sequester carbon or lose carbon, until a new equilibrium state is reached (***Figure 4***).

Figure 4: Changes in soil organic carbon (SOC) stocks, in a hypothetical agricultural field. The SOC level of a given soil is a dynamic property, not a fixed one.



1.1.3. Carbon in soil includes 'labile' and 'stable' forms

The organic debris released by plants is the main direct source of soil organic matter. Additional inputs such as manures, compost, etc., may be of great importance in agriculture. This organic debris includes many kinds of macromolecules (proteins, cellulose, hemicelluloses, lignin, suberin, etc.), and also small molecules (sugars, amino acids, small organic acids, etc.). These compounds differ by their resistance to microbial decomposition. Some compounds are labile, meaning they can be decomposed easily and quickly (i.e. carbohydrates and proteins). Other compounds are more stable and are more difficult to decompose, and thus prone to persist in soil for a much longer time (i.e. lignin, suberin and many lipids). As debris decomposition proceeds, supramolecular recombination of the primary sub-products occurs, and humus is formed. **Humus** generally constitutes less than 1 to about 10% of the soil mass, but it is a very important fraction, because humus formation leads to long-term storage of organic carbon in soils thank to increasing proportion of SOC stable forms.

1.1.4. Carbon in soil includes 'free' and 'protected' forms

Once in the soil, the added organic matter may become stabilized through interactions with the soil mineral matrix. Most soil scientists agree that such interactions are the main factor responsible for the long-term stability of soil organic matter (von Lützow et al., 2006).

The organic matter associated with fine mineral particles is often referred as mineral-associated organic matter (MAOM), or organo-mineral complex, and assumed to be the main stable fraction of soil organic matter. The soil capacity for stabilizing and accumulating C is related to its richness in fine active mineral matter (Feng et al., 2013). Sandy, coarse-textured soils have a much lower capacity for SOC storage than clay-rich, finely textured soils.

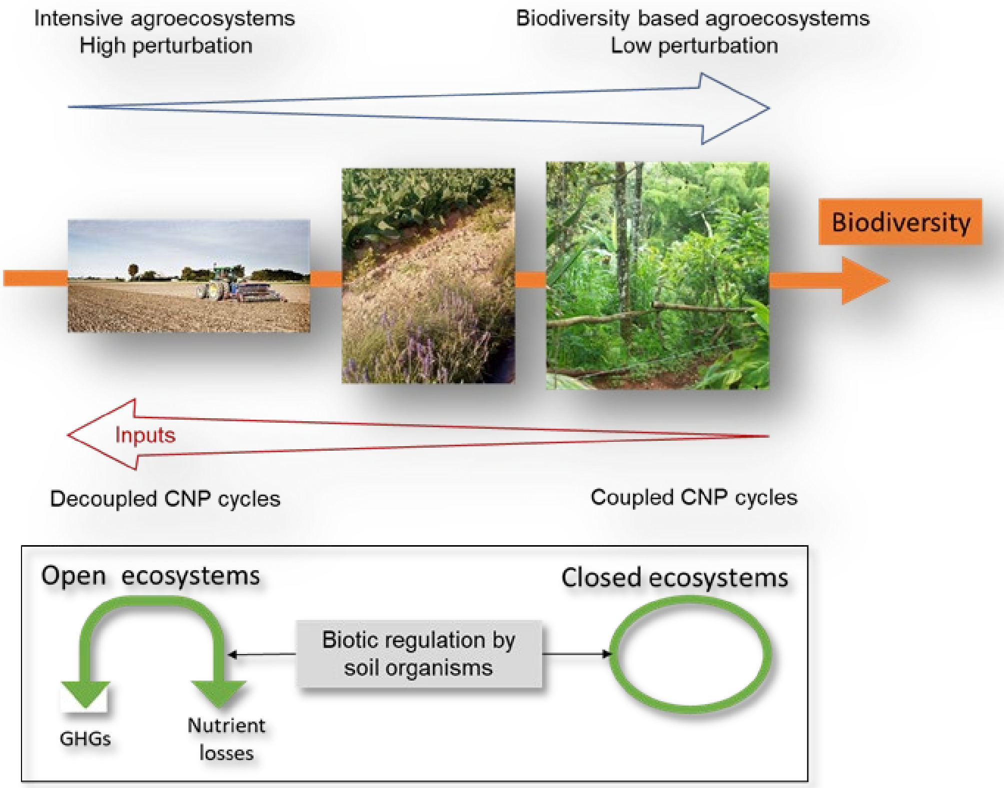
The capacity of soils to stabilize SOC in their organo-mineral complex is often referred to as the 'protective capacity' of soils, and the organic matter associated with fine mineral matter as 'protected organic matter'. A substantial part of this protected organic matter is found within soil aggregates. Again, the capacity of soils to generate aggregates depends on their richness in fine particles, and organic carbon content. Soil texture appears as one of the main factors that determines the SOC accumulation capacity of soils.

Because texture is a soil property that is virtually impossible to change (the economic cost would be huge), SOC storage capacity of soils is fixed. It is a task of good farm managers to have in-depth knowledge about the soil characteristics of their farms, and be aware of their possibilities, including a realistic view about their SOC sequestration potential.

1.2. The soil carbon cycle and other linked biogeochemical cycles

Increasing organic matter content in soils is generally seen as a 'win-win' strategy as it removes excess of CO_2 from the atmosphere while improving soil function, mainly by supplying energy and nutrients to soil organisms (Janzen, 2006). But improving soil function requires organic matter decay that may counteract the build-up of organic matter required for C sequestration. When aiming to increase soil organic matter pools while maintaining or enhancing agronomic productivity, a trade-off between accrual and decay will be required. To achieve relevant increases of soil organic matter in agricultural soils and to optimise its benefits we must pay attention to the links between soil organic matter (SOM) composition and other mineral nutrients. Agricultural practices can strongly affect the relationships between nutrients and C by generally decreasing nitrogen/phosphorous (N/P) ratios at the soil surface while carbon/nitrogen (C/N) ratios remain constant (Bertrand et al., 2019) (***Figure 5***).

Figure 5: Intensive versus low perturbation agroecosystems and their impact on nutrient cycles.



Source: Adapted from Bertrand et al., 2019.

Intensive agroecosystems are highly disturbed and lead to open agroecosystems, with higher nutrient losses, than low perturbation (such as no till, intercropping) systems with organic matter rich soils. CNP: carbon, nitrogen, phosphorus.

In mineral soils, including agricultural soils, C/N ratios are low thus indicating high relative accumulation of N mainly retained in organic forms. The traditional view is that organic matter retaining N is mainly exploited by soil microbiota (Schimel and Bennet, 2004). However, there is increasing evidence that such pools of organic N can also be taken up by plants, as plants may control soil microbial activity, typically limited by C, by releasing exudates in the rhizosphere – the thin soil space surrounding plant roots- (Keiluweit et al., 2015) or by carbon rich plant residues from roots, leaves or shoots that enter the soil as particulate organic matter (POM) (Daly et al., 2021). While root exudates are often free of N and other mineral nutrients, plant residues hold a proportion of mineral nutrients with highly variable C/N ratios (from 20 to 250). However, C richness of plant residues is always much higher than that of soil microbiota, ranging from a C/N ratio of 5 for bacteria to 10-15 for fungi (Paul, 2016).

The soil organic matter C/N ratio ranges from 13 to 8 and shows the lowest values in soils with low amounts of POM. Indeed, minerally associated organic matter retains large amounts of N and other nutrients that are not readily accessible to plants (Jilling et al., 2021). Organic C inputs, either as root exudates, plant residues or other exogenous sources of organic matter, are needed to mobilize soil C and N reserves and give plants access to nutrient pools retained in SOM (Clarholm et al., 2015). The process of mobilizing minerally associated C and nutrient reserves is defined as “priming” and it contributes to both soil organic matter turnover and nutrient supply. The scarcity or the reduced abundance of nutrients triggers the priming processes that are mainly mediated by soil biota and thus favours the cycling of soil retained nutrients (Romanyà et al., 2017). Moreover, the presence of decomposers such as earthworms may accelerate the terrestrial C and N cycles by rapid plant use of earthworm excreted compounds.

This would suggest a previously unknown shortcut in the terrestrial N and C cycles (Shutenko et al., 2022) that will likely involve the direct use of some organic N compounds by plants (Hill and Jones, 2019; Farzadfar et al., 2021).

2. EFFECT OF CLIMATE CHANGE AND LAND USE CHANGE ON SOIL CARBON

KEY FINDINGS

- Climate change and land use are main contributors to soil degradation. Soil degradation is the depletion of soil quality resulting in the reduction of its potential to provide ecosystems services and to support animals and plants.
- Soil degradation has an impact on climate change due to an increase in soil organic matter (SOM) mineralization and in desertification.
- Climate change impacts are provoking adverse effects on European agroecosystems. Farmers collect poorer and more variable harvests and suffer from a lower product quality and higher production costs which affect both prices and market organization.
- SOM content is positively correlated with precipitation and negatively with temperature, explaining the general pattern of its decline from northern to southern Europe.
- Land management practices that cause less soil disturbance increase soil organic carbon (SOC) accumulation. Conversion of grasslands and forests to croplands causes a depletion of SOC.

Climate change is well accepted as one of the main factors contributing to soil degradation. Soil degradation is the depletion of the quality of soil resulting in the reduction of its potential to provide ecosystem services and to support animals and plants. Soil degradation may also feed back into the climate system by reinforcing ongoing climate change due to an increase in soil SOC mineralization and the increase of desertification. Soil degradation involves changes in chemical, physical and biological properties of the soil.

2.1. Expected effects of climate change on soil degradation

2.1.1. Impact on soil hydro-physical properties

Changes in precipitation intensity or (seasonal) temperatures directly affect soil hydrological properties. The hydrological characteristics of soil (water retention, hydraulic conductivity) are determined by soil physical properties (structure, porosity, bulk density and pore-size distribution) that contribute to water, air and heat dynamics in the soil profile.

SOM loss (due to increased decomposition rate or erosion) will lead to soil compaction with a consequent decrease in soil porosity and inhibition of root growth. Increasing temperature coupled with consequent lower water availability, less biomass and less SOM, will lead to a decrease in aggregate stability, and intensive rainfall will contribute to soil aggregate destruction. Changes in the spatial and temporal distribution of annual precipitation will result in an increase of duration and severity of soil water stress. Waterlogging and drought could result in unfavourable soil conditions for both natural and agroecosystems.

2.1.2. Impact on soil chemistry and nutrient levels

Changes in precipitation and temperature could affect soil nutrient pools in different ways. Increases in precipitation can intensify leaching, leading to soil acidification and promoting the mobilisation of potential toxic elements and the depletion of basic cations. Downward movement of water in soil due to increasing rainfall leads to nutrient loss. Temperature increase could act to keep nutrients within the soil because of raised evaporation and reduced leaching, while a decrease in rainfall and increase in temperature may cause upward movements of nutrients and thus lead to soil salinization.

2.1.3. Impact on soil biology

Soils host an incredibly diverse biological community that contributes to a wide range of functions essential for ecosystem maintenance and functioning. Soil biota includes microorganisms such as bacteria, fungi, archaea and algae, soil animals such as protozoans, insects, nematodes, earthworms, and plants (Orgiazzi et al., 2016). Soil microbial communities play a pivotal role in biogeochemical nutrient cycles and greenhouse gas (GHG) emission and uptake. Climate change can affect soil biota in different ways, like altering species composition, abundance and activity. When microorganisms involved in key ecological processes are affected, the ecosystem services they provide are also affected.

2.1.4. Effect of warming: different climate sensitivity of soil organic matter according to its form and characteristics

In the EU, C losses from the top 20 cm of soils have been forecasted for the 2015–2080 period and amount to 2.5 ±1.2 Gt C, equivalent to 7.9 ± 3.8 t C ha^{-1} (Lugato et al., 2021). This value challenges previous estimates (Crowther et al., 2016) which reported topsoil carbon losses between 30 and 150 t C ha^{-1} by 2050 in central–northern Europe under a 1°C warming scenario. Despite known responses of C stocks to warming and altered precipitation (i.e. SOC mineralization increases with warming and increased precipitation and decreases with decreased precipitation) there are still uncertainties about the effects of climate change on SOC content and vulnerability, due to interactive effects. Physical and chemical stabilisation mechanisms play a critical role in controlling carbon storage in mineral soils which suggests that climate warming-induced C losses may be lower than previously predicted (Hartley et al., 2021).

Lugato et al. (2021) indicated how separating soil carbon into particulate organic matter (POM) and mineral associated organic matter (MAOM) aids in the understanding of its vulnerability to climate change and identification of carbon sequestration strategies.

Warming would reduce soil C, with a more than expected C sensitivity associated with MAOM in grasslands and especially in croplands, due to reduced plant inputs (Zhao et al., 2017) and MAOM persistence (Haddix et al., 2020). So, preserving and augmenting POM is a soil carbon storage strategy with lower nitrogen costs, an important advantage given that nitrogen availability is one of the major limiting factors for soil carbon sequestration (Kicklighter et al., 2019) and that some experiments highlight N loss from systems as a side effect of warming (Marañón-Jiménez et al., 2018, 2019).

In any case, although the above-mentioned estimates in overall C stock loss seem lower than expected, they still suggest a potential long-term CO_2 debt (of 9.2 Gt CO_2-eq under the worst-case scenario described by the IPCC) which would necessitate a greater reduction of the current EU emissions (in the order of 4.5 Gt yr^{-1} of avoided or compensated for) through targeted land management and policy.

2.2. EU agriculture, land use, and land-use change in recent decades

2.2.1. Climate change and agriculture

Recent reports of the EU Commission (2019) confirm that climate change is provoking adverse effects on European agroecosystems. Farmers collect poorer and more variable harvests, and products of lower quality at higher production costs. Impacts on the vulnerability of the agroecosystem increasingly depend on relative changes in environmental controlling factors such as atmospheric CO_2 concentration, temperature and rainfall. While climate change is projected to improve conditions for growing crops in parts of northern Europe, the opposite is true for crop productivity in southern Europe. Drier conditions and increasing temperatures in the Mediterranean region and parts of eastern Europe will likely lead to reduced yields and force the adoption of new varieties and cultivation methods (Olesen and Bindi, 2004).

Extreme weather events, such as spells of high temperature, heavy storms, or droughts, can severely disrupt crop production. Thus, the projected increases in temperature variability over Central Europe may have severe impacts on the agricultural production in this region.

On the other hand, agriculture remains a driver of climate change. Although the EU Member States (MSs) are struggling to control GHG emission, the agricultural sector still has a crucial role to play in mitigating GHG effects. Agriculture accounts for around 10% of total GHG emitted in the EU. Methane gas (CH_4) emissions from enteric fermentation make up the largest share, although nitrous oxide (N_2O) from fertilisers and CO_2 emissions from land use and land use change (LULUC) in agricultural areas should be also considered under an agricultural smart climate scenario. Ammonia (NH_3) and primary particulate matter are the two most important air pollutants from this sector. While GHG emissions from agriculture have decreased since 1990, in the last decades this pattern has been stagnating. So, more will need to be done by the sector to contribute to reaching EU GHG emission reduction targets by 2030 and 2050. This would imply reshaping our food system, reducing agricultural emissions from fertilisers, manure storage and livestock, and developing policies aimed at storing C in agricultural soils.

2.2.2. Effects of land use and land use change on soil organic matter

Land use and land management determine whether soil will be a source or sink of atmospheric carbon (Lal, 2004). Land management practices that consist of less soil disturbance increase SOC accumulation. SOC depletion occurs when native forest ecosystems are altered to cultivated systems. In general, grasslands and forests are characterised by low disturbance, high C input by litter and roots and high content of soil organic matter. Conversion of grasslands and forests to croplands causes a depletion of SOC. This decrease is estimated in Europe to be about 1-1.7 t C ha^{-1} y^{-1} from land use change from grassland to arable and 0.6 t C ha^{-1} from forest to arable land. The inverse conversion from arable land to grassland has more variable effects ranging from 0.3-0.6 to 1.2-17 t C ha^{-1} y^{-1} (Freibauer et al., 2004).

3. ORGANIC CARBON STOCKS IN EUROPEAN AGRICULTURAL SOILS: CURRENT STATE AND POTENTIAL EVOLUTION

KEY FINDINGS

- There is a great uncertainty about the real size of soil carbon stocks in Europe and about their evolution under diverse climate change scenarios (differences are due to technical difficulties for measurement but also because of very divergent estimation):
  - according to some estimates, soil organic carbon (SOC) stocks in the top 20 cm of our soils could be about 34 billion tonnes (EU-27, without date for Cyprus and Malta)

  - using a different methodology, the European Environment Agency has estimated SOC stocks in the EU-27 to 75 billion tonnes (in the top 30 cm); around 50 % of which is located in Ireland, Finland, Sweden and the United Kingdom (because of the large area of peatlands in these countries).
- All simulations predict overall increases of the EU soil carbon stocks, as the result of decreasing SOC stocks in Mediterranean countries compensated by SOC accumulation in others, notably Ireland, France and Germany.
- Soil organic carbon is unevenly distributed across Europe, with carbon content decreasing from Northeast to Southwest.
- Soil organic carbon content also depends on land cover, with lowest values per area unit in permanent crops and arable lands.
- 31,7% of total SOC stocks in the EU are found in agricultural soils (9,3% in grassland and 21,4% in cropland). Depending on carbon stock estimates, this represents between 10,7 to 23,7 billion tonnes of SOC.
- 20 to 25% of European SOC is stored in peatlands, even if they cover only 6 % of the EU-27's land area When untouched, peatlands act as carbon sinks. When degraded or drained for agricultural use, they are powerful net GHG emitters

3.1. Organic carbon stocks in agricultural soils

Since 2015, there have been several attempts to offer a harmonized vision of the European soil's organic carbon content. SOC stocks in the top 20 cm of our soils have been simulated to be about 34 Gt (in the current EU-27 zone, in the absence of data for Cyprus and Malta) (***Table 1***) (Yiguini and Panagos, 2016). Based on Jones et al. (2005), the European Environmental Agency had previously estimated these stocks at 75 Gt for the top 30 cm of the soils[3].

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[3] around 50 % of which is located in Ireland, Finland, Sweden and the United Kingdom (because of the large area of peatlands in these countries) : https://www.eea.europa.eu/data-and-maps/indicators/soil-organic-carbon-1/assessment.

Table 1: Total stocks of organic carbon (OC) in the 20 top cm of the EU-27 soils

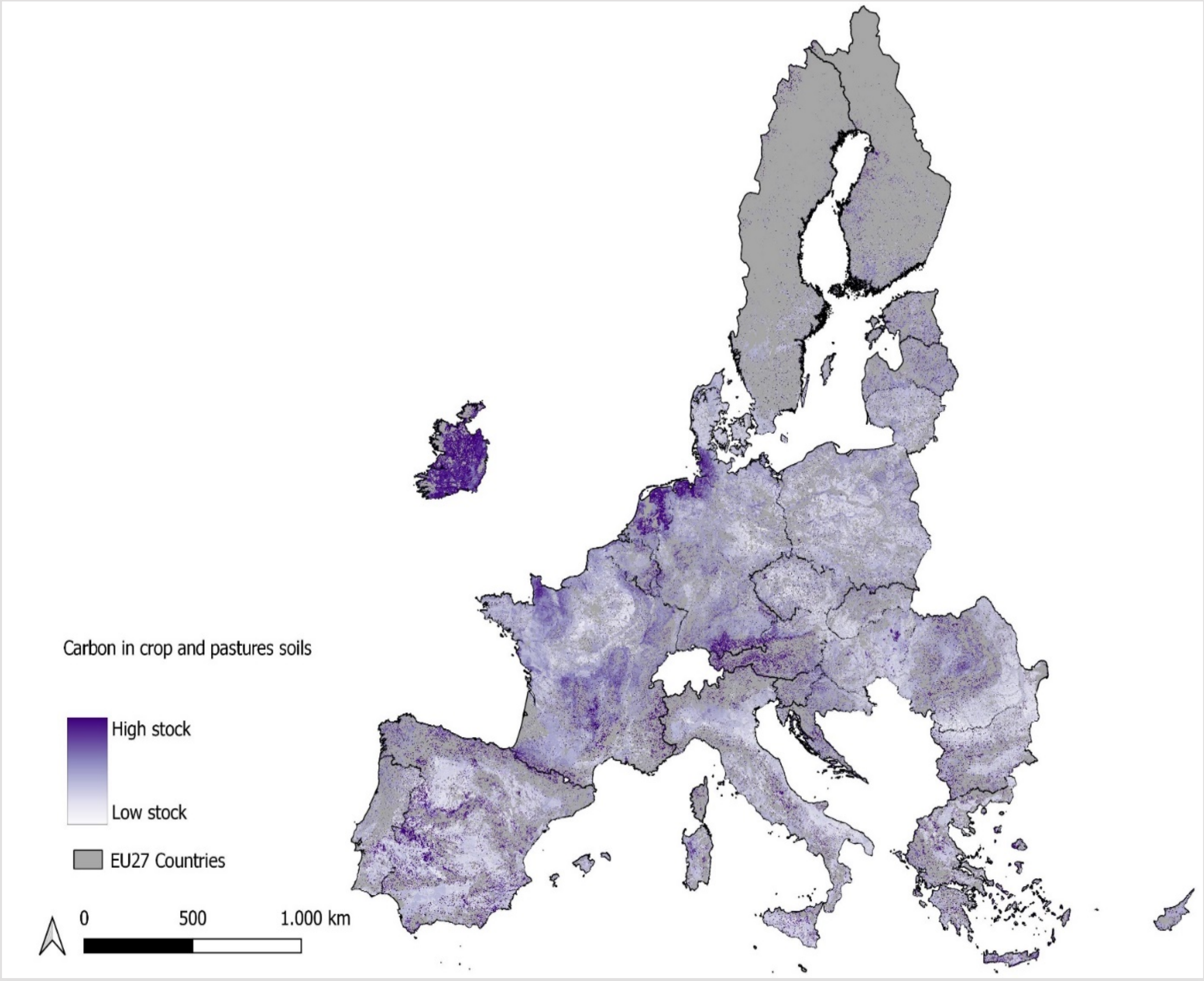
	Total OC (Mt C) (1)	**Mean OC content (g C 100g dry soil^{-1}) (2)**	**Total OC in grassland (Mt C) (3)**	**Total OC in cropland (Mt C) (3)**
Austria	790	5.85	64.2	115.4
Belgium	180	3.28	35.4	80.5
Bulgaria	540	ND	40	244.3
Croatia	ND	ND	ND	ND
Cyprus	ND	ND	1.5	19.7
Czech Rep	500	3.37	71.1	178.4
Denmark	330	3.31	6.9	202.2
Estonia	500	9.91	37.8	83.1
Finland	5,270	9.79	3	335.6
France	3,810	3.38	717.2	1,180
Germany	2,720	3.5	629.5	705.5
Greece	650	3.4	57	207.6
Hungary	500	2.21	61.3	252.8
Ireland	1,090	13.29	528.6	107.2
Italy	1,960	3.37	55.9	672.8
Latvia	630	6.92	75.2	124.7
Lithuania	590	5.91	30.6	191.9
Luxembourg	20	3.01	3.5	7.1
Malta	ND	ND	0	0.6
Netherlands	270	3.3	102.2	86.6
Poland	2,200	2.91	197.3	632
Portugal	560	2.68	10.8	173.1
Romania	1,360	ND	173.8	488.4
Slovenia	170	5.92	14.9	43.4
Slovakia	320	3.22	23.8	103
Spain	2,960	3	190.6	804.8
Sweden	6,540	11.15	60.2	325.6
Total	**34,460**		**3,192.3**	**7,366.3**

Source: (1) Yiguini and Panagos, 2016; (2) Aksoy et al., 2016), (3) Panagos et al., 2020.

SOC spatial distribution is uneven, with the greatest average C concentrations (in g C per 100 g dry soil) found in Ireland (13.3%), Sweden (11.1%), Estonia (9.9%) and Finland (9.8%), and the lowest in Poland, Portugal, Italy, Spain, Greece, and Hungary (about 3% on average) (Aksoy et al., 2016).

Soil organic carbon content is also highly dependent on land-cover. The lowest C content is found in permanent crops such as vineyards and orchards (1.9%) and arable lands (2.0%), and the highest in wetlands (13.5%-36.5%) and woodlands (7.5% to 10.0%), with intermediate values under scrubs, pastures and natural grasslands (5.9%, 5.2% and 4.2% respectively) (Askoy et al., 2016; de Brogniez et al., 2015). In the EU-27 zone 31.7% of total SOC stocks are found in agricultural soils (9.3% in grassland and 21.4% in cropland) (Panagos et al., 2020) (***Table 1***, and ***Figure 6***).

Figure 6: Distribution of soil organic carbon stocks in the agricultural soils of EU-27.



Source: Adapted from Aksoy et al., 2016.

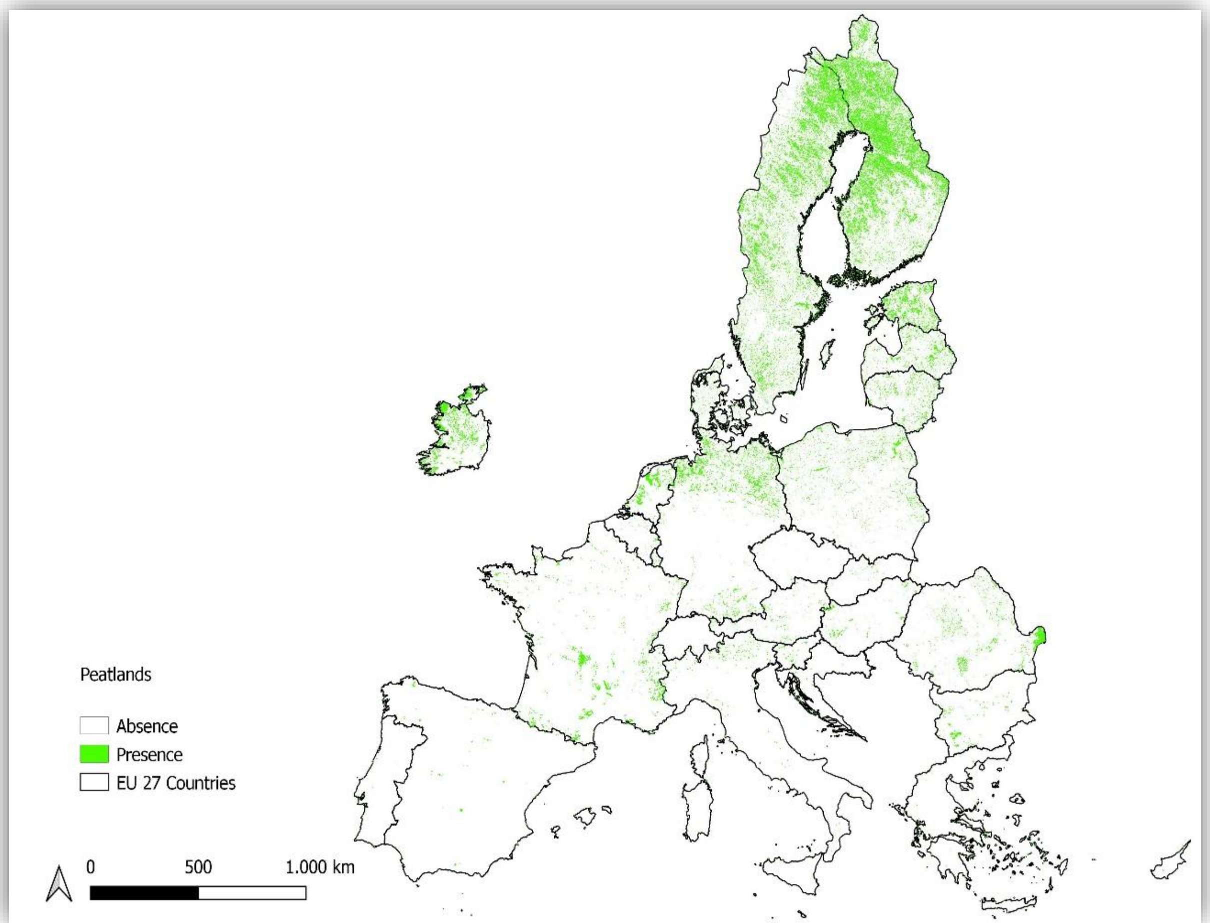
SOC values have been transformed to an ordinal scale where higher stocks (currently representing more than 400 t C ha-1) correspond to 1 and lower stocks (less than 40 t C ha-1) to 0.

3.2. The great peatland SOC warehouse

Peat cartography is inconsistent due to divergent criteria about how to define peatlands (e.g. how deep the peat layer is and how high the SOC content must be for soils to deserve the name of "peatland"), and about how they appear in soil classifications (e.g. as "organic soils" or as "Histosols", among others). Additional difficulties arise from diverging methodologies used to build-up national peat maps and inventories, and from the inclusion (or not) of mires in peatland inventories. Peatlands are areas with a naturally accumulated peat layer at the surface (30 to 40 cm depending on classifications). The organic matter content in peats is high and variable (from 30% to 80-90%). Mires are lands where peat is actively being formed and accumulating. All mires are peatlands, but sites no longer accumulating peat can not be considered mires.

The latest attempts to harmonize peatland cartography at the European scale are by Montanarella et al. (2006) and Tanneberger et al. (2017). Although using different methodologies, the global data are totally comparable, with 246 and 241 km^2 of the 4,137,390 km^2 of the land area of the EU-27 occupied by peatlands (5.9 and 5.8% in the respective studies), and 43% of the peatland area corresponding to active mires. Peatlands are unevenly distributed across Europe, with much higher density in the North-Western, Nordic, and Eastern countries (***Figure 7***), and they store about 20-25% of the total carbon in EU soils (ECA, 2021).

Figure 7: Peatland occurrence in the EU-27.



Source: Tanneberger et al., 2017.

Currently, more than 50% of these peatlands are degraded (Greifswald Mire Centre, 2022), to varying degrees (***Table 2***). According to the FAO, in 2019 about 11 million ha of the total European peatland area were exploited for (58% as cropland and 42% as grazing land)[4].

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[4] https://peatlands.org/peatlands/agriculture-on-peatlands

Peatlands converted into agricultural land represent about 2% of the total EU-27 agricultural area, but account for 20% of the agricultural emissions (European Court of Auditors, 2021). This elevated emission tax is owing to the fact that the agricultural use of peatlands requires lowering of the water table to 0.4- 0.8 m below the soil surface for grassland and to 1-1.2 m for cropland. Drainage and cultivation of peatlands significantly increase the emissions of CO_2 and N_2O to the atmosphere whilst reducing CH_4 emissions, following which peatlands shift from being long-term C sinks into being net sources of GHGs (Joosten and Clarke, 2002; Page and Baird, 2016; Smith and Conen, 2004).

In the EU-27, over 4 million ha of organic soils, including peatlands, are drained and managed as cropland or grazeland.

Table 2: Peatland area in the EU-27 MSs and estimated degradation extent per country.

	Country area (Km^2)	Peatland area (Km^2) (1)	Peatland/ country area (%)	Degraded peatland area (%) (2)
Austria	83,871	1,200	1.43	81-90
Belgium	30,528	248	0.81	61-80
Bulgaria	110,900	208	0.19	61-80
Croatia	56,594	33	0.06	91-100
Cyprus	9,251	0	0.0005	91-100
Czech Rep	78,866	285	0.36	41-60
Denmark	43,094	2,029	4.71	91-100
Faroe Islands	1,393	18	1.26	0-20
Estonia	45,227	9,150	20.23	61-80
Finland	337,010	90,000	26.71	61-80
France	551,500	2,875	0.52	61-80
Germany	357,137	12,800	3.58	91-100
Greece	131,957	103	0.08	81-90
Hungary	93,026	300	0.32	61-80
Ireland	69,825	14,665	21	81-90
Italy	301,339	750	0.25	81-90
Latvia	64,562	7,514	11.64	41-60
Lithuania	65,300	6,460	9.89	61-80
Luxembourg	2,586	4	0.14	91-100
Malta	316	0	0	ND
Netherlands	37,354	2,733	7.32	91-100
Poland	311,888	14,950	4.79	81-90
Portugal	89,879	271	0.29	91-100

Romania	238,391	7,690	3.23	81-90
Slovenia	49,036	60	0.12	81-90
Slovakia	20,273	84	0.41	91-100
Spain	505,992	350	0.07	41-60%
Sweden	450,295	66,450	14.76	21-40
Total	4,137,390	241,229	5.83	

Source: (1) Tannenberg et al., 2017; (2) Tannenberg et al., 2020.

3.3. Expected evolution of the land cover

The EC aims to be climate-neutral in 2050 with net-zero greenhouse gas emissions under the Green Deal and in line with the EU's commitment to global climate action established in the Paris Agreement. With The 'Fit for 55' package (EU, 2021), the EU fixed a target of at least 55% reduction of emissions in 2030. This ambitious objective will rely, at least partially, on the role of natural C sinks from the land use, land-use change and forestry (LULUCF) sector to compensate residual emissions.

According to recent estimates (Eurostat, 2018), woodland covered by far the largest proportion of the EU area — some 41.1%, followed by cropland with 24.2% and grassland with 16 %. Shrubland covered 5.7% of the total, followed by artificial areas (4.2%) and bare land (2.4%), while the least common forms of cover were water bodies (3.2%) and wetlands (1.7%). At the European level, the most important changes in land cover over the last years have been the abandonment of croplands and the increase of forest cover (NIR, 2019). These trends can be positive for C balance, but they are not sustainable at the social level.

In this context, it seems unlikely that possible agricultural land changes (excluding forests) fulfil the expectations of achieving GHG emission neutralization. Therefore, for the achievement of these goals the MSs have a role to play (by putting in place the necessary policies) in enhancing carbon sequestration in soils. To achieve this objective, the international "4 per 1000" Initiative, launched by France on 1 December 2015 at COP 21, aims to increase the level of carbon stored by soils in the top 30 to 40 centimetres of soil by 0.4% (or 4‰) per year, the annual increase of carbon dioxide (CO_2) in the atmosphere would be significantly reduced[5]. Zomer et al. (2017) estimated that global cropland soils could sequester 26–53% of the target carbon storage of the 4 per 1000 Initiative. Still, it is important to protect permanent grasslands, as they function as a sink of GHG emissions (and their area is decreasing), and to properly manage peatlands to avoid GHG emission.

3.4. Predicted evolution of soil carbon stocks by 2050

Predictions of the future evolution of the soil C stocks at the European scale are subject to high uncertainty.

Yiguini and Panagos (2016) simulated soil C content in the EU-27 soil under four climate scenarios for 2050, assuming increasing radiative forcing. With a previewed 3.1% increase in forests and semi-natural

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[5] this growth rate of 4‰ per year in soil carbon stocks is not a normative target for each country, but a direction to follow (the initiative indicates that this 0,4 % increase would significantly reduce the increase of Co2 in the atmosphere) : https://4p1000.org/discover/?lang=en.

lands, and a decrease in agricultural lands (-4.16%), pastures (-5.18%) and wetlands (-0.31%), all simulations converged to predict overall increases in soil C stocks.

Under the business-as-usual management scenario, and for the 2010 to 2050 period, total SOC stocks were predicted to increase from the initial 34.5 Gt to 43.1- 44.3 Gt, depending on the severity of the climate projections. Per land use type, SOC will increase from 16.4 to 22.3-23.2 Gt in forests, from 12.8 to 13.9-14.1 Gt in cropland, from 6.7 to 8.9 -9.4 Gt in pastures and from 1.8 to 2.3-2.5 Gt in wetlands.

However, the overall SOC increase predicted for the year 2100 at the pan-European scale (Lugato et al., 2014) will be the result of decreasing SOC stocks in Mediterranean countries compensated by SOC accumulation in other countries, such as Ireland, France and Germany.

4. EUROPEAN AGRICULTURE: GREENHOUSE GAS EMISSIONS AND POTENTIAL CARBON SEQUESTRATION IN SOILS

KEY FINDINGS

- The inventoried GHG emissions of EU-28 agriculture reached 429 million of carbon dioxide equivalent tonnes (MtCO2eq) in 2019, representing about 11% of total emissions generated in the EU.
- Emissions of Carbon dioxide (CO_2) only account of 2 % of carbon-equivalent emissions of the agricultural sector, as the bulk originate from Methane (CH_4) (54 % of agricultural emissions) and Nitrous oxide (N_2O) (43,6 %).
- Agricultural GHG emissions decreased by 108 Mt CO_2-eq from 1990 to 2018, but this reduction occurred until 2005 and the emission rate has remained stable since then.
- Achieving further substantial GHG emission reductions in the agricultural sector will require significant changes in farming practices and agricultural policies.
- The land use, land use change and forestry (LULUCF) sector is behaving (in 2019) as a GHG sink with a total removal capacity of -233.9 Mt CO_2-eq, due to the increase in forest cover. However, when excluding forests, the LULUC sector acts as a GHG source (around 80 Mt CO_2-eq).
- Emission intensity of agricultural production can be further reduced if we are able to overcome the barriers that have limited adoption of GHG mitigation measures and innovations.
- Predicting the technical and realistic mitigation capacity of agricultural soils is challenging due to the enormous variety of possible scenarios arising from the combination of management practices and their possible areas of application, and interactions with other socio-economic drivers.
- More than 55% of the technical mitigation potential in the EU-27 agricultural sector lies with agricultural soils and manure management. Carbon sequestration in agricultural soils is a cost-effective option. To achieve agriculture related mitigation targets, together with stimulating SOC sequestration, reducing CO_2 emissions from drained peatlands and rewetting and restoring them is crucial.

4.1. Total GHG emissions[6]

In 2019, total GHG emissions (including indirect CO_2 emissions), excluding the LULUCF sector, amounted to 4,057 Mt CO_2-eq in the EU-KP (EU-27 MSs plus Iceland and UK). The largest emitters were Germany (20%), UK (11%), France (11%), Italy (10%), Poland (10%) and Spain (8%).

Excluding the LULUCF sector, the most important emitter by far was energy, which accounted for 77% of the total EU-KP emissions, followed by agriculture (11%) and industrial processes (9%).

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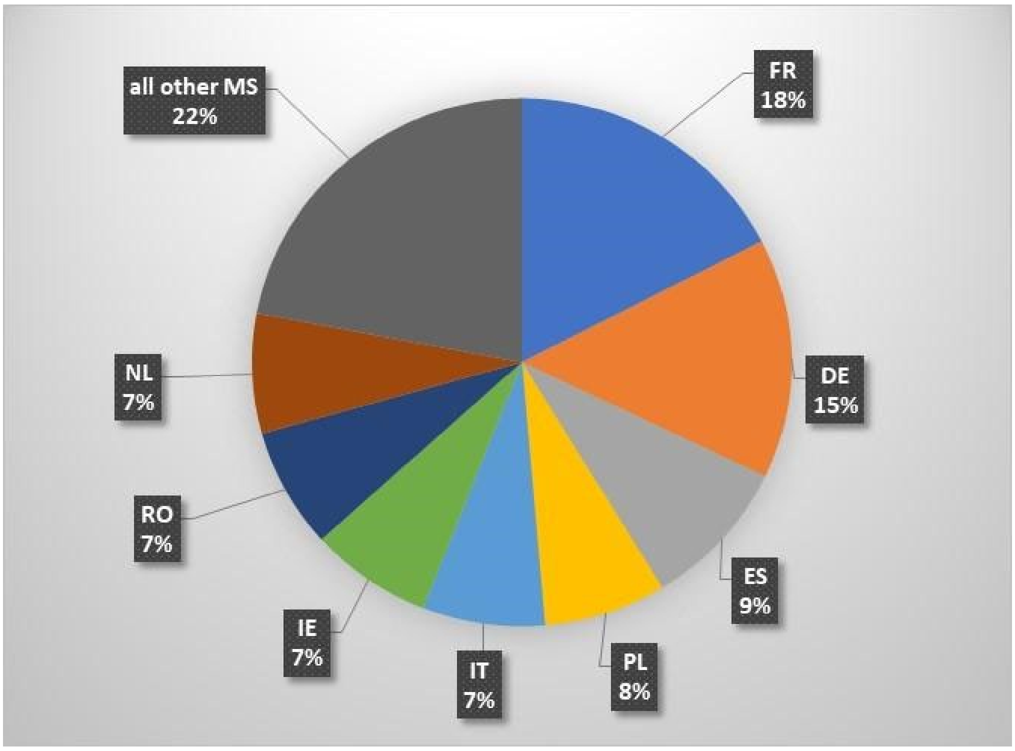
[6] Data provided in section 4.1. have been obtained from the Annual European Union greenhouse gas inventory 1990- 2019 and inventory 2021, Submitted to the UNFCCC Secretariat. (European Commission, DG Climate Action European Environment Agency, 27 May 2021). This EU GHG inventory comprises the direct sum of emissions from the national inventories (NIR) compiled by the countries making up the EU-27 plus Iceland and the UK (EU-KP).

4.1.1. GHG emission from Agriculture in EU-KP

In 2019, emissions from agriculture accounted for 429 Mt CO_2-eq. France, Germany, Spain, Poland, Italy, Ireland, Romania, and the Netherlands, were the main contributors (***Figure 8***).

Figure 8: Relative contribution of MSs to total European Agriculture GHG emissions in 2019.



Source: NIR, 2019.
Total emissions accounted for 429 Mt CO2-eq. FR: France; DE: Germany; ES: Spain; PL: Poland; IT: Italy; IE: Ireland; RO: Romania; NL: Netherlands.

Contribution of the most important GHG gases to total GHG emissions are shown in ***Table 3***.

Table 3: Agricultural GHG emissions in the EU-KP.

	Total Mt CO_2-eq	**%**
Methane (CH_4)	231	53.8
Nitrous oxide (N_2O)	187	43.6
Carbon dioxide (CO_2)	11	2.6

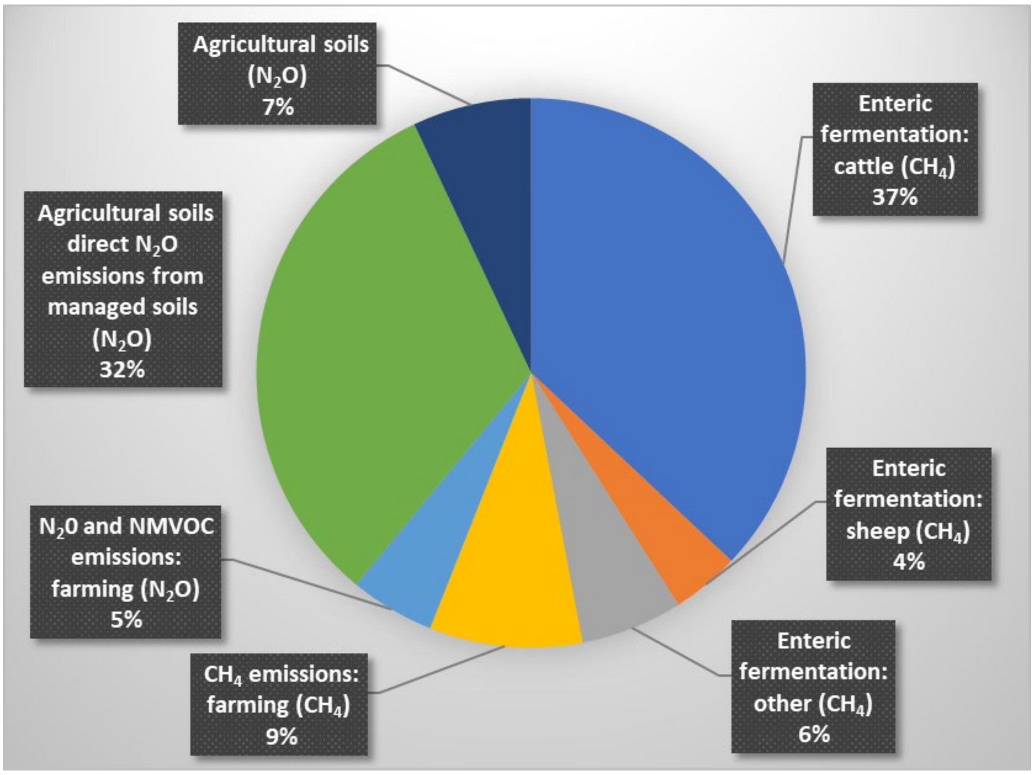
Cultivated soils emit most of the N_2O, (with a global warming potential over 100 years -GWP100- 298 times greater than that of CO_2) due to organic and inorganic fertilisers and to crop residue incorporation into soils. Livestock is the main source of CH_4 (GWP100 28 times greater than CO_2), mainly from enteric fermentation of ruminants (dairy and beef cattle). Agricultural soils marginally contribute to EU inventory CO_2 emissions.

Looking in more detail, the key sources responsible for these emissions are shown in ***Figure 9***.

Enteric fermentation accounted for 157.9 Mt CO_2-eq, direct N_2O emissions from managed soils for 135.1 Mt CO_2-eq, and emissions from farming for 40.60 Mt CO_2-eq.

It is worthwhile noting that the inventory does not consider GHG emissions resulting from fossil fuel consumption or transport emissions associated with feedstock transport, or leakage due to imports of animal products to compensate for decreasing productivity in the EU following a transition towards organic agriculture (Guyomard et al., 2020).

Figure 9: Agricultural GHG emissions distribution among the different source categories, in 2019, in CO_2-eq.



Source: NIR, 2019.

NMVOC: non-methane volatile organic compounds.

Total agricultural emissions declined by 20% (108 Mt CO_2-eq) from 1990 to 2018. The most important contributors to this reduction were agricultural soils (N_2O emissions) and enteric fermentation from cattle CH_4 (-41 and -28 Mt CO_2-eq, respectively).

However, most of the reduction occurred from 1990 to 2005, and emissions have remained stable since 2005 or have increased slightly from 2005 to 2019. For this reason, it is assumed that it will be difficult to achieve further substantial GHG emission reductions in the agricultural sector without significant changes in practices, systems, activity levels and policies. From that perspective it is also important to consider the potential importance of both the carbon storage capacity in agricultural soils and of possible changes in human diets.

4.1.2. GHG emission from LUCLUCF

LULUCF net emissions include anthropogenic GHG emissions, mainly CO_2, and CO_2 removals resulting from land management.

For many years, the EU environmental and agricultural policies have had a dominant impact on landscape. The Common Agricultural Policy (CAP), including Rural Development Programmes (RDPs) have fuelled progress towards sustainability by promoting less intensive agricultural practices. Other EU environmental policies (e.g., Natura 2000 network) have resulted in an increase in the area under conservation thus contributing to the preservation of biodiversity and landscapes. These trends, together with the current socioeconomical context, have driven changes in land cover, from the abandonment of croplands to the increase in forest cover.

During the 1990-2019 period, the proportion of arable land (-8%) and grassland (-4%) decreased, while urban areas (+26%), forest land (+5%), and wetland (2%) increased. These changes are among the main drivers of the final carbon balance of the LULUCF sector. Increasing forest area and the consequent build-up of biomass has resulted in increasing net carbon removals by the EU forests.

In 2019, the LULUCF sector of the EU-KP acted as a total net sink of -233.9 Mt CO_2-eq, which represents an increase of 23% relative to 1990, mainly due to the increase in forest cover.

However, if we focus on the agricultural sector, its capacity to neutralize GHG emissions falls, as most of the land covers act as sources, with a net balance of around 80 Mt CO_2-eq (see ***Table 4***). Overall, emissions from this sector have been decreasing since 1990. The Land converted to Cropland subcategory, that represents only 9% of the total cropland area of the EU-KP, accounts for 73% of the net CO_2 emissions reported for cropland (***Table 4***).

However, arable land and grasslands could revert, at least partially, this situation. Some member states have reported that croplands with woody biomass and grasslands managed in low intensity act as carbon sinks. The Land converted to Grassland subcategory represents 15% of the total grassland area but the reported carbon sink offsets about 70% of the emissions resulting from Grassland remaining Grassland (***Table 4***). Finally, we should keep in mind that grasslands (-8%) and croplands (-4%) have been decreasing in area since 1990.

Table 4: Changes in area and CO_2 emissions for each of the land use and land use change categories of the LULUC sector (excluding Forest).

Land Use/land use change	Area (Kha)	Change in area from 1990 (%)	MSs with the biggest % of the land use area *	Emissions (2019) Mt CO_2-eq	Change in emission from 1990 (%)	This change is mainly driven by MSs that:	
						contribute as source	reports sink
Cropland remaining Cropland	113,087	-9	SP, FR, PO, DE	14.5	-55	DE, UK, FI	FR, RO, SP
Land converted to Cropland	11,655	4	FR, DE, RO	35.7	-26	FR, DE, UK	CY, RO
Grassland remaining Grassland	79,662	-8	UK, SP, FR	36.2	-34	DE, IR, NT	RO, IT
Land converted to Grassland	15,495	24	RO, FR, UK, DE	-25.4	22	RO, SW	FR, IT, DE, UK
Wetlands remaining Wetlands	25,647	2	SW, FI	9.2	-	DE, IR, FI, ES	
Land converted to Wetlands	1,483	72	SW, PO, DE, IT	5.3	-	PO, DE, RO	

Source: NIR, 2019.

EU-KP countries with the highest proportion of each of the land cover area and with the highest impact on emission trends from 1990 to 2019, both as source (emitter) or sink (removal). Emissions from these land uses are mostly CO2. SP: Spain; FR: France; PO: Poland; DE: Germany; UK: United Kingdom; FI: Finland; RO: Romania; IT: Italy; SW: Sweden; IR: Ireland: NT: Netherlands; ES: Estonia; CY: Cyprus. * all together account >50%.

4.2. Abatement potential of agricultural emissions

Agricultural GHG emissions in the EU-KP, as described in the previous section, have changed little since 2005 despite climate mitigation action supported through the CAP and other legislation related to environmental protection.

Besides the CAP, other important policies affecting greenhouse agricultural gas emissions are:

- *The National Emission Ceiling Directive (NEC – Directive 2016/2284/EC),* that sets national emission ceilings for nitrogen oxides and ammonia;
- *The Industrial Emission Directive (IED – Directive 2010/75/EU)* that aims to minimise pollution from different production sectors (i.e. intensive livestock production, that is required to apply techniques for preventing ammonia emissions - Best Available Technologies, BAT); and
- *The Nitrate Directive (Directive 91/676/CEE*), that aims to reduce and prevent water pollution caused by nitrates from agricultural sources. It is one of the policies with the largest impact on GHG emissions from agriculture.

4.2.1. Projections

Different studies have been tackling this issue, trying to answer questions such as "is there still room for emission mitigation?", "which practices have the largest effect?", and "what other actions should be undertaken for emission abatement?"

Projections indicate that EU agricultural emissions will only fall by less than 5% by 2030 relative to 2017 (OECD, 2020). German et al. (2021) showed that the emissions will remain almost flat (falling by 1.5%) "*with the existing measures*" and that, "*with additional measures*" a slightly larger decrease (of 5%) may be reached by 2040.

Despite efforts for reducing emissions, current trends show that reaching Green Deal agricultural targets and becoming "*the world's first climate-neutral continent by 2050 (EC, 2019)*" will not be easy. Significant changes in farming practices and systems are required to achieve further substantial reductions (Guyomard et al., 2020).

However, historical and projected trends do not mean that actions aimed at mitigating agricultural GHG emission are ineffective. The effectiveness of a measure depends on the degree of adoption (or implementation), its technical potential, and the accurate measurement of its impact. In this sense, further work is needed to improve the accuracy of the models used to estimate ex ante emissions by developing Tier 2 and Tier 3 models (IPCC, 2006 and 2019), and the models used to estimate emission reduction after implementation of the mitigation measures (ex post emissions inventory).

4.2.2. Agriculture and livestock measures for GHG emission abatement

In the following section, measures for GHG mitigation already implemented in at least one MS, are briefly discussed. A deep analysis and discussion of these measures can be found in Ricardo-AEA (2016) and German et al. (2021).

4.2.2.1. Livestock measures

Most of the measures for GHG mitigation in livestock production come from the Nitrate Directive, the IED Directive and the derived Best Available Technologies (for pigs and poultry) (Commission Implementing Decision (EU) 2017/302).

Measures that have been implemented in many MSs although with different degree of adoption, include optimizing livestock diets, increasing digestibility, and reducing surplus protein in feed to reduce nitrogen excretion, breeding to increase productivity, and health disease management. In contrast, measures to promote the use of feed additives to reduce enteric methane emission, as well as incentives to reduce livestock heads, two measures with a high GHG mitigation potential, are still rare.

Almost all MSs have promoted measures to improve manure management systems (processing and storage) in order to reduce emissions of methane and nitrous oxide (direct and indirect), although with different degrees of implementation. The most common measures are to cover manure storage facilities (with rigid or flexible covers), mechanical separation systems, rapid removal of manure from housing to prevent NH_3 volatilization and increasing storage capacity, and to match manure generation to fertilization requirements.

Special attention should be paid to anaerobic digestion of manure to produce biogas that is being promoted in almost all MSs. This practice reduces methane emission from manure storage and reduces CO_2 from the avoided fossil fuel combustion; biogas is usually used for producing electricity in combined heat and power generation (CHP) engines or injected to the natural gas grid.

In 2010, anaerobic treatment took place on 5,256 installations treating 88 million tonnes of livestock manure and other products, equal to 6.4% of the entire livestock manure production in the EU (Foged et al., 2011). Regarding biogas production, in 2011, 10 Mtoe of biogas primary energy were produced in the EU; from these, almost 5.7 Mtoe came from organic residues (manures, sewage sludge and other wastes) (EurObserv'ER, 2012). In 2019, 16.6 Mtoe were produced (14 Mtoe from organic wastes). Germany is by far the EU-KP country with higher biogas production, followed by the UK, Italy and France (EurObserv'ER, 2020).

Despite this large increase in biogas production, it is believed that there is still room to expand anaerobic digestion of manure.

4.2.2.2. Crops and soil N_2O mitigation measures

Reducing the quantity of nitrogen applied to soil (derived, in part, from the application of the Nitrates Directive), and promoting the use of organic fertiliser (e.g. manures, sewage sludge, compost) instead of synthetic fertiliser are the most common practices implanted. Other practices that still have scope to expand are the use of low NH_3 emission spreading techniques (e.g. hanging hoses, injectors), low emission synthetic fertilisers, cover/catch crops, precision farming, inhibitors of nitrification and promoting biological nitrogen fixation by legumes.

Promoting organic farming is also a measure in which great hopes have been placed to mitigate GHGs. However, it should be accompanied by a dietary shift in order to avoid emission leakage.

4.2.2.3. Energy mitigation measures

Finally, another relevant issue that should be tackled is the improvement of on-farm energy efficiency, the production of biomass feedstocks and production and use of renewable energy (e.g. solar energy). Production of energy crops, despite their impact on CO_2 emissions through fossil fuel substitution, is a controversial practice that should be closely analysed to avoid other side effects.

4.2.3. Gaps, opportunities, and limitations of GHG emission abatement measures

There are two components that drive GHG emissions from agriculture, the productivity (i.e. the rate of output per unit of input) and the emission intensity (i.e. the quantity of emissions per unit of product). In this sense, a decrease of emission intensity will not, by itself, result in a decrease of emissions. Lower

GHG emission intensity, often due to an improvement in efficiency and productivity, may contribute to an increase in production because producers are more competitive (German et al, 2021). This rebound effect occurred in Europe during the last decade (ECA, 2021).

Therefore, it would be logical to assume that measures which reduce inputs, lower productivity and reduce GHG emissions (e.g. organic farming) would be the most suitable measures to be implemented. However, if food demand from Europeans does not change, there is a high risk of emission leakage through the increased demand of food imports. Conversely, if Europeans shift to plant-based-protein diets and eat less meat and dairy products, European farmers could export their excess production to the rest of the world.

It is then necessary to have a broad view when implementing new measures to avoid possible emission leaks. This is of major relevance as GHG emission is not only a European issue but a global one.

According to Guyomard et al. (2020), to reach the major objective of the Green Deal related to climate neutrality, further actions should be undertaken. In this sense, they have defined three sets of actions:

i. Actions to promote the adoption of innovations to induce efficiency gains at the farm level and food chains.

There is still room for GHG emission abatement by promoting the adaptation of the existing measures, but several gaps that required new measures have also been identified by Ricardo-AEA (2016), ECA (2021) and German (2021):

- Livestock breeding and feed additives to reduce enteric fermentation emissions;
- Manure cooling and acidification to reduce CH_4 and N_2O (direct and indirect) emissions;
- Use of sexed semen for breeding dairy replacements;
- Reduction of livestock production; and
- Use of nitrification inhibitors.

ii. Actions to re-design production systems based on agroecological principles

These actions may result in a reduction of the use of chemical inputs (pesticides, fertilisers and antibiotics) and a lower yield will be expected. The effects on GHG are not clear and emission leakages should be prevented.

iii. Actions to encourage dietary change and reduction in food waste

The dietary shift to more plant-based proteins will have a direct effect on GHG mitigation because animal products have much higher GHG emissions (10-15 times) than plant products and require a much larger area of land and fertiliser inputs. Concomitant with these direct reductions, GHG emissions associated with feed and food imported from overseas (e.g. soya) will be expected to decrease.

Finally, reductions in food waste will have a double effect, as the demand for food products will be reduced, and less methane will be generated in the landfills from organic waste.

There is clear scope for further reductions in GHG emissions from agriculture. Emission intensity of agricultural production can be further reduced if we are able to overcome the barriers that have limited the adoption of GHG mitigation measures and other innovations, closing nutrient cycles and developing new measures when necessary.

4.3. Technical and realistic mitigation potential of carbon sequestration in European agricultural soils

Technical mitigation potential refers to the maximum mitigation possible with full implementation of all available mitigation measures. The realistic (or achievable) potential is calculated considering barriers of different types that restrict the adoption of mitigation measures, such as cost-effectiveness and social, cultural, farm-level and political constraints to adoption. Predicting both the technical and realistic mitigation capacity of agricultural soils under climate-friendly management is very challenging due to the enormous variety of possible scenarios arising from the combination of management practices and their possible areas of application and interactions with other socio-economic drivers.

Smith et al. (2000) estimated the technical C sequestration potential of a set of sustainable options applied to different land areas at up to 200 Mt CO_2-eq y^{-1}. Freibauer et al. (2004) estimated a realistic achievable carbon sequestration potential for EU-15 agricultural soils of 16–19 Mt y^{-1} for the 2008-2012 period (from a technical capacity of 80–95 Mt C). Frank et al. (2015) simulated the achievable SOC mitigation potential in the croplands of the EU-28 zone as 9 to 38 Mt CO_2 y^{-1} until 2050 for carbon prices between 10 to 100 $100/t CO_2.

Lugato et al (2015) simulated the evolution of soil C stocks from 2013 to 2100 under contrasting climate and CO_2 concentration scenarios, for the business-as-usual situation and for three alternative management situations resulting from implementing combinations of good management practices to 12%, 24% and 28% of the European agricultural area, and concluded a realistic mitigation potential, based on plausible policy oriented scenarios, of 101–336 Mt CO_2-eq from 2013 to 2020, and of 549-2,141 Mt CO_2-eq from 2013 to 2100.

Roe et al. (2021) simulated the technical mitigation potential of carbon sequestration in agricultural soils for different EU countries in the 2020-2050 period. They also estimated the feasible mitigation potential by selecting only practices that can be applied at a cost up to $100/t CO_2-eq. Shifting from current management to no-till management and cover cropping implementation were considered for croplands and shifting from current practices to improved sustainable management with moderate grazing pressure were simulated for grasslands. Results for the EU-17 countries are shown in ***Table 5***. Total technical mitigation potential resulted in 74.9 Mt CO_2-eq for crops and 54.0 Mt CO_2-eq for grasslands, and achievable potential in 67.5 Mt CO_2-eq for cropland and 32.4 Mt CO_2-eq for grassland.

To achieve agriculture related mitigation targets, together with stimulating SOC sequestration, reducing CO_2 emissions from drained peatlands is crucial. Roe et al. (2021) estimated the technical mitigation potential of rewetting and restoring the EU-27 peatlands at about 185 Mt CO_2-eq y^{-1} and the cost-effective mitigation potential of these operations (at a cost of US$ 100/t CO_2-eq) at about 54 Mt CO_2-eq y^{-1}, on average for the 2020-2050 period. Therefore, peatland restoration is not only desirable but also a cost-effective measure (Glenk and Martin-Ortega, 2018; Günther et al., 2020).

Research suggests that the potential for increased carbon sequestration in cropland ranges between 9 and 58 Mt CO_2-eq y^{-1} (Böttcher et al., 2022), and that the climate mitigation potential associated with rewetting organic soils ranges between 48 –54 Mt CO_2-eq y^{-1}. Overall, more than 55% of the technical mitigation potential in the EU-27 agricultural sector lies with agricultural soils and manure management. Carbon sequestration in agricultural soils is therefore a cost-effective option that should be promoted (Grosjean et al., 2016).

Table 5: Technical and realistic (cost-effective at $100/t CO_2-eq) mitigation potential in European agricultural soils for the 2020-2050 period.

	Cropland				Grassland			
	Annual technical potential	Cumulative technical potential (2020-2050)	Annual cost-effective potential	Cumulative cost-effective potential (2020-2050)	Annual technical potential	Cumulative technical potential (2020-2050)	Annual cost-effective potential	Cumulative cost-effective potential (2020-2050)
	Mt CO_2-eq y^{-1}	Mt CO_2-eq	Mt CO_2-eq y^{-1}	Mt CO_2-eq	Mt CO_2-eq y^{-1}	Mt CO_2-eq	Mt CO_2-eq y^{-1}	Mt CO_2-eq
Austria	1.19	35.63	1.07	32.07	2.00	59.86	1.20	35.92
Belgium	1.53	45.83	1.37	41.25	1.06	31.66	0.63	19.00
Croatia	1.85	55.48	1.66	49.93	0.90	27.15	0.54	16.29
Cyprus	0.07	2.19	0.07	1.97	0.05	1.36	0.03	0.82
Czech Republic	1.75	52.63	1.58	47.37	1.68	50.43	1.01	30.26
Denmark	3.19	95.70	2.87	86.13	0.22	6.47	0.13	3.88
Estonia	1.46	43.70	1.31	39.33	0.18	5.46	0.11	3.28
Faroe Islands	0.00	0.09	0.00	0.08	0.00	0.00	0.00	0.00
Finland	4.02	120.69	3.62	108.62	0.24	7.17	0.14	4.30
France	10.74	322.32	9.67	290.08	7.58	227.41	4.55	136.45
Germany	9.77	293.11	8.79	263.80	6.67	199.98	4.00	119.99
Greece	1.30	38.92	1.17	35.03	1.36	40.65	0.81	24.39
Hungary	1.44	43.33	1.30	39.00	0.65	19.47	0.39	11.68
Iceland	0.00	0.00	0.00	0.00	10.06	301.75	6.04	181.05
Ireland	0.65	19.39	0.58	17.45	1.52	45.67	0.91	27.40
Italy	5.87	176.17	5.29	158.55	3.05	91.64	1.83	54.98

Latvia	2.46	73.78	2.21	66.41	1.76	52.89	1.06	31.73
Lithuania	4.21	126.20	3.79	113.58	0.93	28.02	0.56	16.81
Luxembourg	0.08	2.30	0.07	2.07	0.11	3.31	0.07	1.99
Malta	0.00	0.08	0.00	0.07	0.00	0.00	0.00	0.00
Netherlands	1.17	35.20	1.06	31.68	1.10	32.98	0.66	19.79
Poland	7.05	211.62	6.35	190.45	2.57	77.01	1.54	46.21
Portugal	0.54	16.29	0.49	14.66	0.13	4.02	0.08	2.41
Romania	3.80	114.13	3.42	102.71	3.81	114.19	2.28	68.52
Slovenia	0.49	14.55	0.44	13.10	0.18	5.25	0.11	3.15
Spain	5.91	177.42	5.32	159.68	4.42	132.66	2.65	79.60
Sweden	4.39	131.79	3.95	118.62	1.81	54.38	1.09	32.63
Total	74.95	2,248.53	67.46	2,023.68	54.03	1,620.87	32.42	972.52

Source: Roe et al., 2021.

For modelling, shifting from the current management to no-tillage, and cover cropping were considered for croplands and shifting from current to light to moderate grazing pressure were considered for grasslands.

5. AGRICULTURAL PRACTICES WITH DIRECT IMPACT ON SOIL QUALITY AND SOIL ORGANIC CARBON STOCKS

KEY FINDINGS

- Sustainable agricultural practices that can positively affect soil quality and soil organic carbon stocks include:
    - Tillage reduction, carried out in combination with the other pillars of conservation agriculture.
    - Cover and catch crops can easily improve soils, reduce erosion, and avoid nutrient losses.
    - Increasing plant diversity can contribute to increase soil organic matter and enhance carbon sequestration.
    - Organic fertilisation with manure (raw or preferably composted) can increase carbon stocks locally, with little impact however on total carbon sequestration. Organic rich biowaste composts originating from urban waste will be of great interest when their quality may be correctly certified. Manures can be combined with mineral fertilisation.
    - Biochar cannot be recommended yet for widespread use in Europe, due to extreme variability of the product quality and of its effects on different soil types. A strict and widely accepted system of classification and labelling of commercial biochars is first required and may be of great help for biochar manufacturers and farmers.
    - Precision agriculture does not necessarily result in enhanced SOC sequestration. However, by contributing to reduce the input of mineral fertilisers, in particular ammonium nitrogen, it may be highly positive for avoiding the soil acidification and subsequent carbon emission from carbonated soils.
- The benefits of sustainable practices on increasing soil carbon stocks and soil fertility are best attained by the intelligent combination of many of them into integrated management strategies. Among them are organic and regenerative farming, as proposed in the EU Green Deal. When applied in degraded soils, they may be useful to stop and reverse soil degradation.
- Rewetting of peatlands (for natural use or wet cultivation, i.e. paludiculture) can turn them into carbon sinks, even if it results in methane emissions.
- Agroforestry systems and permanent grasslands (which represent a third of the European agricultural area) are agricultural systems of great potential to sequester carbon and must be preserved and properly managed for them to deploy their maximum potential.

From 1950 to 1985, world cereal production increased from around 700 to over 1,800 million tons and, by 2010, world food production was around 2,200 million tons. This extraordinary growth was due to the combined effect of the expansion of arable land and agricultural intensification, based on increasing use of farm machinery, deployment of the fertiliser and agrochemical industry, and genetic crop improvements. Intensive agriculture allowed rising food demand, associated with population growth, to be satisfied, while slowing down the need for transformation of natural ecosystems (Borlaug, 2000). However, progress was accomplished at the expense of severe environmental degradation, of which soil carbon loss and land desertification are key components (Gupta, 2019). Currently, 60-70% of European soils are not healthy, with some of the key active threats being associated with intensive agriculture. Severe degradation processes include erosion, compaction, loss of biodiversity and organic matter decline (European Soil Bureau Network, 2005; EU Soil Strategy for 2030).

About 50% of the Earth's ice-free land has been converted into cropland and pasture (Ellis et al., 2010) and, under the current climate crisis, food production must be guaranteed while avoiding additional land take and reversing environmental damage in the already exploited areas through application of sustainable agricultural practices.

5.1. Sustainable agricultural practices and their effect on soil quality and SOC stocks

5.1.1. Cover and catch crops (CCs)

A catch crop can be defined as a crop grown between two crops in ordinary sequence, between the rows of a main crop, or as a substitute for a staple crop that has failed. The mission of a 'catch crop' is to protect soil against erosion and to gather as much as possible of the nutrients spread in the soil (often in poorly available forms). If the crop is not harvested but used as a green manure, the gathered nutrients will be available for the next crop, assumed to be the main one for the farmer. A cover crop is 'a crop planted to prevent soil erosion and to provide organic matter to soil'. The mission of a cover crop is to act as a cover for the soil surface and to reduce the risks of erosion, in the time gap between two 'true' crops. The cover crop may be also harvested, but not necessarily: this was not its initial purpose. The terms 'cover crop' or 'catch crop' are almost synonymous in practice, because the use of the cover crop as green manure for the next crop is an obvious option. We will use the abbreviation 'CCs' to name both.

It is widely accepted that CCs result in increased SOC stocks in the plough layer (see below), where crops grow over, and where increases in fertility are most crucial for agricultural productivity. Poeplau and Don (2015) calculated a mean annual increase of 0.32 t SOC ha^{-1} y^{-1}, for the topsoil (down to 22 cm). More recently, Abdalla et al. (2019) calculated 0.56 t C ha^{-1} y^{-1}, a 75% higher figure. This difference may be due to the higher number of studies considered in the latter and to differences in the calculations of SOC stocks, in selected studies.

CCs enhance SOC quality and increases in labile organic matter and in soil microbial activity have been reported under CCs (Steenwerth and Belina, 2008; Zhou et al., 2012).

The positive effects of CCs on SOC stocks seem general, with very few exceptions (Poeplau and Don, 2015). Decreases in SOC stocks can be explained by a 'priming effect' (see section 1.2) of the green manure derived from CCs on soil microbial activity. This is important in suggesting that, in order to ensure more effective SOC sequestration, cover crops with relatively recalcitrant plant matter should be selected.

Poeplau and Don (2015) stated that CCs do not provoke decreases in the productivity of the primary crop, whereas Abdalla et al. (2019) calculated a mean yield decrease of about 4%. The decrease depends on the kind of CC, with the presence of a legume suppressing this negative effect.

Because CCs are meant to become incorporated into the soil as source of SOC, an important consideration is the biomass reached by this CC: the higher the biomass, the higher the amount of CO_2 removed from atmosphere, and also the higher the amount of carbon further added to soil when the CC is incorporated as green manure (Pawlowska et al., 2019). Under both conventional and conservation tillage, the crop system whose CC has the highest biomass also results in the highest yields in the main crop (Pawlowski et al., 2021). Because the productivity of a given CC will be highly site-dependent, this is a matter to be decided for each specific site. However, it is worth considering that within a given crop system, CC use as a strategy for SOC sequestration offers ample space for manoeuvring. Adequate plans for CC + fertilisation + additional practices for SOC sequestration (e.g., manuring) must be designed for each geographical area, always considering that any cover or catch crop will compete with the primary crop for soil nutrients.

The repeated use of CCs for decades should result in soils with greatly increased SOC stocks and total N reserves. Indeed, CC can favour symbiotic N fixation. This process has always been related to legume crops but can also occur in some other crops (Kennedy et al., 2004; Yoneyama et al., 2017, 2019) and can be favoured under low or moderate N availability occurring in organic matter enriched soils (Romanyà and Casals, 2019).

In Mediterranean countries, the use of CCs in rainfed systems may be severely limited by summer drought. Moreover, in some countries (e.g. Spain) keeping the soil surface covered with weeds is often seen by farmers as a sign of poor care in crop management. A proper policy of subsidies could allow for the acceptation of these practices (Cerdà et al., 2022). The fact that many farmers see CCs as a benefit for soil health would facilitate wider distribution of these practices.

5.1.2. Reduction in tillage, including no-till (NT) options

Intensive tillage results in high SOC losses because it disrupts soil aggregates and exposes soil organic matter to direct microbial attack, thus facilitating its decomposition. Reducing tillage should be thus the condition to allow for a recovery of SOC stocks. No-tillage, the extreme example in this trend, was widely recommended from 1990 onwards, to enhance SOC sequestration. In the second decade of 21st century, however, experiences with NT were long enough to have a balanced view of NT as a strategy for crop fields management.

Most results of NT show a lack of a clear positive effect on SOC stocks: they increase strongly in the first few cm of soil, but often decrease below 10-15 cm, so that the overall result in the topsoil (0-30 cm) is neutral (Meurer et al., 2018). The net SOC increases are often small, and highly site-dependent, meaning that viewing NT as a procedure for SOC sequestration is at best unclear (Luo et al., 2010).

SOC decreases under NT are expected to occur when NT results in a decline in plant production, as explained below. If this decline is avoided (for instance, by combining NT with other measures, such as green manuring, addition of compost, etc.), SOC depletion may not occur. For example, the capacity of NT for SOC sequestration may be improved if combined with inputs of manures to the soil, that contribute to the translocation of organic matter to subsurface soil layers (Nicoloso et al., 2018).

A recent meta-analysis (Bai et al. 2019) highlights that reduced tillage is almost as efficient as NT in sequestering SOC. This is relevant, because a common practice is to perform a standard plough periodically, even in agricultural fields where NT is applied. This ‘occasional tillage’ has been recommended (Dang et al., 2015; Blanco-Canqui and Wortmann, 2020) to avoid excessive soil stratification in NT plots, where both SOC and nutrients become excessively accumulated at the very soil surface (e. g. Dos Santos et al., 2008).

The main problem, and the main deterrent for farmers, is that the less soil-aggressive practices (NT in particular) may result in substantial reductions in crop production (Parent et al., 1995; Zhang et al., 2011; Ogle et al., 2012; Ziaeyan et al., 2020).

The relevance of this problem is obvious, for it may deter many farmers from reducing tillage operations. In Germany, for instance, this is the main reason for the low uptake of reduced tillage (only 34% of farmers) and especially NT (1% of farmers) (Zikely and Gruber, 2017). The problem could be temporal, related to the need of crops to adapt to the new conditions.

Despite the difficulties in combining NT with other practices such as cover crops or catch crops, and in controlling weed proliferation (Vincent-Caboud et al., 2017), NT (or at least tillage reduction) is seen as a necessity for regenerative farmers, and thus the challenge for them is how to combine all practices efficiently. When this can be done, NT has proven positive effects, including reductions in energy costs, soil erosion, improvement in the soil health and reduction of GHC emissions (Dang et al., 2015).

5.1.3. Increasing plant diversity: multicropping and mixed cropping

Increasing plant diversity including crops and accompanying plants is a widely used strategy in regenerative agronomic systems aiming, amongst other things, to increase net primary production. Increased net primary production in plant diverse ecosystems has been widely studied in grasslands (Venail et al., 2015), in some tree crops (Cierjacks et al., 2016) and in intercropping systems (García-Palacios et al., 2019). Increased net primary production will increase both above and belowground soil organic matter inputs and will thus enhance C sequestration (Johnston et al., 2009). Indeed, previous reports of low plant productivities were most likely due to mining of nutrients retained in protected fractions of soil organic matter (Romanyà and Rovira, 2007; Romanyà et al., 2017). Multicropping and mixed cropping involve increasing crop diversity either in space or in time, and their use will contribute to both increasing crop yield and to ameliorating soil structure. Some plant species have greater abilities to penetrate a dense clod or soil layer and make it porous. In highly degraded soils the use of thick rooting crops or the transitory use of natural vegetation with high rooting capacity will help in improving subsoil layers or compacted zones of soils (Yunusa and Newton, 2003). On the other hand, the increased carbon availability in improved soils will promote non-symbiotic nitrogen fixation (Schleuss et al., 2021) and contribute to some extent, to plant nitrogen supply.

5.1.4. Application of manures and compost

Manures. Manures have been applied to soils since antiquity, often combined with crop residues, and such a mixture may be applied to soil in an advanced state of composting. Therefore, it is very difficult to separate both practices when reviewing the current situation.

The response of crop yields to manures is plant species dependent. At any rate, manuring seems essential to ensure crop production when mineral fertilisers are not widespread.

Addition of manures or compost to soils is widely seen as compulsory to increase SOC levels to a relevant level, usually combined with nitrogen-phosphorus-potassium (NPK) nutrition (Yan et al., 2007; Rasool et al., 2008; Mahanta et al., 2015; Prashanth et al., 2021). A relevant approach was given by Yan and Gong (2010), who concluded that, while SOC sequestration is better ensured by the addition of organic amendments, crop yields are better ensured by mineral fertilisation (NPK). Of special relevance is their observation that a treatment including half the NPK dose plus half the OM dose resulted in almost the same crop yield than the complete NPK dose, suggesting that a strong reduction in the use of NPK fertilisers is possible.

Manure addition is also recommended in no-tillage (NT) management (Roberson et al., 2008; Sainju et al., 2008). As mentioned before, a problem of NT systems is that the increases in SOC content occur mainly at the top of the soil profile (first 5 cm), which may become easily carbon saturated. The addition of manures facilitates translocation of SOC from the C-saturated layers to the underlying, not C-saturated layers. In this way, the capacity of soils to accumulate and stabilise C is more far-reaching (Nicoloso et al., 2018).

Manures improve soil physical properties, in particular aggregation. The abundance and activity of earthworms, which particularly improve soil physical properties, is also enhanced by soil manuring (Leroy et al., 2007). The added manures and/or compost become stabilised in soil through incorporation into the organo-mineral complex (for soluble components) or occlusion into microaggregates (for POM). This is an important detail, because in soils not prone to aggregation (e.g. highly sandy soils) the stabilisation of the added manures or compost is very difficult. When soils have enough clay and fine silt to generate aggregates and stabilise the added amendments, the addition of manures or composts generally results in an increase in SOC content (Lejon et al., 2007).

Passive strategies for manuring fields may be envisaged to avoid the cost in fuel of spreading manures or compost along the crop fields. Thus, the temporal corralling of herds (sheep, goats) into crop fields, allowing them to directly enrich the soil with their manure, is a very effective option widely practised in developing countries, and also traditionally in European areas such as the Pyrenees (Taüll, pers. comm.). In arid countries, the effect of such corralling on SOC stock is highly relevant in the first 5 years (Freschet et al., 2007) though effects could be shorter lasting in more humid areas.

Compost (versus) manure. To attain relevant levels of SOC sequestration, organic amendments must be chosen carefully: different organic amendments decompose in soil at very different rates (Costa et al., 1989; Levi-Minzi et al., 1990). Quickly decomposed amendments enhance soil microbial activity, whereas those that are slowly decomposed are better for increasing SOC. Since both objectives are desirable, a balance between them should be attained.

Composting reduces the abundance of labile organic compounds; thus, for any given organic amendment the positive effects on SOC increase will be larger for the 'composted' variant than for the 'fresh' or 'uncomposted' variant (Fernández et al., 2007). Actually, the application of fresh or uncomposted amendments to soils – leaving aside amendments widely verified and used, such as manures – may be risky, owing to the (possible) presence of toxic organic components (e.g. Beauchemin et al.,1992; Makni et al., 2010), or highly labile organic fractions capable to drive a 'priming effect' and provoke the accelerated decomposition of the native soil organic matter, eventually resulting in SOC losses.

Composting needs physical space, time and sometimes also energy and physical work. For instance, some composting methods may need the composting pile to be moved and re-built, at least once. These operations have a cost. Because of these needs, any compost will be necessarily more expensive than the original starting material from which it has been obtained. On the other hand, composting is a form of decomposition, and therefore it involves the loss of part of the organic matter. So, overall, compost is inevitably less abundant and more expensive than manures, and this makes its wide use in agriculture less common, except for some crops involving high benefit.

5.1.5. Integration of municipal waste to agricultural practices: the use of urban refuse compost (URC)

Composting is the predominant municipal bio-waste treatment in Europe. With the publication of the soil fertilisers EU regulation (2019/1009) the EU has paved the way for using the composted products of bio-waste collected separately at the source as organic amendments. The increase of separate biowaste collections and their composting, in many European countries, will soon make increasingly available high quality biowaste compost of agronomic interest.

Urban refuse compost is a compost of a very special type, not generated from livestock manures but from the organic fraction of urban rubbish. At first sight, URC looks like typical compost obtained from manure and plant residues, but it comes from different materials, which results in a different chemical composition (Pascual et al. 1999; Bastida et al. 2008; Haghighi et al., 2016; Gattullo et al., 2017; Jodar et al., 2017; Dadi et al., 2019; Srivastava et al., 2020).

At any rate, the use of URC must be restricted to countries where it is obtained under quality controls strict enough to guarantee the absence of harmful components. For instance, the absence of plastics or microplastics should be verified. The same can be applied to the levels of heavy metals or contaminant elements.

Because the degree that these conditions are accomplished is still highly unequal across the EU, the use of URC cannot yet be recommended at an EU-wide scale. Once modern and evolved composting devices for organic urban refuse become widespread, URC should be seriously considered as an alternative to manures and/or conventional composts.

When its quality has been proved, URC application in agriculture has long lasting beneficial effects, including increasing SOM and nutrient availability and the promotion of soil biological activity (Emmerling et al., 2010). A single addition of URC compost may improve soil physico-chemical properties in the long term (> 20 years), and the URC carbon becomes added to the recalcitrant SOC pool, contributing to increase soil organic matter and to reduce GHG emissions (Albaladejo et al., 2008; Razza et al., 2018).

Moreover, in compost amended soils nitrogen mineralization takes place at relatively slow rates and virtually no nitrogen leaching has been reported (Erhart and Hartl, 2010). Thus, the use of this compost can contribute to the circular economy by replacing mineral fertilisers while improving crop yields and reducing the risk of nitrate leaching (Morra et al., 2021).

5.2. Potential of innovative practices for C sequestration

5.2.1. Biochar

In the last decade, the application of biochar to soil has been investigated more intensively than any other agricultural practice. This is probably because the practice is linked to commercial interests, as it depends on a specific product currently obtained at an industrial scale by manufacturers. Unless the experiments with biochar are carried out by strictly independent research groups, there is a risk of presenting experimental results in a positive way, and not always objectively. Thus, the review of Gurwick et al. (2013) notes that the most studied topic in biochar research is how to obtain it (+160 papers), much more than the second most studied topic, which is its stability or fate (75 papers). Most experimental studies have been carried out in laboratory settings, and only a minority involved field work.

Biochar addition is the most effective method for increasing SOC content, better than cover crops or conservation tillage. This result is consistent, for all climates and all soil types, at all soil pH at all soil textures. However, the effect of biochar seems higher under warm climates (tropical and subtropical) and low-input agriculture (Bai et al., 2019), and all European soils are outside this group, suggesting that, for Europe, no remarkable effects are to be expected, either for crop production or for SOC sequestration.

In the same sense, high inputs of mineral N seem to reduce the SOC sequestration effect of biochar. Low levels of N inputs (1-100 kg N ha^{-1}) seem ideal for a maximum effect of biochar on SOC sequestration. Obviously, however, these low levels will be rarely met, since maximizing plant production will be a main concern for farmers.

The (expected) high stability of biochar is the key to its usefulness in SOC sequestration, and the main reason claimed for its use. Biochar stability in soil is highly variable, from several years to millennia (Gurwick et al., 2013), owing to highly diverse climatic conditions, highly diverse soil characteristics, variety in agricultural treatments, and variety in biochar characteristics (Spokas, 2010). The search for an ideal biochar should seek for an equilibrium between the needs of adding an organic amendment to the soil, which is stable enough to be maintained for decades, but that it is not so extremely stable that it represents an inert pool of carbon, without any influence on the soil biochemistry.

Positive effects on plant production and soil biochemistry have been widely reported (Panwar et al., 2019), but it seems proven that “certain biochars function well to improve soil, and other biochars do not. Why? Because it is not clear how to prepare the best biochar for soil” (Tan et al., 2017). Effects on microbial activity and nutrient dynamics depend on the characteristics of the biochar, which depend on how they have been obtained (Rasul et al., 2021), thus the question of whether biochars have positive effects on any soil property will have never a single, clear answer.

It is evident from the previous paragraph that there is an urgent need for sound criteria for biochars. Due to the variety of their effects, depending on their precise composition, it is necessary to establish several classes of biochar; these classes should enable commercial labelling of the biochars currently available in the market. For a reader (such as an agronomist, or a well-informed farmer) the label should inform about the main properties of the biochar, and therefore should predict the effects of this biochar on soil fertility. Several proposals for this have been made. Thus, the International Biochar Initiative (Westerville, Ohio, USA) suggested classifying biochars according to their carbon content, fertiliser value and particle size distribution. Further, it has been suggested to classify biochars according to their organic carbon content (Klasson, 2017).

The establishment of sound criteria for 'qualifying' biochars should be a previous condition for the proliferation of their use at the EU scale. Without a system of biochar labelling and qualification, a generic recommendation about using biochar in European croplands as a method of increasing SOC stocks would be very risky.

A final consideration about biochar is its energetic cost. Owing to the variety of methods for obtaining biochar, its energetic cost is highly variable. According to Alhashimi and Aktas (2017), the energy needed to obtain biochar is less than 1/10 that needed to obtain activated carbon. Biochar seems, thus, not particularly costly in energetic terms. It is worth, however, giving a close look to this problem. If the cost of biochar, in CO_2-eq terms, is higher than the net SOC gains we expect to obtain, then the use of biochar will make no sense, in terms of carbon economy.

5.2.2. Precision agriculture (PA)

The term 'precision agriculture' is often used to refer to the measuring techniques applied (up-to-date and advanced), rather than to specific agricultural practices applied at specific times and moments, and in specific ways. Enhancing SOC sequestration does not seem a main concern for the researchers working under the PA label, which makes it difficult to assess whether the practices and principles of PA may substantially contribute to the goal of enhancing the carbon sink of European agricultural soils. Despite this, several principles of PA should contribute to that goal, if properly applied.

Increased precision in the amount and timing of the addition of mineral fertilisers (NPK) should avoid excess nutrient in soils, and therefore losses of nutrients through leaching, particularly nitrogen (N). This will be beneficial because N is usually added to soils in massive amounts as ammonium (NH_4^+), and a substantial part of it undergoes nitrification (oxidation to nitrate). The biochemical process of nitrification generates free protons (H^+) and thus contributes to soil acidification. This may be a serious problem in the Mediterranean basin, where carbonate-rich soils are abundant. The nitrification-driven acidification of calcareous soils may destroy part of their carbonates (Datta and Mandal, 2018; Perrin et al., 2008), and the release of huge amounts of CO_2 to the atmosphere can put at risk any attempt of converting these crop soils into carbon-neutral ones. This phenomenon has been studied in China, where the soils of entire provinces, calcareous in origin, have lost all their carbonates owing to the massive use of ammonium-rich fertilisers (Raza et al., 2020). In this matter, a thorough control of the amounts of mineral fertilisers may be of great help.

5.3. Integrated sustainable management strategies for carbon sequestration and soil quality: organic farming and regenerative agriculture

As suggested in the previous section, sustainable practices must be implemented in combination for best results in carbon sequestration in soil, soil health and plant production and quality. A variety of intelligent combinations of these practices includes organic farming and regenerative agriculture.

Organic farming in Europe falls under regulation (EU) 2018/848. To maintain and improve the state of soils the regulation restricts the use of external inputs by promoting or maintaining soil life and natural fertility, stability, water retention and diversity. Because the regulation includes maintaining the soil current state, organic farmers are not necessarily obliged to regenerate or restore soil fertility. This will be a problem in organically farmed degraded soils as these soils will not necessarily be regenerated when applying the organic farming regulation. Indeed, a great part of organically farmed soils do not support high yields. However, a significant number of organically managed soils get increased yields when compared to conventionally managed systems (de Ponti et al., 2012). Thus, to improve soils there is a need to identify and apply an array of sustainable agricultural practices capable to regenerate degraded soils and to sustain agronomic production in healthy regenerated soils while sequestering a critical mass of CO_2 and promoting biodiversity in soils and cropping systems.

Despite a high variability of methods due to adaptation to local environmental and socio-economic characteristics, **regenerative agriculture** includes a variety of the above-mentioned sustainable practices with the aim of regenerating agricultural soils, increasing water quality and availability, increasing ecosystem biodiversity and resilience, and fostering carbon sequestration in soils[7]. Regenerative agriculture has identified several practices to achieve these goals addressed at both farming and grazing systems. Such practices include those used in organic farming and conservation tillage such as no till or reduced tillage, crop rotation, composting, and pasture cropping, among others.

5.4. Agricultural systems favourable to carbon storage in soil

Rodrigues et al. (2020) summarized the importance of some agricultural systems in enhancing soil carbon storage in mineral soils, among which we will consider agroforestry, permanent grasslands, and paludiculture.

5.4.1. Agroforestry

Agroforestry is the practice of combining trees with crops or livestock to increase diversity, productivity, profitability, and environmental stewardship, and is recognized as an integrated approach to sustainable land use. Agroforestry systems (AFSs) have a high potential to sequester carbon because of higher efficiency in the use of resources (light, nutrients, and water) than in single-species crop or pasture systems (Marconi and Armengot, 2020). It has been estimated that AFs have, on average, 46.1 Mg ha^{-1} more C in tree biomass compared with other agricultural land uses (Ma et al., 2020). On the other hand, the mean SOC storage rate for croplands converted to agroforestry systems has been estimated at 0.75 t C ha^{-1} y^{-1} (Cardinael et al., 2018). Several studies show that tree-based agricultural

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[7] https://foodtank.com/news/2022/01/initiative-investigates-regenerative-agriculture-across-the-u-s/; https://www.csuchico.edu/regenerativeagriculture/

systems store more C in deeper soil layers and in more stable forms (Nair et al., 2010). Mixtures of two or more plant species (trees, shrubs, or herbs) can increase soil C and N storage through mutualism (the existence of one species supports the other by assisting growth conditions) and optimal soil utilisation of single plant species resources (Marquard et al., 2009; Wu et al., 2020). Improved soil quality, through organic matter input from trees and crops also leads to increased crop yield and soil C stocks.

5.4.2. Permanent grasslands

Grasslands occupy more than a third of the European agricultural area, contain important stocks of soil C, and their use for grazing livestock provides a critical contribution to food security. Improved management of grasslands to increase soil C stock benefits soil fertility and could mitigate agricultural GHG emission and improve the resilience of the agricultural system to extreme weather events. In fact, permanent grasslands consist of land which is used permanently (for several consecutive years, normally five years or more) for growing herbaceous fodder, forage or energy purpose crops, through cultivation (sown) or naturally (self-seeded), and which is not affected by crop rotation. It is known that in these systems moderate grazing, manure returns, introducing legumes, increasing sward diversity, rotational and lower grazing or cutting intensity can minimise carbon losses, maintain soil carbon stocks, and mitigate GHG emissions (Gregory et al., 2016).

5.4.3. Paludiculture for climate-smart peatland cultivation

Climate-smart management of peatland does not demand increasing their naturally high carbon stocks but avoiding net carbon emissions to the atmosphere.

Two possible scenarios are available to reconvert European peatlands that have been degraded after desiccation for agricultural exploitation from GHG emitters to GHG sinks: rewetting and returning them to natural use and rewetting them for agricultural use while maintaining shallow water tables. Restoring managed peatlands for natural use has very high mitigation efficiency but infers a decay in agricultural production that may require being compensated by increasing production in mineral soils locally or abroad. Since totally halting peatland exploitation does not seem a viable option, paludiculture appears to be a win-win option (Joosten, 2012).

Paludiculture is a climate-friendly modality of peatland cultivation that produces biomass from wet and rewetted peatlands while preserving the peat body, thus facilitating peat accumulation and maintaining natural peatland ecosystem services (FAO, 2014). To maintain or reinstall peat formation, paludiculture requires the exploitation of only that part of net primary production (NPP) that is not necessary for peat formation (about 80-90% of NPP). Plants recommended for use in paludiculture must thrive under wet conditions, produce sufficient biomass of good quality and contribute to peat formation (Wichtmann and Joosten, 2007). Cultivation methods must be adapted to local conditions and, in general terms, to achieve a zero or negative carbon balance the whole peat layer must be water saturated throughout the year. Soil disturbance (e.g. ploughing) must be avoided if peat stocks are to be preserved.

Although rewetting peatland re-establishes the emission of methane (Abdalla et al., 2016), CO_2 emissions are reduced, and the net effect on GHG emissions is negative, therefore it should be considered as an important measure for climate mitigation (Paustian et al., 2016; Günther et al., 2020). In this sense, several paludiculture projects are emerging in Europe, mainly addressed at growing biomass for fodder, fuel production, and raw materials for construction but also for grazing with cattle adapted to wet conditions (Ziegler et al., 2021).

6. THE EU CLIMATE ACTION STRATEGY, CARBON SEQUESTRATION AND THE CAP

KEY FINDINGS

- The new common agricultural policy (CAP) contains a number of policy reforms which can prove instrumental in achieving the goals of the European Green Deal.
- Within this policy framework, a new model to reward land managers for GHG emission reductions and carbon removals could possibly be set up, notably through the carbon farming initiative.
- Member States will have to translate these policy objectives in their CAP strategic plans, including conditionality, Eco-schemes and Agri-environment-climate measures.
- Based on a first analysis of the CAP Strategic Plans submitted to the Commission, it appears that there is room for improvement regarding the level of detail of environmentally beneficial practices, the need to favour a holistic approach, the key role of peatlands and capacity building.

6.1. The EU Climate action strategy

The European Council, in its conclusions of 12 December 2019, agreed on the objective of achieving a climate-neutral EU by 2050, in line with the objectives of the Paris Agreement. On 4 March 2020, as part of the European Green Deal, the European Commission adopted a legislative proposal for a European Climate Law[8] that sets the objective of a decarbonised EU economy and establishes a framework for achieving that objective.

Negotiators from the European Parliament (EP) and the Council reached a provisional deal on this new EU Climate Law on 21 April 2021, including a target for net greenhouse gas (GHG) emissions reduction of at least 55% by 2030 compared with the 1990 level (as foreseen by the 2020 new EU Climate Target Plan).

In the context of the “Fit for 55” package, launched in June 2021, the Commission will now engage with sectors to prepare specific roadmaps charting their path to climate neutrality.

With this end in view, the Commission shall proceed to the quantification of the mitigation potential in agriculture up to 2030, which will include reductions in GHG emissions, effects of land use changes and carbon storage in agricultural soils. An integrated policy framework covering agriculture, forestry, and land use (AFOLU) is proposed from 2030 with the view of achieving carbon neutrality in these sectors by 2035. Regarding the Land Use, Land Use Change and Forestry sector (LULUCF) as a whole, the Commission proposed to amend the policy framework by setting an EU target for net annual removals of 310 Mt CO_2-eq by 2030 and setting targets for each Member State, with the aim of reaching climate neutrality in the entire land sector by 2035.

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[8] commission-proposal-regulation-european-climate-law-march-2020_en.pdf (europa.eu).

Negotiators from the EP and the Council agreed, in line with the Paris Agreement, to give priority to emissions reductions over removals in the EU Climate Law to reach the 2030 target[9]. However, they also stated that the Union shall aim to achieve a higher volume of carbon net sink by 2030.

For this reason, carbon sequestration in agriculture has become an objective of the Union's climate policy, as highlighted in the Commission's communication on '*Stepping up Europe's 2030 climate ambition*'[10] which states that '*carbon farming and certification of carbon removals should increasingly be deployed in the run up to 2030*'. This is in line with the new Common Agricultural Policy (CAP) legislative framework and the more recent '*Farm to Fork strategy*' and its Action 12 which foresees an "EU carbon farming initiative (see below). Finally, carbon sequestration has also been included in the '*taxonomy regulation*' as an economic activity which shall qualify as contributing substantially to climate change mitigation [11].

6.1.1. The Green Deal and the EU-27 agricultural sector

A key objective of the EU's Green Deal is to promote a new green business model to reward land managers for greenhouse gas (GHG) emission reductions and carbon removals.

- GHG emissions: for agriculture, reductions will be achieved through agreed national emissions targets, which are calculated, based on the country's gross domestic product per capita. Agricultural non-CO_2 GHG emissions are covered by the Effort Sharing Regulation (ESR), while Agricultural CO_2 emissions/removals are covered by the LULUCF Regulation. The latter are mainly related to changes in carbon stored in soils and biomass due to cropland and grassland management practices. Member States should follow a 'no-debit' rule set in the Regulation. In other words, they must ensure that credits, or accounted removals from all land-use categories within the LULUCF sector, compensate debits, or accounted emissions, in the period of 2021 - 2030. Member States will retain a certain flexibility in dividing the effort between the ESR and LULUCF sectors. In order to assure the compliance of such objectives by Member States, national adaptation strategies and plans should be adopted, implemented and regularly updated. Those must be based on robust climate change and vulnerability analyses, progress assessments and indicators, and guided by the best available and most recent scientific evidence.

- Carbon removal through the carbon farming initiative[12]: the Commission has committed to developing a robust and transparent regulatory framework for accounting and certification of carbon removals, while ensuring no negative impacts on the environment, public health and social or economic objectives (EC COM(2020) 493 final). In February 2022, 68 ministers meeting in the 14th Berlin Agriculture Ministers' Conference on 'Sustainable Land Use: Food Security Starts with the Soil'[13] declared their intention to 'maintain or increase the stocks of soil organic carbon by supporting agricultural practices that sequester carbon while improving soil health and water holding capacity'.

There is a need to increase the capacity of the EU's forests, soils, wetlands and peatlands to act as carbon sinks and stocks. In the agricultural sector it is also necessary to regenerate the quality of soils to ensure food security. These aims are directly related to the new **EU Biodiversity Strategy**, which includes

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[9] In order to ensure that sufficient efforts to reduce and prevent emissions are deployed until 2030, they introduced a limit of 225 metric tons of CO_2 equivalent to the contribution of removals to the net target : European climate law: Council and Parliament reach provisional agreement - Consilium (europa.eu).

[10] EUR-Lex - 52020DC0562 - FR - EUR-Lex (europa.eu)

[11] Regulation 2020/852 (OJ 22.5.2020, L198/13), article 10.1.(f), which focuses on carbon sequestration : "*strengthening land carbon sinks, including through avoiding deforestation and forest degradation, restoration of forests, sustainable management and restoration of croplands, grasslands and wetlands, afforestation, and regenerative agriculture*" (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0852&from=EN)

[12] https://ec.europa.eu/clima/news-your-voice/news/commission-sets-carbon-farming-initiative-motion-2021-04-27_es

[13] https://www.gffa-berlin.de/en/berliner-agrarministerkonferenz-2/

actions to put nature on a path to recovery by 2030 (COM/2020/380 final). The new strategy aims to strengthen the implementation of existing biodiversity policies, but also to introduce new initiatives, such as the **EU Nature Restoration Law**[14]. Other initiatives partially related to agriculture are the new **EU Forest Strategy** (COM/2021/572 final) presented together with the Fit for 55 package.

On November 2021, the EC published the **EU Soil Strategy for 2030** (COM/2021/699 final), a non-legislative document that refers to the abovementioned policies, the Zero Pollution Action Plan and the new EU CAP. The Strategy is a first step towards a legislative proposal on soil health which, in combination with the future Nature Restoration Law aims to have soil health in a good condition across the EU by 2050. Some of the actions the EC promoted under the Soil Strategy (to limit drainage of wetlands and organic soils, to present a legislative proposal on carbon removal certification in 2022 to promote a new green business model, and to prepare a set of sustainable soil management practices) are of crucial importance for the agricultural sector and are also partially covered by the CAP[15].

Finally, the **Farm to Fork strategy** (COM/2020/381 final), also part of the Green Deal, set out ambitious targets including reducing nutrient loss by 50% and chemical fertiliser use by 20% by 2030, as well as an increase in the land area used by organic agriculture to make up 25% of total agricultural land. Through this reduction in fertiliser use, together with the increasing use of high-quality organic fertilisers, half of all agricultural GHG emissions could be prevented (Beste, 2021).

6.1.2. The EU carbon farming initiative

The EU carbon farming initiative acknowledges the fact that maintaining and increasing European SOC stocks is a multidimensional action that will benefit climate change mitigation while contributing to soil biodiversity and fertility, food security, water protection, agricultural resilience and the circular economy (Lal et al., 2007; Montanarella, 2015; Montanarella and Panagos, 2021). Developing strategies to support EU farmers in preserving and increasing their soil C stocks goes beyond delivering environmental benefits and shows great promise for fuelling new green business on "Sustainable C Cycles" (EC COM(2021) 800 final).

Based on the final report of a two-year study on how to set up and implement carbon farming in the EU published in April 2021, the Commission launched the carbon farming initiative in December 2021 through the adoption of its Communication on Sustainable Carbon Cycles.

This communication sets out short- to medium-term actions aiming to address current challenges to carbon farming in order to upscale this green business model that rewards land managers for taking up practices leading to carbon sequestration, combined with strong benefits for biodiversity. These include:

- promoting carbon farming practices under the CAP and other EU programmes such as LIFE and Horizon Europe, in particular under the Mission "A Soil Deal for Europe", and under public national financing;

- driving forward the standardisation of monitoring, reporting and verification methodologies to provide a clear and reliable framework for carbon farming;

- providing improved knowledge, data management and tailored advisory services to land managers.

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[14] https://ec.europa.eu/environment/system/files/2022-01/EU-restoration-targets-consultation-strategy.pdf

[15] https://www.farm-europe.eu/travaux/eu-soil-strategy-for-2030-%E2%80%A8reaping-the-benefits-of-healthy-soils-for-people-food-nature-climate/

It builds on the above-mentioned preparatory study (‘Technical Guidance Handbook – setting up and implementing result-based carbon farming mechanisms in the EU‘), which reviewed existing schemes that reward climate-related benefits in five promising areas:

- peatland restoration and rewetting;
- agroforestry;
- maintaining and enhancing SOC in mineral soils;
- managing SOC in grasslands and
- livestock farm carbon audits.

It also explored how a widespread adoption of carbon farming can be triggered in the EU.

6.1.3. Key factors for success

The EU Green Deal includes many promising elements to reduce EU agricultural emissions. However, questions remain over whether new policies will be sufficient to meet the ambitious targets, and how to navigate around complex issues.

In fact, the results of the **carbon farming initiative** will depend on the targets for agriculture and land use set by the 2021 European Climate Law and the Fit for 55 package. It remains to be seen if the Initiative, together with the Carbon Removals Certification Mechanism, will cope with setting sectoral targets and with robust and transparent monitoring and verification of agricultural mitigation (McDonald et al., 2021a).

There are close links between carbon farming and biodiversity that could lead to both favourable and conflicting situations. **The Habitat Directive** could be used to implement biodiversity-friendly carbon farming actions, since 40% of the Natura 2000 area is farmland. However, the Nature Directives also set out obligations for Member States for protecting habitats and species outside designated Natura sites. There are over 50 habitat types and 260 protected species under the Habitats Directive that are closely associated with agriculture (EC, 2017). To ensure common benefits, carbon farming must be designed, targeted and implemented in a way that ensures it also achieves biodiversity outcomes by monitoring biodiversity impacts and considering the local context (McDonald et al., 2021b). For example, where carbon farming leads to restoration of degraded habitats, it would be surely in line with the objectives of the EU Biodiversity Strategy and EU Nature Restoration Plan. However, in order to maintain SOC and healthy soils, the focus must be on soil fertility, ecosystem services and greater resilience to climate change, and not solely on CO_2 sequestration (Beste, 2021).

A good example are **Peatland ecosystems**, covered by thirteen different habitat types in the Habitats Directive (EC, 2020). Apart from soils in permafrost regions, peatlands and grasslands contain the largest part of the carbon stored in soils. Restoring these habitats and maintaining them under the obligations of the Directive have positive consequences for biodiversity and for the climate. Another related potential conflict is the reduction of animal numbers due to their methane emissions. Ruminants are essential for the protection of **grasslands** because only grazed grassland will persist and the more regularly it is grazed, the more SOC is built up (Beste, 2021). **Agroforestry systems**, including long established silvo-pastoral systems, also are included in the Directive and show great potential across a large area of farmland across the EU. These systems can deliver carbon sequestration and can provide wider benefits for ecosystem services and biodiversity (COWI, Ecologic Institute and IEEP, 2021).

6.2. CAP instruments for enhancing carbon sequestration in soils

The post 2020 CAP reform offers MSs opportunities to promote soil carbon conservation and sequestration in agricultural soils while contributing to good soil condition and a green economy (Massot Martí, 2020 and 2021).

6.2.1. Lessons learned from previous CAP periods: CAP failure in reducing agricultural carbon emissions during the 2014-2020 period

The 2021 evaluation of the environmental performance of the CAP in the 2014-2020 period (ECA, 2021) highlighted that the €100 billion invested in climate action failed to reduce agricultural GHG emissions, that overall, carbon removal by mineral soils and carbon released from organic soils remained stable from 2010 to 2018, and that the CAP measures did not lead to an overall increase in carbon content stored in soils and plants.

Failure might be attributable, amongst other factors, to contradictory stimuli (such as allowing farmers that cultivate drained organic soils to receive direct payments, while not always funding peatland rewetting), to supporting practices with unclear impacts on emissions (such as those related to soil fertilisation and organic farming), to allocating direct payment to high input production (Pe'er et al., 2020), and to inefficient management of soils (as in the case of peatlands drained for cultivation). On the other side, in recent years, mitigation policies and efficiency gains have reduced the emissions intensity of agriculture, but this has been offset by an increase in agricultural production.

Further increase in soil C stocks requires greater uptake of supported measures amongst farmers which in turn demands policies to provide holistic support to farmers to overcome barriers.

Despite the reduced number of enrolled farmers, in 2016, CO_2 removals attributable to CAP measures amounted to 20.2 Mt CO_2-eq, whilst emission reductions were 6 Mt CO_2-eq. These removals were due to changes in soil carbon stocks and in N_2O emissions from soil and manures (Alliance Environment and Ricardo, 2019) which reinforces the important role of managing agricultural soils for climate mitigation.

6.2.2. The new CAP (2023-2027)

The new Common Agricultural Policy adopted in December 2021 and due to be implemented as of 2023, paves the way for a fairer, greener and more performance-based agriculture. The new CAP looks for a sustainable future for farmers, especially for smaller farms, and provides greater flexibility for Member States to adapt measures to local conditions. Each EU country has recently designed a national CAP strategic plan around national needs and capabilities, combining funding for income support, rural development, and market measures through a toolbox of broad policy measures provided by the Commission. The new CAP legislation includes a common set of indicators for performance, monitoring and evaluation that will be monitored through annual reports and a biannual review of the progress of Member States' strategic plans[16].

In any case, the main and more discussed set of reforms are focused on mitigating the climate and environmental impacts of agriculture. The new CAP contains a number of policy reforms, in line with environmental and climate legislation, to support the transition towards sustainable agriculture and forestry in the EU, making a much stronger contribution to the goals of the European Green Deal. Each EU country is obliged to display their own national CAP strategic plan, including national targets against the agriculture-related EU Green Deal targets under the precept of no "backsliding" (higher ambition on the subject compared to the previous programming period). Also, national plans will be required to

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[16] https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/new-cap-2023-27_en

monitor and evaluate the performance of the plan with transparency and with the involvement of civil society, and thus provide updates when legislation is modified[17].

Three policy tools to be included in the national strategic plans of MSs could prove instrumental in promoting carbon sequestration:

Conditionality requires all farmers to maintain certain environment- and climate-friendly practices (such as the protection of grasslands, peatlands, buffer strips along rivers, soil cover, crop rotation and biodiversity spaces) to qualify for direct support. It replaces the cross-compliance mechanism and 'greening' requirements, by setting strict and common rules in conditionality and shall ensure that the CAP does not fund unsustainable practices and production systems.

Eco-schemes, where farmers are paid for applying climate-and environment-friendly farming practices and approaches (such as organic farming, agroecology, carbon farming, etc.) as well as animal welfare improvements. Such actions will make up 25% of the direct payment budget, although member states only have to commit 20% of the budget during the first two years after the CAP takes effect. Any money between 20-25% that MSs do not spend can be transferred to second pillar funding for other environmental and climate action measures.

Agri-environment-climate measures. Through the CAP's second pillar, 35% of the budget will go towards climate, biodiversity, environment, and animal welfare measures, implemented through voluntary schemes (agri-environmental climate measures), organic farming, Natura 2000 sites, environment-related investments, and support to areas with "natural constraints" for farming, such as mountainous regions.

6.3. CAP instruments to stimulate carbon sequestration in agricultural soils

In order to amend the gaps identified by the impact assessments of previous CAP periods, the new framework proposes two main novelties: shifting towards a more performance-based delivery model and giving much more responsibility to MSs for determining how to achieve EC overarching objectives through National Strategic Plans tailored to local conditions (Hart et al., 2018).

The most evident innovation for the 2023-2030 period is the central importance assigned to MSs to define the deployment of the CAP objectives in their territory, including different approaches to efficient management of natural resources.

It is worth noting again that, under this new framework, the "greening" measures of the 2014-2020 CAP period will be transformed into Good Agricultural and Environmental Conditions (GAECs) standards, as is the case of GAEC 1 (Maintenance of permanent grassland), of great importance for soil C dynamics. This displacement is not trivial, since the old "greening" requirements will be now equated with GAECs and transferred into the cross-compliance system. The "cross-compliance" term is also going to disappear in the renewed CAP to be substituted by "Conditionality", a system under which beneficiaries receiving direct payments who do not comply with the statutory management requirements (SMR) and the standards for GAECs will be given administrative penalties (Raffelsiefen, 2021).

One more novelty for the 2023-2027 period refers to the eco-schemes, that will be eligible for direct payment under the first pillar. Enrolled farmers will be paid annually on eligible hectares. Practices oriented to foster efficient management of soil are eligible for eco-schemes. In addition, at least 35% of CAP rural development funds will be allocated to agri-environmental commitments to support

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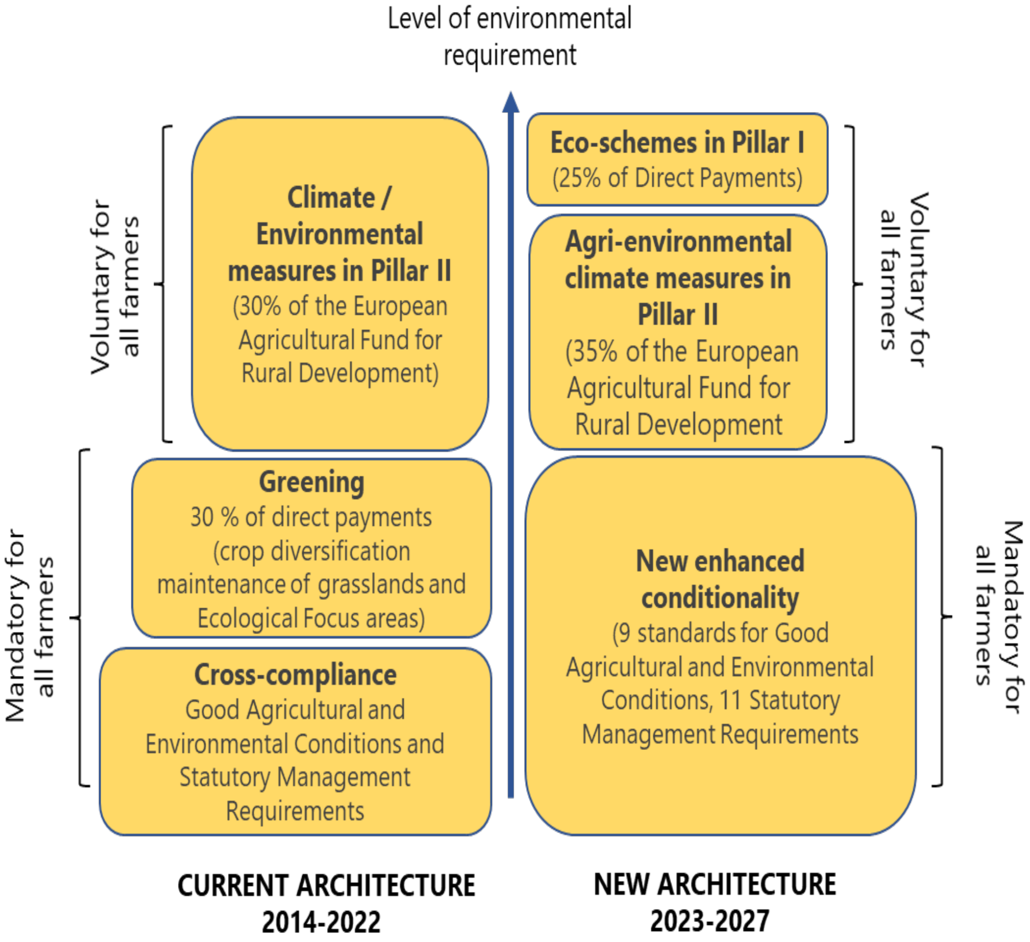
[17] https://www.carbonbrief.org/qa-will-eu-common-agricultural-policy-reforms-help-tackle-climate-change

complementary environmental legislation on nitrates (91/676/EEC Directive), water (2000/60/EC Directive), pesticides (2009/128/EC Directive), biodiversity (92/43/EEC Directive) and climate (EU 2021/1119 Law).

Among the three types of environmentally friendly interventions of the new CAP (***Figure 10***), conditionality was well established in previous CAP periods, but the eco-scheme is a new tool that can be customized and adapted by MSs, while being 100% financed by EU funds (Lampkin et al., 2020).

Figure 10: Main changes in the CAP green architecture.



Source: Meredith and Hart, 2019.
Current subsidy schemes (left) and the proposed new structure (right) ranked by level of environmental requirements.

The reformed CAP wants to shift from compliance towards performance, as well as from action-based towards result-based schemes. In the new performance-based approach, MSs will have to report their achievements each year relative to the settled objectives using Annual Performance Reports. Under this approach, Strategic Plans will be required to include robust monitoring and reporting frameworks, based on an adequate set of result indicators. The indicators proposed to evaluate progress toward carbon stocking in soil and GHG emission reduction in agriculture are listed in ***Table 6.***

Table 6: Proposed indicators to evaluate progress toward carbon farming

EU Specific objectives	Impact Indicators	Result Indicators
Climate change adaptation and mitigation	Contribute to climate change mitigation: reducing GHG emissions from agriculture	Reducing emissions in the livestock sector: share of livestock units under support to reduce GHG emissions and/or ammonia, including manure management
	Enhancing carbon sequestration: Increase the soil organic carbon	Carbon storage in soils and biomass: Share of agricultural land under commitments to reducing emissions, maintaining and/or enhancing carbon storage (permanent grassland, agricultural land in peatland, forest, etc.)
Foster sustainable development and efficient management of natural resources	Reducing soil erosion: percentage of land with moderate and severe soil erosion on agricultural land	Improving soils: share of agricultural land under management commitments beneficial for soil management

6.4. Potential effectiveness of the diverse CAP mechanisms on C sequestration in soils

6.4.1. Conditionality

Enhanced conditionality with increasingly ambitious basic requirements means farmers must fulfil environment- and climate-friendly requirements and standards in order to receive income support. This proposed conditionality is stricter than the current systems of cross-compliance and 'greening' and sets a higher baseline for the proposed measures. However, basic requirements are lower, putting at risk the capacity of the CAP to tackle climate change and protect the environment.

6.4.2. The eco-schemes

If carbon sequestration in soils is to be further stimulated, shifting from compulsory and action-based to voluntary result-based schemes is a promising but also risky effort (***Table 7***).

Table 7: Exemplary eco-schemes from different sources

EC, 2021		Lampkin et al., 2020	RICARDO-AEA, 2016
Agro-ecology	Crop rotation with leguminous crops	Rotation with legumes	Biological N fixation in rotations and in grass mixes
	Mixed cropping - multi cropping		

	Cover crop between tree rows on permanent crops - orchards, vineyards, olive trees - above conditionality	Grass cover in permanent crops	
	Winter soil cover and catch crops above conditionality	Mulching regime	Leaving soil residues on the soil surface
		Over winter stubbles	
		Green or vegetative cover	Use cover/catch crops
	Low intensity grass-based livestock system	Restricted management dates (grass)	
		Grazing regime	
	Mixed species/diverse sward of permanent grassland for biodiversity purpose (pollination, birds, game feedstocks)	Maintain area of land out of production	
	Practices and standards as set under organic farming rules	No machinery	
		Ploughing-in of crop	
		Tillage regime	Reduced Tillage
Agro-forestry	Establishment and maintenance of landscape features above conditionality		New Agroforestry
	Establishment and maintenance of high-biodiversity silvo-pastoral systems		
High nature value (HNV) farming	Shepherding on open spaces and between permanent crops, transhumance and common grazing	Shepherding	
	Semi-natural habitat creation and enhancement	Take land out of production	Woodland Planting
		Strips or patches for wildlife	
	Reduction of fertiliser use, low intensity management in arable crops	Restricted management dates (crop)	
		No tillage	Zero tillage
		Fallow	
		Limits to fertiliser application or specified regimes	Improved nitrogen efficiency
	Conservation agriculture		

Carbon farming	Rewetting wetlands/peatlands, paludiculture		Wetland/peatland conservation/restoration
		Restriction on peat cutting	
	Minimum water table level during winter	Water level management	
	Appropriate management of residues, i.e. burying of agricultural residues, seeding on residues		
	Establishment and maintenance of permanent grassland	Maintain permanent pasture	Conversion of arable land to grassland to sequester carbon in the soil
	Extensive use of permanent grassland		
Precision farming	Nutrients management plan, use of innovative approaches to minimise nutrient release, optimal pH for nutrient uptake, circular agriculture		Use of nitrification inhibitors
Improve nutrient management	Implementation of nitrates-related measures that go beyond the conditionality obligations	No fertiliser application	Soil and nutrient management plans
	Measures to reduce and prevent water, air and soil pollution from excess nutrients such as soil sampling if not already obligatory, creation of nutrient traps	No lime application	
		No growth regulators	
		Limits to PPP or specified regimes	
		No PPP	
Other practices beneficial for soil	Erosion prevention strips and wind breaks	Runoff furrows	
		Non-riparian buffer strip	Management of existing woodland, hedgerows, woody buffer strips and trees on agricultural land
		Erosion prevention strips	
	Establishment or maintenance of terraces and strip cropping	Riparian buffer strips	
		Irrigation management	
		Training of farmers	

A basic rule of the eco-schemes is that participation is voluntary and thus farmers' willingness to participate is central to achieving the climate CAP objectives. A recent study maintains that the most favourable scenario for eco-scheme adoption are farms in marginal areas if the eco-scheme demands preserve the ongoing low intensity practices. On the contrary, where the eco-scheme requires that intensive farmers shift towards climate-friendly practices that impede increasing the productivity of land (e.g. tillage cessation in intensive cereal crops), fixed payments based on forgone income may not be sufficient to lead them to comply fully with the scheme conditions (Hasler et al., 2022).

Farmers might also feel reluctant to engage in result-based schemes, due to several factors, among which are the increasing risks of non-compliance outside their control or the sensation of having their farms exposed to public inspection (Matzdorf and Lorenz, 2010). Surveys conclude that the level of payment offered is of primary motivational importance for farmers' choice. Other key factors are the availability of consistent information about the scheme, technical advice or extension services, access to reliable data about the actual effects of their practices, opportunity to learn new skills, and positive examples from agricultural leaders and neighbours (Lastra-Bravo et al., 2015). Issues of legitimacy and transparency in monitoring and auditing, together with complexity, inflexibility and administrative burdens are important barriers to eco-scheme uptake across Europe. Enhancing local social capital, facilitating knowledge transfer to, and between farmers, providing opportunities for participation in policy design, and transparency in policy implementation, must be seen as priorities for policy makers when promoting eco-schemes (Brown et al., 2021; German et al., 2021).

The profitable design of result-based voluntary eco-schemes is open to improvement by MSs in many other ways (Meredith and Hart, 2019):

- In result-based schemes, payments for C sequestration must go further than compensating farmers for additional costs incurred and income foregone resulting from the commitments made. This approach is not appropriate for flexible eco-schemes, where the same environmental outcome may be delivered through different combinations of practices with different costs. Payments must reward farmers for environmental goods provided and incentivise them. Together with public support, auctions and environmental markets have the potential to improve the cost-effectiveness of agri-environmental schemes (Matzdorf and Lorenz, 2010; Burton and Schwarz, 2013).
- Significant positive results will be more likely if MSs design their eco-schemes at the landscape level to optimize the functioning of the whole agricultural sector over wide areas. MSs must ensure that a variety of management actions are available to farmers, leading beyond conditionality and applicable to a whole range of environmental and economic situations.
- To effectively shift towards a result-based CAP, strategic planning, and effective monitoring, reporting and verification (MRV) programmes will be crucial. Implementing these programmes will require significant investments by the MSs in research, training, and capacity building. Contradictory stimuli arising from sectoral consideration of environmental objectives (e.g. climate mitigation versus biodiversity conservation) will lead to unwanted waste of resources and efforts. International experience in carbon credits issued for C sequestration through soil management suggests that the support of certified public labs may be essential to facilitate soil monitoring under unified quality standards at affordable prices free from market speculation.
- Reliable MRV plans at the farm scale must be based on sensitive and cost-effective indicators. Evaluating the real effects of farming practices on carbon sequestration in soil is particularly challenging, and minimizing bureaucracy and complexity is essential to prevent excessive transaction costs that will discourage farmers from innovation (ECA, 2011; Burton and Schwarz, 2013).
- In carbon oriented, result-based schemes, transaction costs, including MRV and financial transaction expenses can amount to 3 to 85% of total carbon credit value (with monitoring and verification comprising up to 42% of the transaction costs). These costs can be lowered through

pooling individual farmer contracts into a larger project. In long-term contracts, transaction costs will also decrease over time as farmers and policy makers find new ways to minimize the time and resources needed to assess compliance with promises (Henderson et al., 2022). Also, innovation in favour of sequestering C in soil requires substantial investment by farmers in terms of renewing machinery but mainly in increasing their skills and building-up knowledge, which requires time. Short-term contracts bring a risk that farmers are not compensated by this investment (Burton and Schwarz, 2013).

The success of result-based payments is strongly affected by appropriate advisory support to farmers which in turn demands adequate backing to advisers in terms of formation and inclusion in the design of strategies, as well as sufficient support to research for innovation (Moxey and White, 2014). MSs are required to programme Farm Advisory Services (FAS). A sound integration of FASs into the national Agricultural Knowledge and Innovation Systems (AKIS), and the proper delivery of the produced data to the AKIS will be of key importance to improve MRV plans. EU national AKISs must cooperate for better international integration to stimulate knowledge flows (EU SCAR AKIS, 2019; Knierim and Prager, 2015).

6.4.3. Agri-environment-climate measures

Part of the Rural Development Support aims to enhance environmental conditions of ecosystems, promote resource efficiency, and help us move towards a low carbon, climate resilient economy.

Soil-oriented agri-environmental and climate measures, including organic farming, can have specific effects on soil quality and seem well suited to facilitate the development and adoption of carbon farming schemes in the EU. While they until now included action-based schemes, they will provide a relevant framework to implement results-based schemes under the CAP for 2023-2027, which now focuses on performance (as opposed to compliance in the previous programming periods). Rural development measures can in particular be used:

- to promote farming practices with carbon farming potential, notably in the four priority areas mentioned in the European Commission's carbon farming initiative: peatland restoration and rewetting, agroforestry, maintaining and enhancing soil organic carbon in mineral soils and managing soil carbon on grasslands.

- to support knowledge transfer, advisory services and co-operation.

Regarding in particular peatlands, a significant barrier to uptake could be overcome if rewetted peatlands were made eligible for both Pillar I direct payments and rural development interventions in the upcoming programming period.

6.4.4. Other key reforms

Careful coordination between different types of CAP payments is essential. Payments granted in the form of a top-up for basic income support must not challenge environmental and climate ambitions. Whilst some elements of flexibility can prove useful, other proposed aspects risk undermining effective expenditure on environment and climate under these schemes, because they would allow resources for environment and climate to be re-allocated to other payments under the first pillar, resulting in a lower impact on climate and environment. Eco-schemes must be designed to be compatible and complementary with agri-environmental and climate friendly organic farming measures, included in Pillar II. For example, in the eco-scheme, payments are made per hectare and annually, which is particularly conflicting for carbon sequestration projects, that yield results in the long-term. Multi-year agreements may be desirable to provide security both to farmers and managers.

The common set of indicators for performance, monitoring and evaluation that will be monitored through annual reports must be credible and robust to steer the plans in the agreed direction. In order to facilitate the process once proven satisfactory, the Council proposes to limit the performance review to 2025 and 2027 on a reduced set of indicators, not covering all interventions or full expenditure. This change may reduce the potential to achieve tangible results.

The expected contribution of the CAP to the Farm to Fork and Biodiversity strategies must be assured and maintained. The sustainability of future EU food systems is rooted in farmers' ability to deliver on these strategies. The CAP can make a substantial contribution to the targets set out in these strategies, but only if the Member States' strategic plans reflect the targets. The Commission should therefore regularly verify the coherence of the different Strategic Plans with the Green Deal targets as well as monitor progress towards these targets through the proposed evaluation framework for the CAP.

6.5. CAP tools for Carbon sequestration in the Member States' Strategic Plans

6.5.1. CAP tools for Carbon sequestration

The EU provided a series of parameters to Member States in order to adapt their own CAP strategic plans to the necessary common guidelines. Although the focus of this report is on carbon sequestration, EU obligations are also related to EU Treaties and other aspects of Sustainable Development Goals (SDG). These parameters were mainly: to set clear objectives and types of interventions and agreed targets on basic requirements. This responsibility means also more accountability for such measures through monitoring and reporting (including measurable indicators) as well as controls and penalties.

As explained before, the new Green Architecture of the CAP that the different MSs should reflect in their Plans is based on three main interventions:

I. Conditionality. Standardized practices are the so-called GAECS; Good Agricultural and Environmental Conditions, which are the following (the most related to SOC sequestration are shown in **bold**):
   1) **Maintenance of permanent grassland based on a ratio of permanent grassland in relation to agricultural area** (previously greening)
   2) **Appropriate protection of wetland and peatland** (new)
   3) Ban on burning arable stubble, except for plant health reasons
   4) Establishment of buffer strips along water courses
   5) **Tillage management reducing the risk of soil degradation including slope consideration** (new)
   6) **Minimum soil cover to avoid bare soil in period(s) and areas that are most sensitive** (new)
   7) **Crop rotation in arable land** (previously greening)**, except for crops growing under water** (new, subject to European Commission approval)
   8) **Minimum share of agricultural land devoted to non-productive features or areas** (previously greening)
   9) **Ban on converting or ploughing permanent grassland in Natura 2000 sites** (previously greening)

II. Eco-schemes. Managing authorities have the flexibility to use them as support to more ambitious rural development obligations, or as independent (but complementary) interventions.

III. Agri-environment-climate measures (AECM). Also available on a voluntary basis but administrated through Pillar II and thus under Rural Development Programmes.

6.5.2. Consideration of carbon sequestration under current CAP Strategic Plans

As foreseen in the EU Green Deal, the European Commission adopted a Communication on Sustainable Carbon Cycles in December 2021[18] in which it promotes the upscaling of carbon farming as a green business model and sets out a series of short to medium-term actions to address current challenges to achieve this.

The CAP Strategic Plans will be a key vehicle to promote improved land management practices that reduce GHG emissions, increase carbon sequestration and provide incentives for land managers, farmers and foresters to increase carbon removals and protect carbon stocks. We provide a brief analysis of the GAECs and eco-schemes related to carbon farming and general soil wealth included by the different Member States in the Strategic Plans already submitted to the Commission presented at the moment of writing the present report (***Table 8***).

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[18] https://ec.europa.eu/clima/system/files/2021-12/com_2021_800_en_0.pdf

Table 8: Overview of currently delivered National CAP Strategic Plans.

Country	**GAEC related to Carbon Farming**						**Eco-schemes**
	1 Permanent grassland	**2 Wetlands and Peatlands**	**5 Tillage management**	**6 Minimum soil cover**	**8 Non-productive areas**	**9 Natura 2000**	
Austria	4% from reference ratio (46.08)	Prohibition of cutting, burning, drainage and land use change	Forbidden on frozen, waterlogged or snow-covered soil and >15% slope	Depending on cultivation	4%	201,939 ha	1. **Cultivation of catch crops on arable land** 2. **Evergreen system on arable land** 3. **Protection against erosion in wine, fruit and hops** 4. **Animal welfare – pasture**
Czech Republic	5% from reference ratio (28.11)	In transition until 2025	Farmers choose the technology according to crop and production	In line with Integrated Plant Protection and organic farming	7%	1,413,530 ha	1. Farm-wide eco-payment 2. *Precision agriculture*
Denmark	5% from reference ratio (8.5)	Reduced N standard on >6% OC soils. Prohibition of ploughing on >12% OC soils	Ploughing ban when soil erosion risk >11 tonnes per ha / year	At least 60% of arable land	4% and 3%	11,000 ha	1. **Nitrogen-reducing measures** 2. **Organic area support** 3. **Environmentally and climate-friendly grasslands** 4. **Extensification with mowing** 5. Diversification of plant production 6. *Biodiversity and sustainability*

Estonia	5% from reference ratio (5.0)	Not applicable until 2025	Forbidden on more than 10% of slope	At least 30% of arable land in specific regions	All	?	1. **Green management** 2. **Ecological plan for organic farming** 3. *Eco areas* 4. *Conservation of ecosystem services on farmland* 5. Beekeeping support
Finland	5% from reference ratio (7.65)	After 2022, peatland taken from other uses become grassland	Depending on region, forbidden on more than 10-15% of slope	At least 30% of arable land	4%	3,581 ha	1. **Winter vegetation cover** 2. **Nature grasslands** 3. **Green manure grasses** 4. *Biodiversity of plants*
France	5% from 2018 reference (for each region)	Under verification	Ploughing ban on flooded soils and soils in slope	Minimum 2 months	4%	1.18 Mha.	1. **Maintenance of permanent grasslands** 2. Diversification of crops 3. **Vegetation cover in permanent crops** 4. *Organic farming certification* 5. *"High environmental value" certification* 6. Other certification 7. *Biodiversity and agricultural landscapes* 8. Sustainable management of hedges
Greece	5% from reference ratio (5.0)	Under study until 2025	Different measures depending on slope	Mandatory on more than 12% of slope	All	?	1. Use of durable and adapted species and varieties 2. *Expansion of the application of ecological focus areas* 3. *Application of ecological focus zones in arboretums*

							4. *Conservation of agroforestry ecosystems rich in landscape elements* 5. *Supporting precision farming methods* 6. **Environmental management-improvement of permanent pastures** 7. **Preservation and protection of crops in areas with terraces** 8. *Conservation of organic farming and animal husbandry methods*
Ireland	5% from reference ratio (89.82)	Under study until 2024	Different measures depending on cultivation and slope	Depending on management	4%	30,134 ha	1. *Space for Nature (Non-productive areas) and landscape features* 2. **Extensive livestock production (low stocking rate, not no stock)** 3. **Limiting chemical nitrogen usage** 4. *Planting of native trees/hedgerows* 5. *Use of a GPS controlled fertiliser spreader* 6. **Soil sampling & appropriate liming** 7. **Planting of a break crop** 8. *Planting of multi-species sward*
Italy	3.5% from reference ratio (20.0)	Under study until 2025	Prohibition of soil crushing of following ploughing, for 2 months in >10% slope	Minimum 2 months	4%	1,622,848 ha	1. **Grassing of tree crops** 2. Protection of olive trees of particular landscape value 3. **Extensive forage systems** 4. Specific measures for pollinators 5. Reduction of antimicrobial resistance and animal welfare

Latvia	5% from reference ratio (24.71)	Agricultural wetlands/peatlands, ploughing only each 5 y and regulated irrigation	Soil cover if slope >10% and monitored drainage	In nitrate sensitive areas, >50% greening in autumn and winter. Permanent cover if watercourse	4%	?	1. *Support for environmental and climate-friendly agricultural practices* 2. *Ecological focus areas* 3. Maintaining optimal soil pH for plant growth 4. *Conservation farming practices* 5. **Agricultural practices reducing carbon dioxide and ammonia emissions** 6. **Promoting grassland conservation on livestock farms** 7. *Promotion of organic production practices*
Luxembourg	5% from reference ratio (53.42)	Several measures of protections applied to wetlands & peatlands since 2018	Depending on cultivation. Total ban on prairies	Mandatory in soils under high risk of erosion (mapping provided)	4% and 3%	?	1. *Creation of non-productive areas* 2. *Creation of non-productive strips* 3. Avoiding the use of plant protection products 4. **Establishment of catch crops and under-seeding on arable land**
Netherlands	Not properly described						1. Whole farm point-system (a series of non-defined recommendations)
Poland	5% from reference ratio (15.31)	Agricultural wetlands/peatlands, ploughing forbidden	Arable land located on slope ≥20%, cover between rows	30% of the arable land, soil cover from 01/11 to 15/02	All	269,000 ha	1. Areas of melliferous plants 2. **Extensive use of permanent grasslands with livestock** 3. **Winter catch crops or legume intercrops** 4. **Develop and follow a fertilisation plan** 5. Crop diversification (minimum 3 crops)

							6. **Mixing manure on arable land in within 12 hours of application** 7. **Application of liquid manures by other methods than spray** 8. Simplified cultivation systems 9. *Maintenance of mid-field trees* 10. *Maintenance of agro-forestry systems* 11. *Water retention on permanent grassland* 12. *Designation of 7% of the agricultural area in the farm to non-productive areas* 13. Integrated plant production system 14. Biological crop protection 15. *Organic farming* 16. Animal welfare
Portugal	5% from 2018 reference	Prohibited drainage, peat mining and land use change, except in rice plots	Different measures depending on cultivation and slope	Vegetation cover on arable land & inter-rows on permanent crops	All	?	1. *Organic farming (Conversion and Maintenance)* 2. Integrated Production - Crops 3. **Management of permanent pasture** 4. **Promotion of organic fertilisation** 5. Improving animal feed efficiency 6. Animal welfare and rational use of antimicrobials 7. *Biodiversity-promoting practices*
Slovenia	Not properly described						1. **Extensive grassland** 2. **Traditional use of grassland**

							3. **Nitrogen stabilisers in manure and use of additives** 4. **Fertilise with organic fertilisers with low air emissions** 5. **Catch crops and sub-crops** 6. **Greening of arable land over the winter** 7. **Conservative tillage** 8. **Use only organic fertilisers to provide N in permanent crops** 9. *Conservation of biodiversity in permanent crops* 10. Composting hops 11. Bare ground patches for the field lark 12. Protection of nests
Spain	5% from reference ratio (27.38)	Information compilation until 2025	Forbidden on more than 10% of slope	Depending on cultivation	All	2,623,763 ha	1. **Increased carbon sink capacity of pastures through extensive grazing** 2. *Maintenance and enhancement of biodiversity through sustainable mowing and establishment of biodiversity areas in grasslands* 3. Rotations in sustainable farmland of inputs in irrigation 4. **Conservation agriculture: direct planting** 5. *Biodiversity spaces on land and permanent crops*

							6. **Practice of spontaneous plant covers in woody crops** 7. **Practice of vegetable covers in woody crops**
Sweden	5% from reference ratio (4.1)	Several national measures of protections	Different measures depending on slope & cultivation	Depending on cultivation and region	4%	?	1. *Organic production* 2. **Substitute for intermediate crops for carbon storage, catch crops and spring processing for reduced nitrogen leakage** 3. *Precision agriculture - planning*

GAEC 1 Maintenance of permanent grassland based on a ratio of permanent grassland in relation to agricultural area

GAEC 2 Protection of wetland and peatland at the latest by 2025.

GAEC 5 Tillage management or other appropriate cultivation techniques to limit the risk of soil degradation, taking into account the slope gradient.

GAEC 6 Minimum soil cover to avoid bare soil in period(s) and areas that are most sensitive.

GAEC 7 is not included because at the time of the publication of this report it was still subject to European Commission approval.

GAEC 8 Minimum share of agricultural area devoted to non-productive areas: At least 4% of arable land at farm level devoted to non-productive areas and features, including land lying fallow. At least 3% of arable land at farm level devoted to non-productive areas and features, including land lying fallow when the farmer commits to at least 7% of arable land devoted to non-productive areas and features. At least 7% of arable land at farm level devoted to non-productive areas and features, including land lying fallow, and catch crops and nitrogen fixing crops, cultivated without the use of plant protection products, of which 3% shall be non-productive areas and features, including land lying fallow. Member States should use the weighting factor of 0.3 for catch crops.

GAEC 9 Ban on converting or ploughing permanent grassland in Natura 2000 sites designated as environmentally sensitive permanent grasslands in Natura 2000 sites.

Eco-schemes directly related to carbon farming are in bold while those partially related are in italics.

The comparison among eco-schemes and, in some cases, a deeper analysis of the proposed measures, guide us to several conclusions.

A general problem is the lack of detail in the eco-scheme description. This is not simply a problem related with later certification, but a potential source of risk leading to payment for an incorrect practice. For example, conservation farming is not necessarily related to carbon farming but to soil conservation and, if not specified in detail, could support practices that are not environmentally friendly such as the use of herbicides.

In fact, another problem associated with the lack of detail is that many countries may already pay for basic and common practices, with no proven environmental benefits. An even higher risk is the abandonment of clear environmentally beneficial practices if they are not better supported than those more 'business-as-usual' practices. Similarly, each eco-scheme should be rewarded proportionally to the expected environmental benefit, avoiding the risk of applying only economically efficient methods.

Another general flaw is that there can be competition among different interventions. In many countries, conditionality clashes with eco-schemes, while in others, eco-schemes are proposed to compensate for weak conditionality standards. Each intervention should show ambitious environmental aims independently. On the contrary, coherence and synergies among CAP interventions should be favoured (WWW-EEB, 2021).

Moreover, many different practices could help to increase soil carbon content, but only if considered together. However, many eco-schemes are very specific and not efficient for carbon farming if not integrated into a holistic approach. Some examples of this are crop rotation with legumes, cover crops, and mulching. Given that eco-schemes are rewarded per surface area, the combination of practices is not incentivized (WWW-EEB, 2021). This should be changed.

Partly related with this is the fact that Member States' CAP Strategic Plans should include relevant policies and governance mechanisms addressed to raising demand for food produced under practices beneficial for protecting and increasing soil organic C pools (IFOAMEU, 2021).

Only one country mentions peatland-related eco-schemes. Although there is a specific GAEC related to the conservation of wetland and peatlands (GAEC 2), specific actions of many countries (even the ones with a higher concentration of such lands) tend to be related to correctly defining or compiling the necessary information. This is one of the most worrying points since the loss of peatlands is the third largest source of emissions from agricultural lands.

Organic and regenerative farming are integrated management schemes of key importance in protecting and increasing soil carbon stocks, but recent impact assessments of the CAP indicate that the budget allocated by many MSs to these strategies has not been sufficient either to meet their declared objectives in this field or to cooperate with the EC objective of attaining 25% organic land by 2030 (IFOAMEU, 2021)[19]. Moreover, organic fertilisation is proposed by many different countries, although no limits in the amount of nutrients applied are indicated. Similarly, some Strategic Plans include precision farming among the eco-schemes, but without indicating limits for fertilisers, generating the same uncertainty. Finally, one country even promotes liquid manure application without spraying, which could cause vast ammonia emissions (WWW-EEB 2021).

Proven beneficial practices such as paludification (conversion of land to peatland resulting from the gradual rising of the water table) are also missing from Strategic Plans, while others such as agroforestry are poorly represented.

Finally, considering the necessary knowledge required to apply many of the measures, although not mandatory, capacity-building actions and advisory support should assist eco-schemes and the implementation of other interventions to ensure high uptake, good performance, and positive synergies among different actions.

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[19] https://www.organicseurope.bio/news/organic-movement-warns-of-insufficient-ambition-in-cap-strategic-plans/

7. REGULATORY OPTIONS TO SUPPORT CARBON SEQUESTRATION

KEY FINDINGS

- Monetary compensation has proved efficient to drive farmers to adopt management practices oriented to carbon sequestration in soil.
- A reliable evaluation of the effects of management on soil C stocks is essential to settle fair payments for results or to certify carbon credits for markets. Due to significant gaps in the European network of soil data, soil sampling for C analysis is still necessary.
- Result-based schemes should be accompanied by reliable indicators and monitoring, and capacity building including Farm Advisory Services and certified public labs.
- To reduce Measurement Reporting and Verification (MRV) costs in organic carbon sequestration in soils, a reliable integrated soil survey system is required in the EU. Increasing the number of long-term experiment sites and the variety of tested management options (e.g. by reinforcing the European living-lab network) is essential.
- Guaranteeing additionality, ensuring carbon permanence in soil, and preventing leakage, are common issues in all offset schemes, and these requirements are thought to be particularly difficult to satisfy in soil C projects.
- Pooling several carbon projects at a regional scale is advisable to reduce MRV costs, and to provide efficient scientific, technical and administrative support to farmers.
- Certification organisms providing support at a fair cost and using standardized and approved methodologies will also reassure farmers.

7.1. Carbon sequestration payment schemes

Setting fair and enticing payments for farmers' efforts to preserve or increase soil C stocks is crucial to engage them in climate-friendly eco-schemes and practices. However, carbon sequestration at the large scales required to bring about significant climate mitigation may be very expensive for public bodies. Complementary options issued from private actors, or from the combination of public and private efforts can help attain the expected mitigation rates. Increasing and preserving soil C stocks may be looked upon as a business model for climate-friendly ecosystems.

Some interesting mechanisms applicable to manage these payments are synthesised in ***Figure 11*** (McDonald et al., 2021b) and explained below.

(a) *Land management practice payments* have been until now the most frequently used mechanism to address environmental issues in the CAP. These payments have been predominantly action-based due to low Measurement Reporting and Verification (MRV) obligations and low risk for farmers (that guarantee their income independently of the results they attain) and benefits have often reached landowners instead of real land managers (Pe'er et al., 2020).

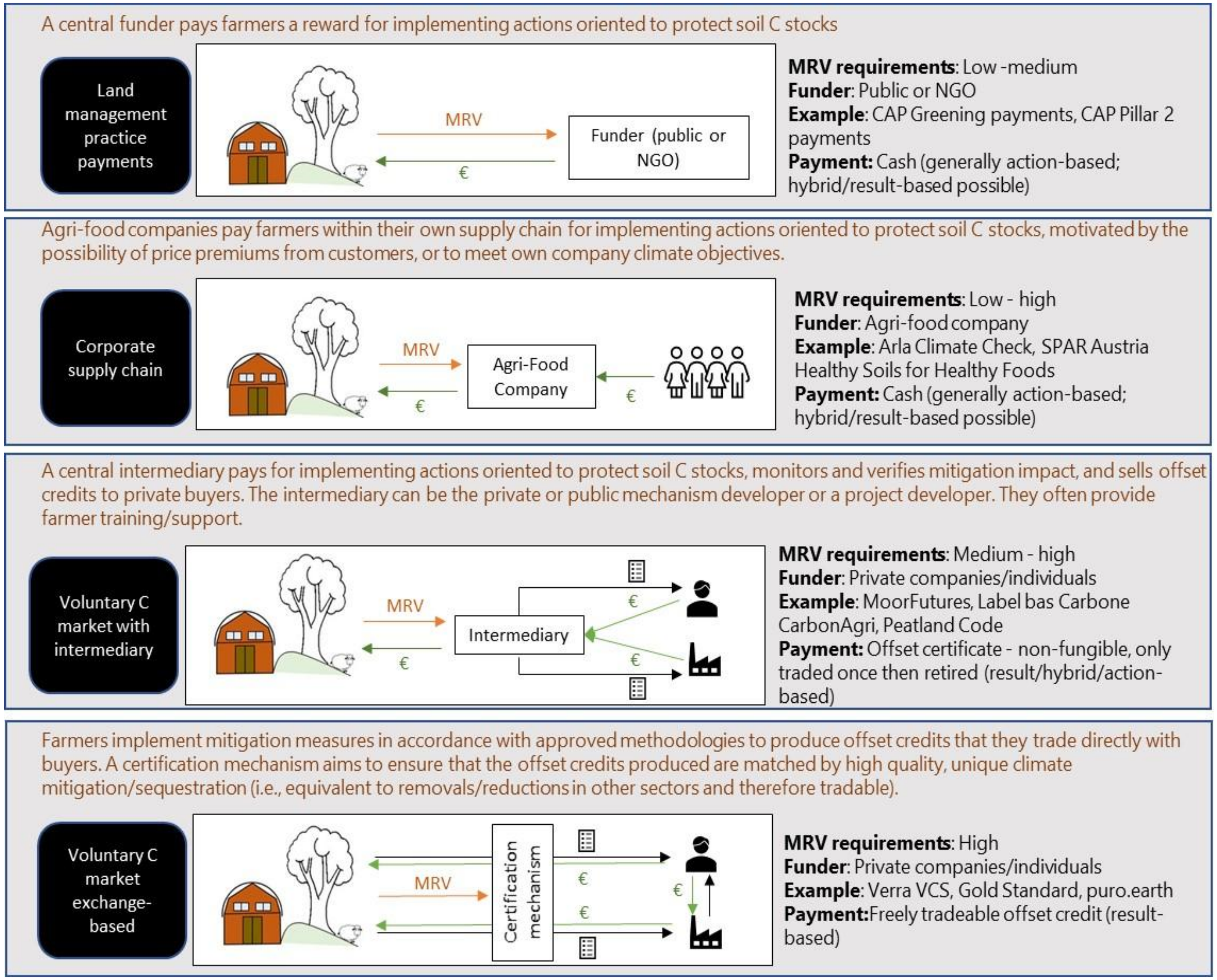
(b) *Corporate supply chains* have identified the growing environmental concern of their customers. Agri-food companies are also recognizing commitment with climate-friendly farming methods as a short-cut to access new markets. Companies and farmers can agree on environmental farming standards and the corresponding reward for applying them. This kind of mechanism is easy to implement and attractive for farmers. However, transactions tend not to be transparent, and the amount of carbon retained or sequestered is not often evaluable unless correct MRV mechanisms are applied.

(c) *Voluntary carbon markets* link voluntary buyers who want to pay for soil carbon sequestration or protection to farmers willing to implement those actions in return for payment. Contribution to mitigation is most often in the form of ‘carbon credits‘, each of them representing the sequestration or reduction of 1 t CO_2-eq. Under voluntary C markets, credits can be traded directly (direct transactions between farmers and buyers) or through intermediaries. In both cases, the amount of C removals or mitigation must be assessed through reliable MRV mechanisms (Thamo and Pannell, 2015). Carbon markets with intermediaries are more attractive for farmers because of lower risks (the intermediary usually guarantees a set price for farmers) and reduced complexity (intermediaries often provide support and training to farmers). Offset credits are commonly allowed to be sold only once and are then retired from the market. This makes this modality of C market environmentally most trustable since it impedes credit reselling and pooling with C credits of different quality generated from other sectors (such as afforestation of energy production).

It is worth giving some attention to the difference between “voluntary” and “regulatory” C markets. In regulatory C markets, a governing body imposes limits on total global C emissions that can be globally allowed for all actors in its area of influence and imposes a tax for emissions. Then, polluters dealing with high costs for reducing their emissions may find advantages in buying carbon credits from farmers at suitable prices and continuing to pollute. In voluntary C markets, there is no emission cap, and credit value only depends on demand.

Carbon credit buyers’ motivations are varied, including benefits derived from green and low-carbon labels to attract environmentally sensitive customers or partners. It is alleged that voluntary markets can be more effective than regulatory markets for C sequestration when the supply-demand balance sets the quantity of tradable C above the cap that would have been set by the corresponding governing body in a regulated market (Havens, 2021).

Figure 11: Models for carbon sequestration payments and mechanisms.



A central funder pays farmers a reward for implementing actions oriented to protect soil C stocks

MRV requirements: Low -medium
Funder: Public or NGO
Example: CAP Greening payments, CAP Pillar 2 payments
Payment: Cash (generally action-based; hybrid/result-based possible)

Agri-food companies pay farmers within their own supply chain for implementing actions oriented to protect soil C stocks, motivated by the possibility of price premiums from customers, or to meet own company climate objectives.

MRV requirements: Low - high
Funder: Agri-food company
Example: Arla Climate Check, SPAR Austria Healthy Soils for Healthy Foods
Payment: Cash (generally action-based; hybrid/result-based possible)

A central intermediary pays for implementing actions oriented to protect soil C stocks, monitors and verifies mitigation impact, and sells offset credits to private buyers. The intermediary can be the private or public mechanism developer or a project developer. They often provide farmer training/support.

MRV requirements: Medium - high
Funder: Private companies/individuals
Example: MoorFutures, Label bas Carbone CarbonAgri, Peatland Code
Payment: Offset certificate - non-fungible, only traded once then retired (result/hybrid/action-based)

Farmers implement mitigation measures in accordance with approved methodologies to produce offset credits that they trade directly with buyers. A certification mechanism aims to ensure that the offset credits produced are matched by high quality, unique climate mitigation/sequestration (i.e., equivalent to removals/reductions in other sectors and therefore tradable).

MRV requirements: High
Funder: Private companies/individuals
Example: Verra VCS, Gold Standard, puro.earth
Payment: Freely tradeable offset credit (result-based)

Source: McDonald et al., 2021b.

There is an ongoing debate about the pros and cons of implementing payments as stimuli to C sequestration in agricultural soils and, in particular, about possible effects of including C sequestration in C markets. Some organizations consider that farmers are already voluntarily involved in applying carbon farming practices when managing their soils. For them, CAP payments will only be profitable provided they do not result in extra work or technical and administrative burden. When considering the possibility of trading carbon credits in voluntary markets, the main concern is about the risk that agribusinesses will feel stimulated to offset emissions instead of reducing them (Copa-Cocega, 2021).

7.2. Roadblocks and opportunities on the way to trading agricultural carbon

Mechanisms addressing carbon sequestration or preservation in soil and emissions from the LULUCF sectors (agriculture, forestry, and land use) are critical for climate change mitigation, and often provide very valuable co-benefits. However, they are classified by carbon markets as "high risk", due to difficulties in bringing about reliable and cost-effective MRV protocols, risks of reversibility, and difficulties in guaranteeing additionality and C permanence in soils and preventing leakage (Schneider et al., 2019).

7.2.1. Cost-effectiveness of assessing SOC stocks in agricultural soils: soil Carbon monitoring issues

It is often claimed that assessing the size of soil C stocks and monitoring their response to agricultural management is technically complicated, and that costs of collecting, processing, and analysing soil samples may be prohibitively expensive to farmers.

There are three approaches to SOC quantification: (a) **modelling only**, (b) a hybrid approach **combining sampling with process-based modelling**, and (c) **soil sampling only**. These approaches correspond, to a certain extent, with the tiered IPCC methodology (Bispo et al., 2017). IPCC tier 1 calculates current and future SOC content using SOC dynamic models, or agricultural SOC models, that are fed with emission factors representing average environmental conditions for large eco-regions of the world, provided by IPCC (2006). Tier 2 is like tier 1, but models are loaded with soil data and emission factors obtained from field measurements at the regional or local scale. Tier 3 demands biophysical modelling and requires field data from the area directly concerned by the project. Therefore, tier 2 and 3 approaches require soil sampling for at least SOC content, bulk density and texture, and a soil profile. Due to the low resolution of the current European soil sampling network, replacing field data by data available from the existing soil inventories will only allow the detection of SOC changes above 5 g C kg^{-1} (Saby et al., 2018).

A variety of models are available to simulate effects of management on soil C stocks and dynamics (Brilli et al., 2017), but serious knowledge gaps about the dynamics of organic matter in the soil matrix under different environmental conditions and at different soil depths still demand that models are fitted with local field data (Stockmann et al., 2013). Unfortunately, the most accessible C models currently available do not consider the many variables that integrate specific management strategies, and sampling or hybrid approaches are still required. Additional improvements to current soil C models should include accounting for potential trade-offs between emissions of diverse GHG resulting from changes in management that might offset the benefits of SOC sequestration. This is particularly important for agriculture in wet environments such as paddy fields and peatlands (Rumpel et al., 2020),

If the response of soil C stocks to management is to be assessed based on field measurements, two types of methods can be used: measuring soil-atmosphere carbon fluxes and analysing soil C content over time. Net balance of C fluxes can be measured with gas chambers (Pumpanen et al., 2004) or calculated by the eddy covariance method (Goulden et al., 1996). However, recently, flux methods are being put aside because of proven uncertainties and the need to do measurements during long (more than 10 years) time periods (Smith et al., 2020).

Ultimately, soil sampling is still necessary to get reliable estimates of annual changes in soil C content at the farm scale. A high number of soil samples may be necessary, due to little annual change relative to total soil C stocks, and to high soil spatial heterogeneity (Smith 2002; Conant et al., 2003). This heterogeneity, that occurs horizontally but also across the soil vertical profile, makes it necessary to sample at least the top 30 cm of the soil (IPCC, 2016), since differences attributable to management are primarily confined to this depth (VandenBygaart et al., 2011).

Soil sampling protocols must also be adapted to cover the specificities of diverse ecosystems. An important example of this requirement is soil C estimation in soil environments holding coarse organic matter fragments. Most SOC monitoring protocols require soils to be sieved at 2 mm, and SOC analyses are only performed on the finest soil fraction. By eliminating large organic residues, conventional monitoring protocols omit a significant part of C stocks, leading to SOC underestimation. This may be the case in soils from agroforestry systems, woody crops and soils enriched in lignified plant materials (e.g. woodchip applications such as mulching). In such cases, this coarse SOM fraction must not be omitted, and soil surface organic layers should be analysed and included in C stock calculation.
Ultimately, the optimum number of samples to collect and the number of soil layers to include will depend on how much uncertainty we can tolerate (Allen et al., 2010; Bispo et al., 2017; Nayak et al., 2019), and efforts to reasonably harmonize sampling costs and accuracy are required (Goidts and van Wesemael, 2007).

Against this background, it remains to be seen how the "European Carbon Removals Certification Standards"[20] which should be made available in 2023 will cope with the above-mentioned issues.

7.2.2. Towards reducing soil sampling effort and analysis costs

The use of remote and proximal sensing technologies may substitute classical field sampling and lab analyses. Depending on C content, minerals, granulometry and water content, soil absorbs light at specific wavelengths and produces specific spectrums that may be measured with different levels of accuracy, using from multispectral sensors (most often satellite-driven) to hyperspectral sensors (most often included in field or lab instruments) (Smith et al., 2020).

Remote sensing technologies based on high-resolution, satellite-based sensors are valuable to remotely measure SOC at low cost but still require further improvement in terms of accuracy and precision. Among the limitations of these techniques are the need for bare soils for measurement and their small penetration (about 1 cm) (Angelopoulou et al., 2019; Sishodia et al., 2020; Smith et al., 2020). Soil sampling is still necessary to inform the calibration of the obtained spectra, as relying on soil libraries still results in substantial losses of accuracy (Breure et al., 2022).

Proximal sensing devices for in-situ and/or in lab measurement of soil C content and bulk density are becoming rapidly available. The **proximal sensing** approach produces accurate and reliable estimates of SOC content in croplands and pastures and is more cost-effective than the classical sampling approach. However, soil sampling and conventional analyses are still required to train the models (through machine learning, deep learning and memory-based learning techniques) that infer SOC content from the measured infrared spectra. In any case, sampling and analytical effort are very low compared with those required under a classical sampling approach (Viscarra Rossel and Brus, 2018).

In contrast to mineral soils, where best agricultural practices are oriented to C sequestration, peatland soils are very rich in C, and best practices are oriented to avoid C (and other GHG) emissions to the

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[20] EU Commission DG CLIMA project CLIMA/2020/0P0006 "*Support on devising a carbon removal certification mechanism*".

atmosphere. GHG fluxes are difficult and expensive to measure by common methods (such as gas chambers), or measurements are uncertain at the farm scale (e. g. eddy-covariance). Therefore, GHG monitoring usually relies on models, the most common being those using mean water table level as an explanatory variable (Joosten and Couwenberg, 2009). Although monitoring water levels is also expensive in the long-term, vegetation cover and species composition may be used as a proxy for water level (Couwenberg et al., 2011, Cowenberg and Fritz, 2012) which allows the simulation of the GHG flux at appropriate scales after calibration (Joosten et al., 2015).

To facilitate soil carbon assessment and reduce MRV costs, an integrated soil survey system is required in the EU, with soil data from long-term experiment sites and coordinated national and regional soil surveys (Montanarella and Panagos, 2021; Lugato et al., 2014; Orgiazzi et al., 2018). It should be desirable that researchers and policy managers cooperate in developing trustable open-access soil datasets for model calibration and in supporting the development of emerging and reliable technologies oriented to reduce sampling efforts (Oldfield et al., 2021). To improve European soil databases, it will also be useful to maintain the already existing long-term agricultural trials and increase the number of experimental locations and management options tested (Smith, 2004). Increasing the number of living labs and distributing them wisely to represent diverse environmental scenarios will make the monitoring of SOC stocks much more cost-effective (Amelung et al., 2020; Lugato et al., 2018).

7.2.3. Difficulties in guaranteeing additionality and Carbon permanence and avoiding leakage

Guaranteeing additionality, ensuring carbon permanence in soil, and preventing leakage are common issues in all offset schemes, and these requirements are thought to be particularly difficult to satisfy in soil C projects.

There is **additionality** when the impact resulting from a C sequestration project or policy would not have occurred in the absence of the scheme (DCCEE, 2010). Assessing additionality requires the quantification and monitoring of C sequestration both in the business as usual and in the alternative management option. Several approaches to guarantee additionality are discussed in Woodhams et al. (2012). The strategy of the Australian government offset scheme is particularly useful, where additionality is estimated by determining how widespread a practice in the region is where a new project is proposed. If, in the absence of a sequestration policy, a practice is undertaken by 5–20% or less of potential adopters it is treated as being additional (Thamo and Pannell, 2015).

To have a real impact on climate mitigation, C sequestration schemes must ensure the **permanence** of the sequestered carbon in a geological time scale. C sequestration programmes normally include instruments to ensure that the sequestered C is maintained in soil for a duration differing greatly between protocols (from 100 years in the IPCC, to permanence only required during crediting period in some cases). A widespread practice is to retain a given percentage of extra C credits to build up a buffer pool as an insurance against reversals. Buffer pools were first developed by the VERRA standard in the 2000's, and are currently the most common tools used in voluntary C markets. Further security against reversal is provided by pooling several C credits' projects and by mutualizing the buffer pools (Oldfield et al.,2021).

Another strategy consists of applying **discount rates** proportional to the risk of reversal. An example is provided by the 'Label Bas Carbone' initiative of the French Government. Before implementing the project, 'Pending Issuance Units' are created as a guarantee of later delivery of verified C units. Twenty percent of these units are retained until verification as a safeguard against errors in modelling future C sequestration, and 20% more are permanently withdrawn as an insurance against non-permanence (Cevallos et al., 2019).

A creative option to deal with potential reversals is provided by the Nori cropland methodology. During the pilot phase, Nori pays farmers both in cash and in tokens (equivalent to a cryptocurrency) that are restricted for 10 years. In case of avoidable C reversal, Nori will quantify the amount of C released in terms of ‘Nori Removal Tonnes’ and will recover their value from the restricted tokens (Oldfield et al., 2021).

Leakage refers to unplanned increases of GHG emissions because of GHG mitigation activities. Direct leakage refers to in situ collateral emissions. For example, rewetting previously drained peat soils reduces CO_2 and N_2O emissions but also leads to an increase in CH_4 emissions that might cause an unwanted GHG balance in the absence of appropriate management (Günther et al., 2020; Bianchi et al., 2021). Indirect leakage is a consequence of substitutions or market adjustments occurring in response a carbon credits project. An example may be likely land use changes overseas to compensate for potential decreases in European agricultural production following large scale adoption of organic farming (Smith et al., 2019). In this sense, SOC projects must be evaluated not only for their efficiency in climate mitigation but also for their effect on productivity.

7.2.4. Facilitating farmers’ involvement in Carbon credit markets

A comprehensive overview of measures aimed at facilitating the implementation of C sequestration mechanisms in farmlands is available in Cevallos et al. (2019). Among them are enhancing international cooperation to mutualize knowledge, developing common guidelines on the financing of carbon projects, and sharing and disseminating existing methodologies and tools. Many of these methodologies have been developed in the framework of domestic standards and include helpful approaches to deal with specific limitations of soil C sequestration projects while reducing costs and guaranteeing reliability.

Among them, it is worth stressing the utility of implementing ex-ante (before the event) credits to provide farmers the necessary funding to embark on long-term C sequestration projects. However, provisioning ex-ante credits requires estimating the increase in soil C stock, as well as its progress over time, with reference to the base-line scenario, which demands accurate modelling of soil C responses to management and reliable soil C monitoring over the project period.

7.3. Inspiring experiences

7.3.1. Available MRV standards

Several thorough reviews on certification mechanisms applicable to carbon sequestration projects in agricultural soils have been recently published. Two reviews of national certification schemes and MRV methodologies can be found in Cevallos et al, (2019) for Europe, and in Bey et al., (2021), McDonald et al., (2021a) and Oldfield et al. (2021) for other approaches at the global scale. Some of the most popular schemes and protocols for MRV of C sequestration in mineral soils are **Climate Action Reserve** (USA agricultural soils)[21], **Verra** VM0042 methodology for Improved Agricultural Land Management[22], **Nori** Croplands methodology[23], **GoldStandard** Soil Organic Carbon Framework Methodology[24], **Carbon farming Initiative** (Australia)[25], **FAO** GSOC MRV Protocol[26], The BCarbon Standard[27], and **Regen** Network Grasslands Protocol (Methodology for GHG and Co-Benefits in Grazing Systems)[28].

Carbon credits produced in peatland restoration projects constitute a particular case mostly due to monitoring difficulties. Assessing GHG fluxes in peatlands through direct measurement is not recommended for crediting because, among other reasons, pre-desiccation GHG flux recovery is very slow and requires long monitoring times (von Unger et al., 2019; Bey et al., 2021). Nevertheless, several

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[21] https://www.climateactionreserve.org/how/protocols/soil-enrichment/

[22] https://verra.org/wp-content/uploads/2020/10/VM0042_Methodology-for-Improved-Agricultural-Land-Management_v1.0.pdf33.

[23] https://nori.com/documents

[24] https://globalgoals.goldstandard.org/402-luf-agr-fm-soil-organic-carbon-framework-methodolgy/

[25] https://www.legislation.gov.au/Details/F2021L01696

[26] https://www.fao.org/global-soil-partnership/resources/highlights/detail/es/c/1308261/

[27] https://bcarbon.org/our-standards

[28] https://www.regen.network/

protocols are being applied successfully in Europe, as is the case of **The Peatland Code** (UK)[29], or **The MaxMoor** national standard (Switzerland)[30]. There is also a voluntary carbon standard verified by **Verra** for Rewetting Drained Temperate Peatlands[31].

7.3.2. Positive European experiences

In 2005, following the coming into force of the Kyoto Protocol, a variety of domestic C markets emerged in Europe under the Track 1 procedure of its Joint Implementation (JI) mechanism. Track 1 required serious efforts to settle MRV frameworks and, after the end of the JI projects (in 2012), several EU countries began to use their accrued experience to develop their own domestic standards (Cevallos et al., 2019). Some inspiring examples are reported below.

France. The French Carbon Standard '**Label Bas Carbone**'[32] is a result-based framework adopted by the French Government in 2018 to stimulate voluntary reduction of GHG emissions and C sequestration in soils and biomass. Companies, public organisations, or individuals willing to compensate their emissions can acquire emission reductions certified through the methodology. To date, the standard includes approved protocols for forestry and for agriculture. Agricultural projects (in cattle raising -beef and dairy- or field crop farms) are managed through CARBON AGRI, a French association representing livestock breeders[33]. The scheme aims to quantify avoided C emissions and C sequestration in soil, and to guarantee the traceability of payments to avoid duplications. Farmers (or project developers) register their project, including a detailed description and an approved methodology (individuals or sectors can propose their own), and submit their proposal to the Label Bas Carbone regulator for approval. Forty types of low carbon practices are eligible. For monitoring removals or reductions, the C base line may be calculated by using default values from the CAP'2ER®[34] national database (to account for higher uncertainty, C reductions are discounted by 10%) or by using real data from the farm. Project developers receive one credit per t CO_2 sequestered/avoided. The reward is paid at the end of the 5-year project period, upon verification by CARBON AGRI. To deal with non-permanence risk, a 20% discount is applied to payments.

Germany. **MoorFutures®** is a result-based voluntary scheme addressing peatland rewetting in Germany[35]. MoorFutures credits were introduced in Mecklenburg-Western Pomerania in 2010 as the first carbon credits issued for peatland rewetting in the world. Credits are currently sold in Brandenburg, Mecklenburg-Vorpommern and Schleswig-Holstein. As of February 2015, 10,413 certificates had been sold only in Mecklenburg-Vorpommern, with a sales volume of €364,455 at a price of €35 per certificate.

Minimum project duration is 30-100 years, with 100 years of permanence required. Since measuring GHG exchange in peatlands is costly, expert opinions and publications are used to assess the base line, and GHG emission reductions are estimated using the Greenhouse Gas Emission Site Types (GEST) approach, based on vegetation mapping[36]. Vegetation is mapped out prior to the start of the project, three years after rewetting, and then every ten years until closure (Joosten et al., 2015). Projects receive one voluntary carbon market certificate per tCO_2-eq reduced, whose price is calculated by dividing the costs of implementation by the total amount of emission reductions over the project crediting period. Projects receive these ex-ante credits upon verification (COWI, 2020). MoorFutures retains 30% of generated credits in a buffer to cover risks of reversals or failure. Additionality is guaranteed by recalculating the baseline scenario every 10 years, and assuming that rewetting is additional if the level

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[29] https://www.iucn-uk-peatlandprogramme.org/peatland-code-0

[30] https://www.wsl.ch/de/projekte/klimaschutz-durch-hochmoorschutz-1.htm

[31] https://verra.org/methodology/vm0036-methodology-for-rewetting-drained-temperate-peatlands-v1-0/

[32] https://www.ecologie.gouv.fr/label-bas-carbone

[33] https://www.france-carbon-agri.fr/france-crabone-agri-association/

[34] https://cap2er.fr/Cap2er/

[35] https://www.moorfutures.de/

[36] https://life-peat-restore.eu/en/wp-content/uploads/sites/7/2019/05/updated-gest-catalogue-40-longlist.pdf

of adoption of this practice is below a certain threshold in the region. Leakage is minimized through site selection.

Austria. The **Humus Programme** of the Austrian Öekoregion Kaindorf [37] is a result-based contract programme aimed at facilitating voluntary CO_2 trading between farmers and emitting companies (purchased carbon cannot be traded again). In February 2022, the project had been implemented in about 4,764 ha of croplands, with around 363 farmers.

A contract is signed between farmers and the Öekoregion Kaindorfm 'quality assurance programmes'. Management recommendations, instead of mandatory requirements, are given to farmers, with the most frequently adopted actions including fertilisation with only compost and green manure, tillage cessation or reduction, permanent cover crops and agrochemicals reduction. At the start of the contract, the soil carbon base line is determined by direct soil sampling and analysis with methods duly certified by an independent expert and an accredited national lab (the Department for Soil Health and Plant Nutrition of the Austrian Agency for Health and Food Safety -AGES). A second sampling will be conducted within 3 to 7 years. From monitoring results, the amount of carbon stocked will be calculated, and the farmers will receive a success fee per additional tonne of CO_2 captured. Farmers must guarantee carbon permanence in soil for 5 years, which will be verified by means of a third soil sampling. If the amount of carbon stocked exceeds the quantity contracted, farmers can claim the correspondent success fees and the continuity of the programme for five more years. In contrast, soil carbon losses can lead to partial or total refunding.

A very different scheme is the **Healthy Soils for Healthy Food** [38] initiative, a producer-retailer-consumer initiative focused on soil carbon sequestration on agricultural land, led by the Austrian supermarket chain SPAR with support from WWF Austria. Since its beginning in 2015, the initiative has engaged 60 farmers representing 1052 ha.

The project offers support and training to farmers, expert sampling and MRV of soil carbon, and rewards for participation. The initiative also guarantees the sale of produced vegetables based on 3-year contracts. Activities covered include fertilisation with compost, reduced tillage, cover crops, crop rotation and intercropping. Initially, the initiative was result-based, with farmers being rewarded per t CO_2-eq certified by a specialist body. Soil sampling is done prior to the start of the project and 2 to 5 years later. Given the resistance of farmers to having to pay credits back if soil carbon later decreased, the payment system has currently shifted to activity-based payment. There are no mechanisms to mitigate risk of long-term reversal.

The Netherlands. In the Netherlands, the **Green Deal National Carbon Market**[39] was signed in 2017 between government, companies, local initiatives and environmental organizations. As a spin off, The National Carbon Market Foundation (Stichting Nationale Koolstofmarkt -SNK) was founded in 2019. With 24 participating organizations, SNK supports the voluntary national carbon market by assessing plans, issuing certificates, mediating between providers and buyers, and offering a variety of methods for calculating emission reductions (the "Rulebook", verified by independent experts). SNK issues certificates to project parties for verified reductions. At the time of writing, rulebooks for carbon sequestration or GHG emission reduction in soils had yet to be released, but land use related actions, including water level management for peat meadows and carbon storage in soil through pilot programmes are expected before 2030.

7.3.3. Extra-European successful experiences

The knowledge accumulated from previous experiences in the US and Australia suggest that shifting from compliance and rules towards results and performance can be highly cost-efficient if monitoring, reporting and verification (MRV) procedures are made available to farmers.

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[37] https://www.humusplus.at/

[38] https://www.wwf.at/de/spar-boden-und-klimaschutz/

[39] https://nationaleco2markt.nl/

The Australian experience. Australia is one of the top GHG emitters in the world, and probably the country with the largest set of methodologies to incentivise farmers for carbon farming. In 2011, Australia introduced the ***Carbon Farming Initiative***, a credit offset scheme for emissions and removals from the LULUCF and waste sectors[40]. In 2014, the Australian Parliament passed the *Carbon Farming Initiative Amendment Act 2014* that established the Emissions Reduction Fund. It includes three key elements: crediting emission reductions, purchasing emission reductions, and safeguarding emission reductions. Approved offset projects can generate Australian carbon credit units (ACCUs) per t CO_2-eq emissions avoided or sequestered. The Australian Government is the main ACCU buyer, but credits can also be sold in secondary C markets.

In 2020, the *Low Emissions Technology Statement* recognized soil carbon as a priority and set out to reduce the cost of soil carbon measurement to under \$3 ha^{-1} y^{-1}. Subsequently, in 2021 the updated carbon credits methodology for estimation of SOC came into force[41] supported by a great effort to make the methodology accessible to farmers.

Project proponents can estimate soil carbon stocks at intervals of 1 to 5 years using one of the following approaches: (a) soil sampling only followed by soil C analyses; (b) using models in combination with soil sampling, intended to reduce sampling intensity and (c) using only models validated for soil carbon stock estimates. Before the project starts, the project area must be classified into homogeneous C estimation areas (CEAs). At each CEA, the first estimation of the C stock (the baseline) must be measurement-based, or model-assisted, and subsequent sampling must occur at least once every 10 years to validate the model. After that, the SOC stock must be estimated with a periodicity of 1 to 5 years. Sampling must include the soil profile to a minimum depth of 30 cm, and 10 cm below the zone affected by operations.

For projects to be eligible, a minimum decrease of 2000 t CO_2-eq is required. As this threshold would exclude small-scale farmers from joining the CFI projects, carbon agencies help farmers to aggregate into big projects. Projects can select 100- or 25-year permanence periods. In the latter case, 20% of the carbon credits are deducted over the project crediting period, and farmers and project owners must properly document carbon maintenance obligations with the land title. To compensate for unexpected loss of sequestered carbon, a buffer of an additional 5% abatement is maintained (Oldfield et al., 2021).

Initially, only a few farmers committed themselves to C sequestration but guaranteed ERF financial incentives positively influenced farmers' participation, and over time more and more farmers became engaged due to positive results achieved by other farmers, including increasing production and revenue from crops (Verschuuren, 2018).

It must be stressed that there was a great effort made by the Australian Government to fund research, development, and outreach programmes for GHG mitigation in the LULUCF sector. Under the Carbon Farming Futures (CFF) programme, the government invested over AUD 139 million in 200 projects over the period 2012 to 2017[42].

Canada. The Alberta Carbon Offset project. Since 2007, Alberta has included agricultural C offset schemes as part of its cap-and-trade system. Farmers can trade in carbon offset credits in the province cap-and-trade market by voluntarily implementing agricultural practices that reduce GHG emissions or increase carbon storage in soil (OECD, 2020). The Government of Alberta required industrial facilities emitting more than 100,000 t CO_2-eq per year to reduce their emissions by 12% below their baseline following diverse strategies, including emission offsets. A range of soil MRV protocols were developed to provide confidence and reduce transaction costs. The Quantification Protocol for Conservation Cropping was published in 2012 to update the preceding Tillage System Management Protocol. Conservation tillage reduction was the most frequently requested type of project, delivering more than 1.5 million tonnes of offsets from 2007 to 2019 (Paustian et al., 2019).

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[40] https://www.legislation.gov.au/Details/C2020C00281

[41] https://www.legislation.gov.au/Details/F2021L01696

[42] https://landcareaustralia.org.au/project/successful-five-years-carbon-farming-futures-programme/, accessed in March 2022.

For MRV, the protocol used a modelling approach, provided with C sequestration coefficients from national soil databases. The scheme did not require landholders to ensure permanence. Instead, to prevent C reversal the sequestration coefficients were discounted by specific percentages (depending on regions), and the produced savings were managed as a financial reserve in case soil C was released in the future. To include small farmers, the scheme relied on aggregator companies to assemble projects large enough to interest buyers.

Over one-third of Alberta growers participated in the Conservation Cropping Protocol, and three-quarters of them declared themselves satisfied. Guaranteeing additionality was always a problem, since reduced and no tillage was already being applied in the province. Despite a 'moving baseline' being developed, the protocol had to be withdrawn in 2021 because of lack of additionality (Team Alberta, 2019; Paustian et al., 2019).

USA. The California Compliance Offset Protocol for Rice Cultivation Projects. In 2005, the government of California adopted the state-wide objective of reducing GHG emissions by 80% relative to 1990 levels. In 2018, this objective was upgraded to aim to achieve carbon neutrality by 2045 at the latest. To attain this target, the California Air Resources Board (CARB) operates a cap-and-trade programme that covers large industrial facilities, electrical distribution, natural gas and other fuel utilities. As a part of the programme, companies are allowed to offset a share of their emissions by purchasing C credits. Among the agricultural projects eligible for offsetting are those concerning livestock, grassland management and rice cultivation. The scheme to produce and manage rice offset credits was successfully adopted by the CARB in 2015[43], becoming the first crop-based agriculture offset for the programme.

The protocol accepts reductions in methane emissions resulting from shortening flooding periods (by seeding fields under dry conditions, draining them earlier, or drying fields periodically during the cultivation period). The protocol uses the DNDC biogeochemical model (Li et al., 1992; Gilhespy et al., 2014) to estimate the effect of these practices on net CO_2, nitrous oxide, and methane emissions. Baseline emissions are defined based on farmers' reports about past cultivation practices, which is considered unreliable (Haya et al., 2020)

At the end of 2020, the programme had not yet generated any credit. This failure may be explained by the high data requirement, farmers' resistance to monitoring and data collection, and limited opportunities to aggregate multiple small fields into a single project (Jackson et al., 2021). MRV is known to be problematic when developing rice offset projects, with verification accounting for as much as 50% of the total cost (Proville et al., 2020).

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[43] https://ww2.arb.ca.gov/es/our-work/programs/compliance-offset-program/compliance-offset-protocols/rice-cultivation-projects/

CONCLUSIONS AND RECOMMENDATIONS

• Climate change and soil carbon

Current climate conditions are already affecting agroecosystems in Europe. The harvests and the quality of products are lower, while production costs for farmers are increasing. In that context, it is crucial to note that soil is also being affected by climate change and land use, and furthermore soil degradation has a negative feedback on the climate system, worsening the ongoing climate change. **Simulations converge in predicting overall increases in soil organic carbon (SOC) stocks in Europe by 2100 due to climate change factors**, but this increase will be the result of decreasing SOC stocks in Mediterranean countries compensated by SOC accumulation in northern ones, **with negative consequences for agricultural productivity in wide regions of the EU unless sustainable farming practices are widely implemented**.

Moreover, in the EU, a large proportion of soils are degraded, including soils from croplands and pastures. Farming practices and, in some cases, overgrazing have contributed to the degradation of soil structure and in reducing soil organic carbon stocks with consequent losses in water and fertiliser use efficiency, and increases in air, water and soil pollution.

There is increasing recognition that responses to warming will differ between different types of soils and geoclimatic zones. Therefore, **to identify the best management practices and policies to maintain C in soil, it is essential to identify not only the distribution of soil organic carbon, but also the soil characteristics**, like soil texture, that determine their vulnerability to current changes.

• Reducing agricultural GHG emissions versus increasing carbon sequestration in agricultural soils

Agricultural GHG emissions decreased from 1990 to 2019, but this reduction occurred from 1990 to 2005 and the emission rate has remained stable or has increased slightly since then.

Emission trend projections demonstrate that agricultural emissions will remain almost flat with the existing measures and that, with additional measures a slightly larger decrease (of 5%) may be reached by 2040. This gives support to the idea **that it will be difficult to achieve further substantial GHG emission reductions in the agricultural sector without significant changes in farming practices, systems, activity levels and policies and that to achieve a path towards a neutral carbon balance of the sector, carbon removal in soils must go together with emission reduction**.

The LULUCF sector, has been acting as a GHG sink, due to the increase in forested areas in the last decades. However, if we put the focus on the agricultural sector, the LULUC (excluding forest) sector capacity to neutralize GHG emissions has a net emitter balance of around 80 $MtCO_2$-eq.

From that perspective, **it is also important to consider both the carbon storage capacity in agricultural soils and the potential role of changes in human food diets**.

Predicting the technical and realistic mitigation capacity of agricultural soils is very challenging due to the enormous variety of possible scenarios arising from the combination of management practices, their possible area of application, and interactions with other socio-economic drivers.

• The agricultural carbon cycle

In natural conditions, soil organic carbon stocks are the result of the balance between (primarily) plant inputs (litterfall, dead roots, root exudates), and carbon outputs which are mainly the result of the decomposition of soil organic matter in the form of gas (CO_2 or CH_4) but can also be via dissolved forms and soil erosion, under very variable soil and climate conditions.

All these conditions may be altered by human activities and in particular by agricultural management, which makes agriculture a key driver of climate change. Since agriculture seeks maximum exploitation of plant primary production for food, a significant amount of the potential plant inputs is exported to markets away from the agroecosystem, which results in soil impoverishment in carbon relative to non-exploited systems.

However, management can tip the balance to either building up or to losing soil carbon. At any rate, for any set of soil and climate conditions, there is an equilibrium level of SOC stock, at which soil becomes carbon neutral. The SOC may either increase or decrease when at least one of the following conditions change: the amount of organic inputs to soil, the quality of these inputs, the environmental conditions (for instance, from rainfed to irrigated), or when some soil features change (e.g., when liming an acid soil).

Increasing SOC stock in agricultural soils can be the result of a smart and locally adapted management of the carbon cycle.

• Agricultural practices and the soil carbon cycle

Increasing soil organic carbon stocks is essential not only for climate regulation, but also to maintain and improve the natural fertility of soils and their health. Merely increasing SOC without enhancing soil microbial activity, soil enzymatic activities and overall soil biota and biological activity may not yield the desired combined benefits for both climate and food production in the long-term.

Thus, the increases in SOC should not result from the addition of inert forms of carbon. Any added organic amendment should become incorporated into the natural soil functions, and thus not be an amendment that results in a distortion of the natural carbon cycle.

Under this holistic approach to soil management, **the reduction of tillage, and even its suppression, are options to consider**. Their usefulness in increasing SOC is debated, but there is little doubt that they may be a necessity in areas affected by strong erosion. Furthermore, tillage reduction may be generally useful everywhere because the continued physical disturbance of soil structure by ploughing is a known cause of soil biodiversity loss. Also, **cover crops, catch crops, addition of manures or (better) composts, are all agricultural practices that enhance natural functions of the plant-soil system, and they are recommended because they involve low- or null ecological risk**. Composting selected biowaste products is also a way of recycling, creating a circular economy and integrating agricultural practices to the urban areas nearby. However, the quality of composts has to be carefully monitored, to avoid soil contamination. **It is usually found that these practices act in a synergistic way: effects are more positive and powerful when combined. No single agricultural practice ensures substantial agronomic results, but the combination of two or more of them result in significant improvements of SOC levels and soil fertility indicators.** Cover-cropping plus reducing tillage intensity, adding compost when incorporating catch-crops to soil (= green manuring), and manuring a crop submitted to occasional tillage, are examples of combinations of several good agricultural practices whose expected result is an improvement of soil biology, an increment in SOC stocks and, possibly, an increase in plant production. Therefore, integrated management strategies more than isolated practices are required to guarantee the delivery of soil environmental services, including crop quality and production, which is a necessary condition for farmers to adopt climate-smart management strategies. **Organic farming and regenerative practices, as proposed in the EU Green Deal, should be applied in degraded soils and may be useful to stop and reverse soil degradation where this process occurs.** The increase of permanent grasslands, green covers in woody croplands and woody and grassy crop combinations or agroforestry also have a great C sequestration potential. The use of N fixing plants in croplands, grasslands and agroforestry systems should be also considered.

Other proposed options, heavily publicised, cannot be recommended yet, owing to the lack of consistent positive results. Biochar, for instance, has been repeatedly shown to be the easiest way of increasing SOC contents. But its effect on soil properties and functioning highly depends on biochar characteristics, which in turn greatly depends on its origin and the precise details of its production. **Biochar is not easy to apply at wide/large scales and depending on its quality/origin it may not**

always benefit soil quality. The use of humic liquid amendments, widely used everywhere in the world as biostimulants of plant growth, is another problem: many of these humic amendments have a fossil origin, and thus their application does not match the concept of SOC sequestration, which refers to the incorporation into soil of carbon extracted from atmosphere, not from the lithosphere. **In the same sense, precision agriculture does not necessarily result in SOC sequestration, although it may reduce inorganic C losses by reducing CO_2 losses due to the use of ammonium fertilisers in carbonate rich soils**.

At any rate, the shift to an agricultural model close to natural processes, using chemical fertilisers as a complementary tool but largely based on the smart management of the carbon cycle, will be compulsory in the long term. The reason for this is the expected reduction in the availability of mineral fertilisers: their production is expensive because they are highly energy-demanding, and as energy becomes more expensive (as widely expected), the cost of mineral fertilisers will also increase, and their widespread use must eventually be submitted to great restrictions.

• Supporting farmers' engagement at manageable costs

Farmers are critical actors in the agricultural and environmental sectors, and their willingness to adopt carbon sequestration strategies will be crucial in achieving the EU Green Deal climate objectives. Together with technical support, financial incentives must be provided to compensate them for providing food while preserving and enhancing the environmental services delivered by their soils.

Priority should be given to result-based payments and to a holistic approach addressing all factors with an impact on carbon sequestration. When it comes to projects addressing carbon sequestration in soil that are naturally long-lasting, ex-ante payment is necessary to compensate for investment cost and a possible decrease in crop production during the initial phase of the project. Result-based schemes should be accompanied by a system of reliable indicators and monitoring rules, which may be facilitated by capacity building in the form of Farm Advisory Services and certified public laboratories. Specific habitats, and notably peatlands, should be protected and restored, while they seem to have been neglected in most of the National CAP Strategic Plans submitted to the Commission.

Minimising the monetary cost and work involved in Measurement Reporting and Verification programmes will require collectivising farmers' efforts. This may be facilitated by national and regional authorities by aggregating carbon sequestration projects at the landscape scale. By making public lab facilities, applying sound carbon standards at a fair price, available to farmers, risks of market speculation will be minimised. To guarantee that investments really result in climate benefits, farmers must feel technically supported to implement the most adequate management strategies after adaptation to the specific characteristics of their farms. At the regional and national scale, this must be achieved by reinforcing cooperative structures and actions for knowledge sharing between scientists, technicians, and agricultural leaders. Agricultural lighthouses (places for demonstration of solutions, training, and communication) should be encouraged to derive maximum benefits from these efforts. Current efforts to develop living laboratories (spaces for co-innovation through participatory, transdisciplinary, and systemic research in agriculture) should be integrated into every National Strategic Plan. Applied research that is well oriented to produce realistic field data to feed agricultural soil carbon models is crucial to reduce the cost of monitoring soil carbon stocks in the medium-term. For the same purpose, research aimed at providing field and laboratory data to calibrate proximal sensing systems for carbon measurement in soil will be very beneficial.

Where public funds are not sufficient to incentivise carbon sequestration at the significant levels required to achieve the proposed 2050 climate goals, business and market solutions may be implemented, based on pioneering experiences both in Europe and abroad.

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To reach the climate neutrality envisaged in the Green Deal by 2050, reducing agricultural GHG emissions is not enough, and efforts to implement large scale carbon sequestration in soil and in European agricultural soils will be necessary. The renewed CAP includes improvements in environmental conditionality and in payments for adoption of Good Agricultural and Environmental Conditions and eco-schemes than can help achieve this goal. Carbon sequestration in soil is cost-effective, but improvements in methodology are still required, as well as the cooperation between the public and private sector

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