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Climate-Smart Sustainable Agricultural Soil Management for The Future - III

Feasible Carbon Sequestration Potential in European Agricultural Mineral Soils Through Improved Management

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ABSTRACT

Soil degradation threatens global agriculture by compromising soil health, while sustainable agricultural management enhances soil functionality and carbon (C) storage, thereby contributing to climate change mitigation. This study estimates the feasible C sequestration potential of ten agricultural management practices across Europe, by applying practice-specific emission factors and identifying areas suitable for additional implementation. For each management option, the implementation area was defined based on environmental and technical limitations and, if applicable, EU regulations. The objective of this study is to identify general patterns, relative magnitudes, and plausible ranges of carbon sequestration potentials across Europe. Considering soil C from 0 to 50 cm depth, biochar application shows the highest and most robust potential, contributing approximately 34%–47% of the total estimated annual C sequestration rate. This is followed by agroforestry, contributing 24%–45% (of which ~10% occurs in soils and ~90% in biomass), and zero tillage with 11%–15%. Optimised crop residue management (4%–6%), forage legumes and temporary ley rotations (4%–5%), and cover cropping (2%–3%) contribute comparatively smaller shares. Non-inversion tillage and irrigation offered a marginal C sequestration potential. By implementing all non-mutually exclusive management options, the greenhouse gas (GHG) mitigation potential is estimated at approximately 20%–30% of current, annual, agricultural GHG emissions in Europe (740 Mt. CO_2e yr.$^{-1}$), including the land-use, land-use change and forestry (LULUCF) sector. For the EU-27, this corresponds to a similar range of 20%–31% of annual agricultural GHG emissions (614 Mt. CO_2e yr.$^{-1}$), also including the LULUCF sector. Evaluating trade-offs and synergies of each management option is essential for achieving sustainable soil management. The success of C sequestration efforts in European agriculture depends on scaling up improved management practices. Meanwhile, soil C stocks decrease and entrenched policy as well as economic and other adoption barriers suggest that even the conservative scenario may be overly optimistic.

Highlights

- A semi-quantitative C sequestration potential of European agricultural mineral soils
- A harmonised European approach to estimate areas suitable for additional implementation of measures.
- Through implementation of all non-mutually exclusive management options, emissions equivalent to 20%–30% of current, annual, agricultural GHG emissions in Europe could be mitigated
- Scaling up implementation of SOC accrual measures is key, but climate, policy, and other hurdles hinder this.

1 | Introduction

Soil degradation contributes to climate change, biodiversity loss, and reduced agricultural productivity, while sustainably managed or restored soils offer key ecosystem services, including carbon (C) sequestration for climate mitigation (Keesstra et al. 2024). Here, we define "C sequestration in soils" as the process by which C is transferred from the atmosphere into the soil through plants or other organisms and retained as soil organic carbon (SOC), resulting in an increase in the global soil C stock (Don et al. 2024). While "C sequestration" can include for example, aboveground biomass of woody features such as hedges. Increasing SOC is central to improving soil functions—such as water regulation, nutrient cycling, and structural stability—which in turn supports microbial activity, crop yields, and overall soil health (Smith et al. 2013; Silva et al. 2014; Varela et al. 2014; Merante et al. 2017; Kätterer and Bolinder 2024; Spiegel et al. 2025). These SOC-related soil functions are crucial to sustainably maintain the productivity of agricultural soils (Chenu et al. 2019). Agricultural management options that increase SOC include among others, non-inversion tillage, zero tillage (Meurer et al. 2018), introduction of cover crops (Poeplau and Don 2015; Fohrafellner et al. 2024), optimised crop rotations (Kremen et al. 2012; Wezel et al. 2014; Garbach et al. 2017; Beillouin et al. 2019; Di Bene et al. 2022), optimised crop residue management (Tiefenbacher et al. 2021), implementation of agroforestry systems (European Commission. Directorate General for Climate Action. et al. 2021), and biochar application (Schmidt et al. 2021). Optimised agricultural management can enhance soil functions and ecosystem services, drawing growing public and policy interest—especially in light of efforts like the European soil monitoring law to protect soil health for future generations (Panagos et al. 2024).

The "4 per 1000" Initiative proposed that a global annual 4‰ increase in SOC could offset all human-induced greenhouse gas (GHG) emissions and enhance food security (Minasny et al. 2017). This global target is theoretical as it includes all soils, not just managed ones. The FAO launched the Global Soil Sequestration Potential project (GSOCseq) to estimate a more realistic C sequestration potential (Peralta et al. 2022). To this aim the amounts of additional C stored in soils were calculated for three different scenarios (low, medium and high C inputs). At the same time, the project did not consider how to realise increases in C inputs to the soil. The amount of C that can additionally be stored in soils through the implementation of agricultural management options remained thus unclear (Büchi et al. 2022; Rosinger et al. 2023). This question has been tackled by few studies and only for a limited set of agricultural measures. Rodrigues et al. (2021) found that mitigation potential varies significantly across the European Union Member States (EU-27). By implementing these management options, the States could reduce agricultural GHG emissions by 0.1%–27%, based on 2020 inventory data excluding the Land-Use, Land-Use-Change and Forestry (LULUCF) sector. The cumulative reported potentials (excluding repetitions of measures within one country) would amount to 15.2 Mt. C $yr.^{-1}$ (equalling 55.8 Mt. CO_2e), representing 13% of the total annual European agricultural GHG emissions recorded in 2020. Lugato et al. (2014) found that when applying reduced tillage, improved crop residue management, increased use of ley rotations and cover cropping in European agricultural soils (considering the EU, Serbia, Bosnia and Herzegovina, Montenegro, Albania, Northern Macedonia and Norway), 549–2141 Mt. CO_2e could be bound as SOC by the year 2100. Based on these numbers, Lugato et al. (2014) estimated that implementing different combinations of such alternative management practices on approximately 12% of arable land would be sufficient to achieve the 20% emission reduction target of the Kyoto Protocol, under which the EU committed to reduce its emissions to 20% below 1990 levels by 2020. Management changes on about 69% of land would strongly contribute to the optional 30% target according to Lugato et al. (2014). Thus, these management practices alone will not be able to lead to climate neutrality by 2050. Furthermore, many other management options, such as biochar application or agroforestry, are still not considered at larger regional scales, and the amount of C that could be sequestered in European agricultural soils especially in a spatially explicit manner, remains unclear.

Management methods geared to C sequestration can increase uncertainty and induce side-effects, which might weigh positively or negatively on the implementation of these methods. For example, one source of uncertainty are changes in subsoil C through a change in soil management, as additional C inputs to the topsoil can lead to increases in C in the subsoil (Skadell et al. 2023). However, this is not yet accounted for in the few studies on quantifying C sequestration on a large scale (e.g., Lugato et al. 2014; Rodrigues et al. 2021; Agora Agriculture 2024). An example of side-effects of management options aimed at increasing SOC is the potentially increased emission of the potent GHG nitrous oxide (N_2O) from the soil. Such increases in N_2O emissions can reduce, or even offset, the climate change mitigation potential of enhanced SOC accrual (Guenet et al. 2021; Nikolaus and Lesschen 2024). The effect of a change in agricultural management on soil C in general, and subsoil C and N_2O emissions specifically, need to be better quantified to allow the EU-27 to evaluate whether the *European Green Deal*'s promise of achieving climate neutrality by 2050 can be achieved or not (Fetting 2020). It is important to highlight that the primary sources of agricultural GHG emissions are N_2O and CH_4, which result from livestock management and fertiliser application. While GHG emissions cannot be entirely eliminated, the hope lies in mitigating the overall global warming impact of agriculture through C sequestration in soils, which reduces or potentially even offsets the emissions (Lamb et al. 2021).

In this context, Agora Agriculture (2024) offered a complex scenario in which the EU may reach climate neutrality by 2050 by implementing a collection of different measures to enhance SOC accrual. These measures include, for example, rewetting all peatlands, with 80% of the wetland area allocated to paludiculture; increasing forest cover by 3% while reducing wood harvest by 10%; incorporating 20% semi-natural landscape features; decreasing arable land required for feed production by significantly reducing livestock and converting 8% of current agricultural area to forest. In this scenario, these and other measures would have to be implemented by 2029 and rolled out completely over the next two decades if climate neutrality should be achieved by 2050, a pace which faces substantial social, economic, and political roadblocks. There are many factors hampering the implementation of specific measures such as environmental (e.g., temperature and precipitation), technical, economic or socio-cultural constraints (Amundson and Biardeau 2018; Bijttebier et al. 2018). Furthermore, some measures, such as integration of woody features such as hedgerows in agricultural systems, may be implementable everywhere; however, a balance between food production and possible C sequestration needs to be ensured, for example, through existing policy strategies. All changes in management must adhere to the principle of minimising their possible negative effect on yields to ensure reliable food production for an increasing global population (Keel et al. 2023).

In our study, we aimed to assess where and how much additional C can be stored in mineral agricultural soils in Europe (including Turkey) through a set of ten agricultural management options. For agroforestry-related measures, C sequestration in biomass is also considered. To estimate the feasible fraction of the theoretical maximum area of implementation, environmental and technical limitations (Heller et al. 2024) and, if applicable, EU regulations were considered. Emission factors (EFs) derived from European mid- and long-term experiments (MTEs and LTEs) were applied to quantify the C accrual potential of the management options as compared to clearly defined business as usual/reference management options. Furthermore, the uncertainties of subsoil C and N_2O emissions were estimated and discussed.

2 | Material & Methods

We considered ten agricultural management practices that are consistently reported in the literature to increase SOC and that are supported by a substantial empirical evidence base (e.g., Beillouin et al. 2019; Drexler and Don 2024; Leifeld et al. 2024; Panagea et al. 2025). For these practices, sufficient data are available to allow a robust, EU-wide assessment. To this end, we compiled a database drawing on approximately 450 experimental studies across Europe that quantify SOC responses to these management options (Ruysschaert et al. 2023, Version 2023_07_07).

The selected management options are non-inversion tillage and zero tillage compared to inversion tillage, irrigation compared to rainfed agriculture, biochar application, increased share of forage legumes and temporary leys including legumes in the crop rotation compared to the reference rotation with no or fewer forage legumes, cover cropping in comparison with bare soil in winter, crop residue retention in comparison with residue removal of cereal straw and establishment of woody vegetation on agricultural land (i.e., hedgerows, alley cropping, and silvopasture) compared to croplands without trees. While additional management practices may also have the potential to increase SOC, evidence for many of these is currently limited to a small number of studies, highly specific site conditions, or single field experiments. Such data constraints prevent reliable upscaling and comparison across diverse pedoclimatic conditions. Therefore, to ensure representativeness and applicability at the EU scale, we focused on management practices with sufficient spatial coverage, methodological consistency, and data availability to support a robust and comparable assessment across Europe.

2.1 | Definition of Agricultural Management Options

The selected options are thoroughly detailed in Panagea et al. (2024), for biochar in Leifeld et al. (2024), and summarised in Table 1.

2.2 | Emission Factors Linked to the Agricultural Management Options

Panagea et al. (2024, 2025) provided quantitative estimates of the impact of these agricultural measures on changes of SOC stocks in European agricultural mineral soils in the form of EFs. For biochar, we applied data derived from Leifeld et al. (2024) as the studies by Panagea et al. (2024, 2025) do not contain biochar as an option. These EFs followed the IPCC guidelines (IPCC et al. 2019) and were derived from the CarboSeq crop and soil management database (Ruysschaert et al. 2023) with results from European MTEs and LTEs. In the literature the EF is also referred to as the C response ratio or management factor (Ogle et al. 2005). An EF higher than 1 corresponds to SOC increase in the considered management option in comparison to the reference option while an EF lower than 1 shows a SOC stock decrease in the considered management option compared to the reference. For example, an EF of 1.05 means an SOC increase by 5%. Alongside the EFs relevant pedoclimatic and management predictors (e.g., precipitation, clay content, share of cereals in a crop rotation) for each option were reported. This harmonised methodological approach applied to estimate and analyse the EFs allowed for a consistent comparison and interpretation of the results across all considered agricultural management options.

For biochar, no EF is required. We only considered biochar that meets the requirements of the European Biochar Certificate (EBC 2012) and of the Delegated Regulation (EU) 2021/2088 on pyrolysis and gasification materials (European Union 2021). The biochar was assumed to be produced from woody materials with a H/C_{org}-range of 0.12–0.22, C yields of pyrolysis around 600°C of 45.3 ± 2.7, and corresponding C_{org} contents of 80.8% (Leifeld et al. 2024). Thus, its dry matter yield was 27% while the decomposition over 100 years was considered to be 8% (Leifeld et al. 2024).

TABLE 1 | Definitions of agricultural management options.

Group	Management option	Definition
Technical solutions	Non-inversion tillage	Non-inversion tillage is a management option where soil is tilled (loosened) but not turned (inverted) throughout the entire crop rotation. This is compared with inversion tillage as a reference.
	Zero-tillage	Zero-tillage is an option where soil is never tilled throughout the entire crop rotation and crops are sown directly into soil. This is compared with inversion tillage as a reference.
	Irrigation	Irrigation is the artificial watering of the land for the purpose of growing crops and the reference system is rain-fed cropping.
	Biochar	Biochar application means the application of pyrolysed organic material, commonly referred to as biochar, to the soil. The reference system is agricultural land without biochar amendment.
Crop management	Forage legumes and temporary leys in the crop rotation	Forage legumes and temporary leys is the introduction of forage legumes (defined as the legumes that are cultivated for their entire aboveground plant parts) and/or a ley (including legumes) in rotation with annual crops. The reference system is crop rotations without or fewer forage legumes and ley.
	Cover crops	Cover cropping is defined as the introduction of additional plant cover within existing cropping systems to temporarily cover bare soils, for example, bare winter fallows. The reference system is cropland with partially bare soil.
	Crop residues	Improved crop residue management consists of leaving crop residues on the field, that is, lower export of plant parts through harvest. The reference system is the removal of crop residues without return for example, straw burning.
Establishment of woody vegetation	Hedgerows	Hedgerows means the additional planting of lines of woody vegetation on cropland or grassland, often forming a boundary or fence around land parcels. The woody vegetation often includes shrubs and small trees and is typically managed. The reference system is agricultural land without hedgerows.
	Alley cropping	Alley cropping consists of the planting of individual trees on cropland in lines covering between 10% and 15% of the field. The trees are grown for more than 25 years before harvest (no short rotation coppices). The reference system is cropland without trees.
	Silvopasture	Silvopasture is the conversion of grazed permanent grassland, commonly referred to as pasture, to silvopasture through the planting of trees. The reference system is pasture without trees.

Moreover, analysis showed that the effect of hedgerows and alley cropping was comparable and was, therefore, grouped in the present study as "*woody features*" (Panagea et al. 2024). Silvopasture was added to this group as well, but only the additional biomass has been considered as no increases in SOC stocks are expected (Drexler et al. 2021; Drexler and Don 2024). It is important to note that for Norway, Sweden, and Finland, no SOC accrual through changes in tillage practices is anticipated due to the climatic conditions (Kätterer et al. 2012; Budai et al. 2024); thus, their emission factor was set to 1.00 (see Table 2).

2.3 | Estimation of the Area of Implementation

In theory, all agricultural land on mineral soil could sequester additional C if land-use and management were optimised solely to maximise SOC stocks. Organic soils under agricultural use are

TABLE 2 | Overview of the agricultural management options leading to soil organic carbon accrual and their emission factors following Panagea et al. (2024, 2025), Leifeld et al. (2024) and Emde et al. (2021).

Agricultural measure	Control	Emission factor (EF) with STD	Additional conditions
Non-inversion tillage	Full inversion tillage	1.03 (±0.18)	1.0 for Norway, Sweden and Finland[a] Only topsoil is considered
Zero-tillage	Full inversion tillage	1.11 (±0.25)	1.0 for Norway, Sweden and Finland[a] Only topsoil is considered
Biochar	No biochar application	Independent of SOC stock	Application rate 50 t dry mass ha^{-1}
Irrigation	Not irrigated	1.059 (±0.02)[b]	
Cover cropping	No cover crops	1.06 (±0.02)	
Crop residue management	Removal of all crop residues considering cereals and other crops (e.g., rapeseed, potato, sugar beet)	1.114560 – 0.75746 * SOC of the control per cm ($Mg\,ha^{-1}\,cm^{-1}$) + 0.214673 * cereals in rotation (%) + 0.002988 * clay content (%) – 0.000147 * annual rainfall (mm)	
Forage legumes, temporary ley	Crop rotations without or fewer forage legumes and temporary leys including legumes	1.182198 + 0.003957 * percentage difference of legumes in the rotation (%) – 0.129105 * SOC of the control per cm ($Mg\,ha^{-1}\,cm^{-1}$)	
Woody features (agroforestry-related measures)	Cropland or grassland without hedges	1.26 (±0.21)	For cropland soil under hedges and the trees No increase in SOC under grassland To account for biomass, 87 Mg C per implemented hectare were added[c]

Note: SOC refers to soil organic carbon. STD refers to standard deviation and appears in brackets after the EF.
[a]Value taken from Kätterer et al. (2012) and Budai et al. (2024).
[b]Value taken from Emde et al. (2021) due to lack of sufficient European data.
[c]Value taken from Drexler et al. (2021).

strong GHGs sources and here, other measures such as rewetting are needed to reduce C losses (Bianchi et al. 2021). Therefore, we refer to all agricultural land with mineral soil as the theoretical area of implementation, A_{theory}. In each region or pixel i, A_{theory} is defined as:

$$A_{theory,i} = A_{land,i} * f_{agr,i} * \left(1 - f_{peat,i}\right)$$

where $A_{land,i}$ is the land surface area of i in km^2, $f_{agr,i}$ is the land fraction of i used for agriculture including annual crops, permanent crops as well as managed grassland, and $f_{peat,i}$ denotes the fraction of agricultural land in i covered with organic soils. The two factors $f_{agr,i}$ and $f_{peat,i}$ can take values from 0 (= none of the land) to 1 (= all land).

The theoretical area of implementation is therefore defined as follows:

$$A_{theory} = \sum_{i=1}^{n} A_{\mathrm{theory},i}$$

where n denotes the number of regions or pixels considered.

A_{theory} was calculated for all the landmass of EU-27 countries, United Kingdom, Norway, Switzerland and Turkey. This landmass was divided into squared pixels, each 10 km by 10 km in size (Figure 1). For each pixel i and management practice, individual areas of implementation were calculated. The factor $f_{agr,i}$ indicated presence (value = 1) or absence (value = 0) of agricultural land based on Corine Land Cover Class 2: Agricultural areas (Corine Land Cover 2018), including arable land, permanent crops, pastures and heterogeneous agricultural areas. The land proportion with organic soil $f_{peat,i}$ was derived from the peatland map by Tubiello et al. (2016). The Inspire conform ETRS-LAEA projection (EPSG:3035) served as the coordinate reference system.

In practice, the area where it is feasible to apply the management practice where it is currently not implemented represents only a fraction of A_{theory} (Figure 2, diagonal stripes). This fraction is affected by:

a. The current intensity of implementation for a given measure in a given region, and

FIGURE 1 | Maps used to calculate the theoretical area of implementation (A_{theory}), from left to right: Landmass (A_{land}), land fraction with agricultural land (f_{agr}), land fraction with organic soils (f_{peat}).

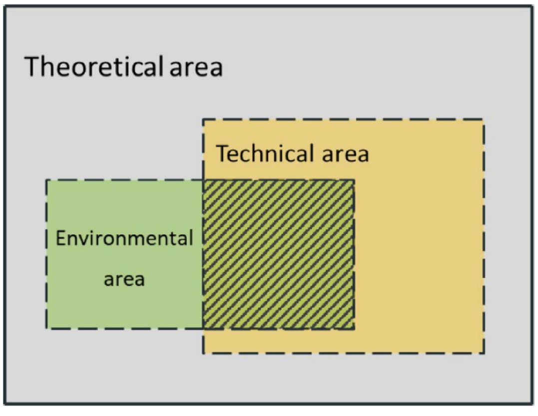

FIGURE 2 | Venn diagram illustrating different areas of implementation for a management option. While the theoretical area is the same for all measures (solid line), the environmental and technical areas of implementation are always areas where the measure is not yet implemented and they differ among individual options (dashed line).

b. Environmental as well as technical constraints, which hamper the further expansion of a given measure in a region, and

c. Other constraints (e.g., EU regulations).

Implementation of a given measure was only considered if it did not lead to significant reductions in productivity or yields, to avoid leakage effects associated with enhanced production and GHG emissions outside the target countries. Additionally, EU long-term policy goals were evaluated and used to help define feasible areas of implementation. These assumptions and calculations are described in detail for each measure in the supplemental materials and are summarised here in Table 3. An implementation intensity was estimated exclusively for the woody features and evaluated across two distinct scenarios. The framework is based on the European Commission's target to dedicate at least 10% of agricultural land to high-diversity features including woody features as well as grassy, riparian (e.g., ponds) and stony elements (e.g., stone walls) (COM 2020). In the ambitious scenario, we focused only on expanding woody features on arable land to meet the 10% threshold, prioritising their superior C accrual potential. Conversely, in the conservative scenario, we assumed that the 10% target is achieved by increasing all landscape features proportionally, applying a uniform country-specific factor across woody, grassy, riparian, and stony elements. Comprehensive details are provided in the Supporting Information.

2.4 | Calculation of the Carbon Sequestration Potential

Emission factors, as listed in Table 2, are used to calculate the C accrual of an implemented measure for European agricultural land as follows:

$$C_{acc,i,\ j} = C\ stock_{ref,i,j} * \left(EF_{i,j} - 1\right)$$

where $C_{acc,i,j}$ is the C accrual potential for measure j (Mg C) in region i, $C\ stock_{ref}$ is the topsoil SOC stock in 0–30 cm depth in i derived from SoilGrids data ($\mathrm{Mg\,ha^{-1}}$) for measure j (Poggio et al. 2021) and $EF_{i,j}$ is the emission factor of measure j in region i.

$C\ stock_{ref,i,j}$ was calculated for measure j in i as follows

$$C\ stock_{ref,i,j} = \sum_{i=1}^{n} A_{theory,i} * f_{i,j} * C\ stock_{today,i}$$

where $A_{theory,i}$ is the theoretical area of implementation in i (ha), $f_{i,j}$ is the fraction of the theoretical area of implementation for measure j in i and $C\ stock_{ref,i}$.

This C accrual potential of a measure has been converted into Mt. CO_2e.

In this work, the baseline of each management option is the current SOC stock which is compared to the implementation scenario. This difference is the C accrual and equals the C sequestration potential following Don et al. (2024).

To calculate the yearly potential C sequestration rates it is important to consider the time period until a new SOC equilibrium is reached as agricultural management options do not indefinitely increase SOC (Don et al. 2024). This has been taken into account for each measure individually. For the annual C sequestration rates, it was assumed that soils reach a new steady state SOC stock after 50 years (Johnston et al. 2009). This is a simplification due to its dependence on climate and soil conditions. Considering that climate change may affect these estimated

TABLE 3 | Definition of area of implementation for different management options.

Land management practice	Eligible Land within A_{theory}	Implementation assumptions	Formula for implementation area	Data sources
Non-inversion tillage	• Arable land used for annual crops • Regularly ploughed	All inversion tillage is stopped	$A_{non\_inversion\_till} = \sum_{i=1}^{n} A_{theory,i} * f_{arable,i} * f_{plough,i}$	EUROSTAT 2020a; FAOSTAT 2023; Porwollik et al. 2019
Zero tillage	• Arable land used for annual crops • Regularly ploughed • Farmed conventionally	All tillage activities are stopped	$A_{zero\_till} = \sum_{i=1}^{n} A_{theory,i} * f_{arable,i} * f_{plough,i} * \left(1 - f_{organic,i}\right)$	EUROSTAT 2023; FAOSTAT 2023
Irrigation	• Not currently irrigated • Equipped with infrastructure for irrigation	Sufficient irrigation assumed to avoid water deficits	$A_{irrigation} = \sum_{i=1}^{n} A_{theory,i} * \left(f_{irrigable,i} - f_{irrigated,i}\right)$	FAO 2013; Siebert et al. 2013
Biochar application	• Cropland (annuals and perennials) • Soils with a pH value of ≤ 7	Cumulative biochar application up to 50 t ha^{-1} over multiple years	$A_{biochar} = \sum_{i=1}^{n} A_{theory,i} * \left(f_{arable,i} + f_{perennial,i}\right) * f_{pH}$	Corine Land Cover 2018; Liu et al. 2013; Poggio et al. 2021; Schmidt et al. 2021
Forage legumes and temporary ley management	• Land currently used for green maize	Replacement of green maize with forage legumes/temporary grass-clover ley	$A_{fodder} = \sum_{i=1}^{n} A_{theory,i} * f_{arable,i} * f_{green\_maize,i}$	EUROSTAT 2020b; 2024
Land management practice	**Eligible land within A_{theory}**	**Implementation assumptions**	**Formula for implementation area**	**Key data sources**
Cover crops	• Under bare fallow for part of the year • Introduction of additional plant cover without irrigation	Replaces winter bare fallows Grown after a primary crop Climatic factors considered following Vanwindekens et al. (2022)	$A_{cc} = \sum_{i=1}^{n} A_{theory,i} * f_{rainfed\_arable,i} * f_{bare,i} * f_{climate,i}$	Corine Land Cover 2018, class 21: arable land; class 2: agricultural areas; EUROSTAT 2020c; BFS 2017; Brun et al. 2022; Vanwindekens et al. 2022
Crop residue management	• Arable land • With open fires	Residue burning practices completely stopped	$A_{residue} = \sum_{i=1}^{n} A_{theory,i} * f_{arable,i} * f_{fire,i}$	Randerson et al. 2017

(Continues)

TABLE 3 | (Continued)

Land management practice	Eligible land within A_{theory}	Implementation assumptions	Formula for implementation area	Key data sources
Woody features (ambitious)	• Arable land • 10% of agricultural area under high-diversity features as foreseen by the European commission (accounting for current high-diversity features) (COM 2020)	Implementation only on cropland	$A_{wood\_ambitious} = \sum_{i=1}^{n} A_{theory,i} * f_{arable,i} * f_{A,i}$ with $f_{A,i} = \frac{0.1*A_{agr,j} - f_{lf\_today,j}*A_{agr,j}}{A_{arable,j}}$	COM 2020; D'andrimont et al. 2023; EUROSTAT 2023
Woody features (conservative)		Implementation on cropland and grassland	$A_{wood\_cons} = \sum_{i=1}^{n} A_{theory,i} * f_{B,i}$ with $f_{B,i} = \frac{0.1}{f_{lf\_today,j}} * f_{wf_{today},j} - f_{wf\_today,j}$	

steady states, they may never be reached. C accrual is mostly a non-linear process with highest C accrual rates in the first years while the new equilibrium of SOC stocks is approached within 50 years after implementation of a measure (Johnston et al. 2009). Further, a time of 100 years is considered for biochar due to its long-term stability (Leifeld et al. 2024). Regarding the woody features, biomass accumulation was calculated over a 50 year horizon; for hedges this included two harvests at 25-year intervals (Drexler and Don 2024). This paper focuses exclusively on C accrual to evaluate which measures offer the greatest sequestration potential. This study does not take climate change scenarios into account.

2.5 | Subsoil Carbon

Subsoil C effects have been considered for all measures, except for biochar, as biochar is only applied to topsoil. We calculated the effects of changes in agricultural management on subsoil C stocks through a ratio of subsoil (30–50 cm) to topsoil (0–30 cm) for each measure and applied it to the respective C sequestration potential (Table 4). For instance, if the effect of irrigation is 1 ton C ha^{-1} for the topsoil, then the C accrual in the subsoil is 1×0.28 ton C ha^{-1} (Table 4).

2.6 | Statistical Analysis

All analyses were performed using R (v4.3.3; R Core Team 2024) within the RStudio environment. Spatial data processing and visualisation were conducted using the R packages sf (Pebesma 2018), terra (Hijmans 2025), and stars (Pebesma and Bivand 2023), and figures were produced using ggplot2 (Wickham 2016) with components of hrbrthemes (Rudis 2025). Relative uncertainty was calculated for five out of the eight measures as the EFs standard deviation divided by the mean and expressed as a percentage. The remaining three measures are the forage legumes, temporary ley, the crop residues and the biochar measure which all have no EF as they are calculated either with an improved European formula instead of a simplified EF or have no EF in the case of biochar.

3 | Results

The potential area for implementing additional agricultural measures in Europe called A_{theory} covered about 220 million hectares, with the highest proportion found in Turkey (15%), followed by France (14%), Spain (11%), Germany (8%), Poland (7%), Italy (7%), Romania (6%) and the United Kingdom (5%). The other 23 countries together accounted for about a quarter of A_{theory} (Table S1). It was observed that more options are implementable in central and eastern Europe (e.g., Germany and Hungary) than in northern and southern countries (Figure 3).

In the present study potential C sequestration in grassland is restricted to the planting of additional woody features. In cropland, the largest areas of implementation are available for technical solutions (tillage > biochar > irrigation) and improved crop rotations (cover crops > crop residues > forage legumes and/or temporary ley), while the area available for additional

TABLE 4 | Subsoil carbon effects of different agricultural management options. The subsoil ratio represents the effect of topsoil carbon content changes (0–30 cm) on subsoil carbon (30–50 cm).

Management option	Subsoil ratio	Data source
Non-inversion tillage	−0.79	Hernanz et al. 2002; Haddaway et al. 2017
Zero tillage	−0.21	Hernanz et al. 2002; Haddaway et al. 2017
Irrigation	0.28	Emde et al. 2021
Forage legumes, temporary leys	0.16	Börjesson et al. 2018
Cover crops	0.00	Jian et al. 2020
Crop residues	0.16	Skadell et al. 2023
Woody features (soil)	0.69	Drexler and Don 2024

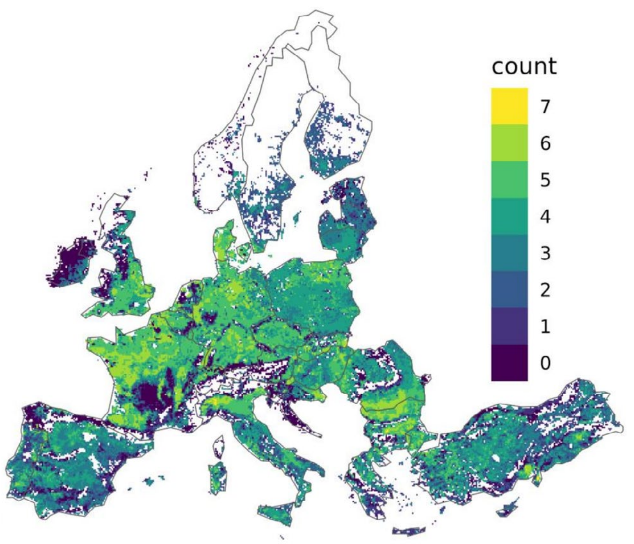

FIGURE 3 | Number of agricultural management options that could be additionally implemented on European scale considering reduced tillage, biochar, irrigation, cover crops, crop residues, legume and ley rotations, and woody features (ambitious scenario) on each pixel of the 10 × 10 km grid. Each measure was counted if it covered at least 1% of the total cell size. Counts are only shown for cells in the target area and with mostly agricultural land-use.

woody features is relatively small (Figure 4). Country-specific areas of implementation for individual SOC accrual measures are available in the Supporting Information (Table S1). Each measure exhibits a unique distribution pattern across Europe, making broad generalisations hardly feasible (Table S1).

The results of the C sequestration potential analysis showed that, at a European scale, biochar application has by far the highest potential to increase C, followed by woody features and zero tillage while only small potentials were estimated with measures affecting crop rotations (Figure 5, Table 5).

The calculation of annual C sequestration potentials (Table 5) showed that the additional implementation of the selected measures could potentially sequester in the topsoil between 148 and 205 Mt. CO_2e per year over 50 years until a new equilibrium is reached (over 100 years for biochar). This number is 123–186 Mt. CO_2e per year over 50 years when only considering the EU-27 member states. The C sequestration potential of all measures increases when considering subsoil C except for tillage practices (Table 5) showing negative effects (Hernanz et al. 2002; Haddaway et al. 2017). Cover crops showed no effect on subsoil C due to scarcity of data on deep rooting species across different pedo-climatic regions (Liang et al. 2022). It is important to note that non-inversion and zero tillage are mutually exclusive as well as the simultaneous implementation of the ambitious and conservative scenario of the woody features. Further, the biochar management option comes with several limitations for its implementation regarding the issues of needed biomass feedstock and current production capacities, which are discussed in chapter 4. Total C sequestration potentials by country and measure can be found in Table S3 and including subsoil C in Table S4. It is important to note that the variability of the EFs indicates that C sequestration estimates are most uncertain for zero tillage, followed by forage legumes and ley rotations and woody features, moderate for non-inversion tillage, and comparatively robust and consistent for crop residue management, cover cropping, and irrigation.

Per implemented hectare, the most efficient options to potentially sequester C taking C changes in subsoils into account are woody features followed by biochar and forage legumes and temporary ley management (Table 6).

The relative uncertainty of the EFs is highest for the tillage related measures, followed by the SOC of woody features. Lowest values were identified for the measures Irrigation and Cover crops (Table 7).

Overall, our conservative and ambitious estimates of C sequestration potential including subsoil C correspond to 31% and 49% of the current GHG emissions from European agriculture, including Norway, Switzerland, the UK and Turkey (UNFCCC 2024), respectively (Table 8).

4 | Discussion

4.1 | C Sequestration Potential

The estimation of C sequestration potential across Europe shows that different soil management practices vary in effectiveness. Farmers in central Europe have more options to increase soil C compared to those in northern or southern regions, due to fewer environmental constraints like climate and soil type, which influence land-use and the feasibility of certain practices. Out of the seven evaluated measures, all are robustly increasing C accrual except tillage related measures. Overall, our estimates of C sequestration potential including subsoil C

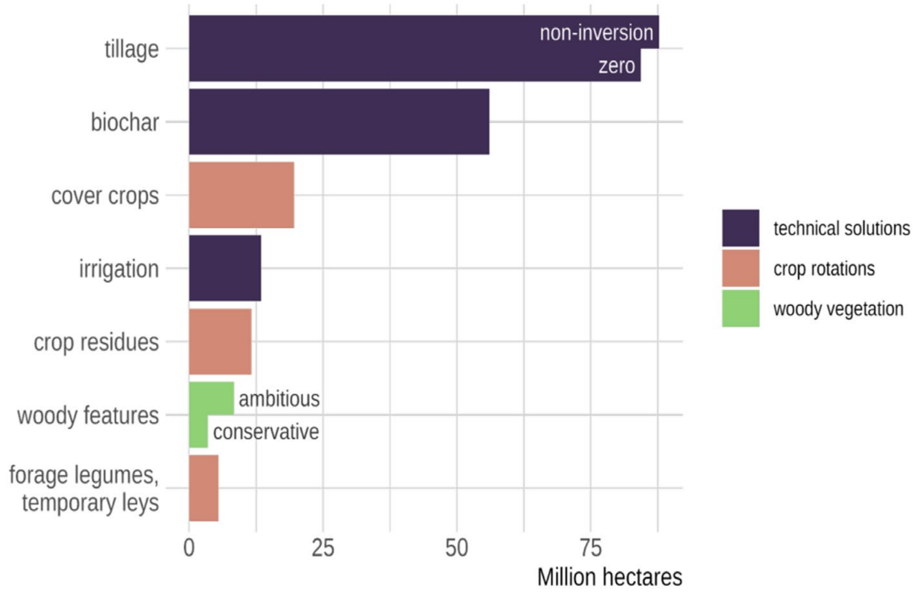

FIGURE 4 | Management options for carbon accrual ranked by total area of additional implementation in million hectares at European scale. Numbers found in Table S1.

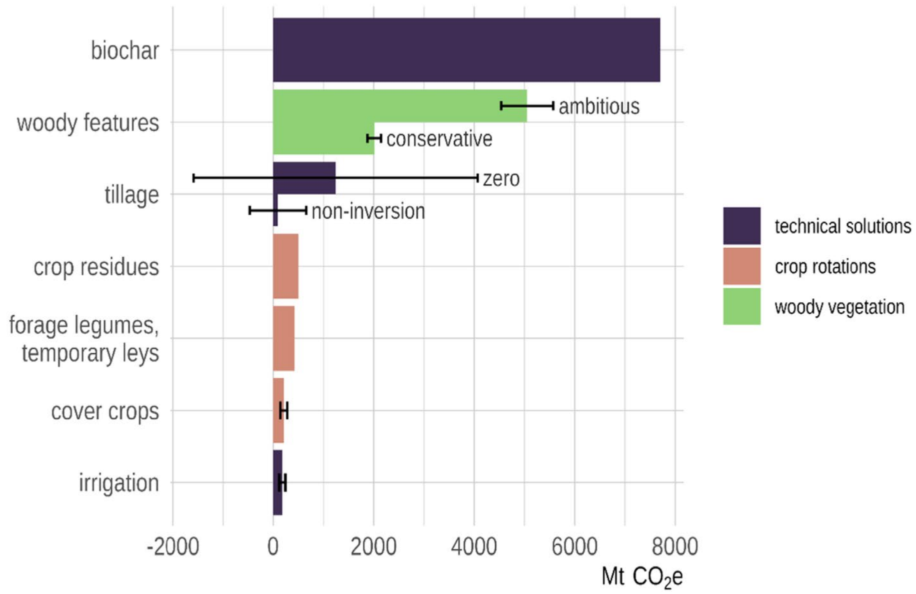

FIGURE 5 | Management options leading to C accrual ranked by total additional C sequestration potential in Mt. CO_2e over a period of 50 years at European scale including subsoil carbon. Numbers found in Table 5.

could mitigate one-third to half of the current GHG emissions from European agriculture, including Norway, Switzerland, UK and Turkey (UNFCCC 2024). These include direct emissions from for example, livestock, manure management and fertilisation. The emissions from agricultural activities, as reported in the LULUCF sector of 236 Mt. CO_2e (Giersbergen et al. 2024, not including Turkey), should also be considered here as these include emissions from land-use change (e.g., grassland to cropland) as well as SOC changes in agricultural land (e.g., emissions from drained peatlands). In this context, compared to the GHG emissions reported in the agriculture and LULUCF sectors, our C sequestration potential corresponds to 21% and 33% under the conservative and ambitious scenario, respectively. Furthermore, it corresponds to 47% and 74% of the EU's ambitious target of 310 Mt. of C removals in the LULUCF sector by 2030 (CRCF 2022). For the EU-27, these values correspond to 32% and 50% of emissions from the agricultural sector alone. When emissions from the LULUCF sector are included, the shares decrease to 20% and 31%.

Our results are in line with the study of Rodrigues et al. (2021), who estimated that agricultural management options could lead to a SOC accrual that was equal to 0.1%–27% of GHG emissions from the agricultural sector at national scale across 13 EU member states. Our estimates are in the upper range due to the inclusion and dominance of biochar as a C sequestration measure. Of the

TABLE 5 | Overview of the selected management options leading to carbon (C) accrual and their C sequestration potential estimated over 50 years at European scale.

Agricultural management option	Total C sequestration potential (0–30 cm) (Mt CO_2e)	C sequestration potential including subsoil C (0–50 cm) (Mt CO_2eq)	Yearly pot. C sequestration rate (0–30 cm) (Mt CO_2e yr.$^{-1}$)	Yearly pot. C sequestration rate including subsoil C (0–50 cm) (Mt CO_2e yr.$^{-1}$)
Non-inversion tillage	446	94	8.9	1.9
Zero tillage	1574	1244	31.5	24.9
Biochar	7703	7703	77.0[a]	77.0[a]
Irrigation	140	179	2.8	3.6
Cover crops	208	208	4.1	4.1
Crop residues	437	506	8.7	10.1
Forage legumes, temporary ley	361	419	7.2	8.4
Woody features (conservative)	99 (SOC)	167 (SOC)	1.9 (SOC)	3.3
	1844 (Biomass)	1844 (Biomass)	36.8 (Biomass)	36.8 (Biomass)
	1943 (total)	2011 (total)	38.8 (total)	40.2
Woody features (ambitious)	380 (SOC)	643 (SOC)	7.6 (SOC)	12.9
	4412 (Biomass)	4412 (Biomass)	88.2 (Biomass)	88.2 (Biomass)
	4792 (total)	5055 (total)	95.8 (total)	101.1
Total conservative (not considering zero tillage and ambitious woody features)	11,238	11,119	147.7	145.3
Total ambitious (not considering non-inversion tillage and conservative woody features)	15,215	15,313	204.7	229.3

[a]Biochar estimated over 100 years due to long-term stability (Leifeld et al. 2024).

TABLE 6 | Carbon (C) sequestration potential per hectare over 50 years (biochar over 100 years) of agricultural management options based on the area of implementation and taking subsoil C changes into account.

Management option	C sequestration potential (0–30 cm) [t CO_2e ha^{-1}]	C sequestration potential including subsoil C (0–50 cm) [t CO2eq ha^{-1}]
Non-inversion tillage	5.1	1.1
Zero tillage	18.7	14.7
Biochar	137.3	137.3
Irrigation	10.5	13.4
Cover crops	10.7	10.7
Crop residues	37.6	43.5
Forage legumes, temporary ley	66.4	77.0
Woody features (ambitious)	134.1	188.1
Woody features (conservative)	64.9	98.5

TABLE 7 | Relative uncertainty of emission factors (EF) per management option.

Management option	C sequestration potential including subsoil C (0–50 cm) in Mt. CO2eq	Relative EF uncertainty (%)
Non-inversion tillage	94 ± 562	17.5
Zero tillage	1244 ± 2826	22.5
Biochar	7703	—
Irrigation	179 ± 61	1.9
Cover crops	208 ± 70	1.9
Crop residues	506	—
Forage legumes, temporary ley	419	—
Woody features conservative	2011 ± 135	16.7
Woody features ambitious	5055 ± 519	16.7

Note: For biochar, no EF was used. For crop residues and forage legumes, temporary ley formulas from Table 2 were used.

total conservative C sequestration potential (not including subsoil C effects), 66% is linked to biochar, which is included by Rodrigues et al. (2021) only for Norway and no other country. Additionally, they estimated that reduced tillage, crop residue management, ley rotations, and cover crops measures could reduce GHG emissions by a total of 549–2141 Mt. CO_2e by 2100. These results align well with our total potential C sequestration estimation for the same subset of measures, with 1452 Mt. CO_2e (not including changes in subsoils C, Table 5). This is despite their estimation running from the year 2013 until 2100 and thus going beyond our 50 years estimate. Further, their considered area differed as well, as they included the EU, Serbia, Bosnia and Herzegovina, Montenegro, Albania, Former Yugoslav Republic of Macedonia, and Norway. The key difference is that they compiled data from different sources and calculated emission reductions for measures with differences in methodology, making comparisons between countries challenging. For example, they found a large variation in relation to soil depths and the periods of time considered when estimating C sequestration potentials, whereas we used one harmonised method and applied limitations to the area of implementation based on feasibility and current management practices across all countries.

Including subsoil C changes increased the overall C sequestration potential by 2%, excluding biochar and hedge biomass, which aren't applied to subsoils (Table 5). The subsoil C contribution (averaging 12% across measures) aligns with reported values by Skadell et al. (2023), who estimated a 20% contribution. However, reliable quantification is limited due to a general lack of subsoil C data, as it is rarely measured in long-term experiments and often excluded from soil monitoring, especially in relation to specific agricultural practices (Harbo et al. 2023; Froger et al. 2024; Meurer et al. 2024).

Based on our results, the most efficient and robust measures to increase C accrual are biochar application due to the high permanence of biochar carbon and robust conversion of application rates into C accrual rates. The implementation of woody features has also a large and easy to quantify C accrual potential while cover crops, crop residues, irrigation and forage legumes, temporary ley measures reliably increase C accrual but on a much smaller scale. Tillage related measures, especially zero tillage may increase C accrual, but these results are much less robust than all the other measures.

4.2 | Non-Inversion Tillage

The IPCC suggests that depending on the climate, non-inversion tillage leads to either decreases or increases in SOC stocks with EFs ranging from 0.98 to 1.05 for boreal, cool and warm temperate regions respectively (IPCC 2019). This factor is a simplification and is on a small scale influenced by variables such as climate, soil type and crop type (IPCC 2019). In contrast, by only considering European MTEs and LTEs, we found no significant differences in EFs across Europe based on pedo-climatic conditions resulting in a single European EF for non-inversion tillage of 1.03 (Panagea et al. 2024). The IPCC reports EFs of 0.98 and 0.99 for dry boreal and temperate climates, respectively (IPCC 2019). Based on the location of the MTEs and LTEs used for our EF calculation, we may overestimate the C accrual from this measure for Norway, Sweden and Finland. To avoid this potential overestimation having an outsized effect on our results, we set the EFs of these countries to 1.00 (Kätterer et al. 2012; Budai et al. 2024), effectively reducing the area of implementation to

TABLE 8 | Overview of the annual C sequestration potentials and reported emissions from agriculture and the Land-Use, Land-Use Change and Forestry (LULUCF) sector.

Scenario	C sequestration potential	C sequestration potential including sub soils	Emissions from the agricultural sector[a]	Emissions from the agricultural and LULUCF sector[b]
	Mt CO_2e $yr.^{-1}$			
Conservative	148	145	432 (504)	668 (740)
Ambitious	227	229		

[a]Data include GHG emissions from European agriculture, including Norway, Switzerland, and the UK in 2021. Values including Turkey in 2021 in brackets (UNFCCC 2024).
[b]Data for the year 2022 not including Turkey (not publicly available). Value in brackets includes emissions from the agricultural sector in Turkey but not its LULUCF sector emissions (Giersbergen et al. 2024).

exclude sites from Norway, Sweden, and Finland, which affects 3.5% of the area of implementation. Further, the European EF has been calculated based on the topsoil (minimum sampling depth 15 cm, maximum 40 cm, mean 22.80 cm) and does not include the whole soil profile up to 100 cm depth. This may lead to an overestimation of the EF and thus the C sequestration potential of non-inversion tillage on subsoil is neglected resulting in a possibly "positive" effect in topsoil, but no effect across the full profile (Haddaway et al. 2017; Meurer et al. 2018).

4.3 | Zero Tillage

The IPCC suggests that zero tillage always leads to an increase in SOC with EFs ranging from 1.03 to 1.10 for boreal, cool and warm temperate regions (IPCC, 2019) and is influenced by pedo-climatic conditions, crop types and may also affect other GHG emissions (IPCC 2019). The new European-wide EF of 1.11 from this study, which was based solely on European experiments, was comparably high and not affected by pedo-climatic conditions. This may be linked to a potential bias in the dataset, with inadequate representation of all climates. In our dataset, 14 out of 27 zero tillage experiments were conducted in a Mediterranean climate, with the majority located in semiarid Spain (Panagea et al. 2024). Further, Kätterer et al. (2012) and Budai et al. (2024) found no positive effects on SOC for Sweden, Finland and Norway. Thus, these areas have been assigned an EF of 1.00 in accordance with the non-inversion tillage option, affecting 3.2% of the total area of implementation. Due to the availability of data, the EF has been calculated based on the topsoil (minimum sampling depth 15 cm, maximum 30 cm, mean 28.40 cm) and does not include the whole soil profile down to 100 cm. This approach may lead to an over- or underestimation of the EF and the linked C sequestration potential, as effects on subsoil are neglected resulting in a "positive" effect in topsoil, but no effect in the full profile (Blanco-Canqui et al. 2021).

4.4 | Biochar

Biochar is identified as the most effective management option for increasing SOC due to its large implementation potential and slow degradation (Leifeld et al. 2024). It stabilises C via biomass pyrolysis (Wang et al. 2016) and can improve soil properties (Joseph et al. 2021). The C sequestration estimate accounts for C losses during processing and assumes a 100-year time horizon (IPCC 2019; Leifeld et al. 2024). However, biochar use is limited by soil pH, as excessive application can lead to over-alkalisation and reduced yields (Jeffery et al. 2017; He et al. 2021). Application should not exceed 50 Mg ha^{-1} in the temperate zone (Jeffery et al. 2017), with typical rates around 1 Mg ha^{-1} $yr.^{-1}$. In Switzerland the potential is further limited by proposed regulations capping application at 10 Mg ha^{-1} (Bundesamt für Umwelt 2021), reducing the estimated CO_2 savings from 30 Mt. CO_2e to 6 Mt. CO_2e.

Large-scale biochar application is limited by feedstock availability and pyrolysis capacity. Current EBC-certified production in Europe is only 0.064 Mt. $yr.^{-1}$ (Hagemann et al. 2024). To scale up, biochar must become more cost-effective, potentially through subsidies. Within the agricultural sector, redirecting biomass currently less efficiently used, like 146 Mt. of straw currently burned for energy, could yield 32 Mt. of biochar annually (Monforti et al. 2015). Yet, this straw could also be added to cropland soil with the related effects discussed in the crop residues management option below. The 14 Mt. of unused hedge prunings across Europe (Dyjakon and García-Galindo 2019) and through implementation of our conservative woody vegetation management option could add another 3 Mt. and 8 Mt. biochar per year. Altogether, producing the needed biochar for agricultural soils would take 68 years, assuming sufficient production facilities. Only EBC-certified biochar should be used to avoid soil contamination (EBC 2012), while long-term effects remain uncertain due to limited data (Schmidt et al. 2021).

However, currently the substitution of fossil carbon (e.g., coal) may be a better climate mitigation option than applying biochar to soil as the pyrolysis of woodchips produces heat and power. In the future, when the energy sector is decarbonised, application to soil will become a better option (Azzi et al. 2019).

4.5 | Irrigation

Irrigation as a C sequestration measure is ranked at the bottom of all measures that foster SOC accrual. A new robust EF could not be derived, as only three European experiments of sufficient quality could be identified by Panagea et al. (2024). More field experiments are needed and, until then, we use the EF of 1.059 suggested by Emde et al. (2021). This EF was determined through a global meta-analysis and is considered more robust. They found that the irrigation method influences the effect on

SOC and only sprinkler irrigation showed significant SOC accrual in their dataset. We restricted the area of implementation to croplands with existing irrigation infrastructure assuming that water would be available with the infrastructure. However, due to climate change effects, the water availability for agricultural irrigation purposes in regions and seasons where irrigation could be beneficial will be increasingly limited. Therefore, optimising water use (e.g., through more efficient irrigation methods such as subsurface drip irrigation) in agriculture for maintaining and enhancing yield are in the focus while C sequestration in soils may remain simply a side product.

4.6 | Cover Crops

The C sequestration potential of cover crops calculated here is lower than previously estimated by Poeplau and Don (2015), who reported much higher values. This difference stems from three key improvements in the current analysis: (i) accounting for climate-based limits on when cover crops can be grown within crop rotations, (ii) reflecting more realistic farming practices where cover crops are not used every year but at least every second, and (iii) using better remote sensing data to identify actual bare cropland, rather than assuming 25% of all cropland is suitable.

While the estimates seem more realistic and are in line with for examplel, Keel et al. (2023), limitations remain—particularly the underrepresentation of studies from the boreal and Mediterranean regions, which could skew results (Panagea et al. 2024). Further, our assumptions may underestimate the C sequestration potential in boreal regions, where cover crops are often undersown in spring to cope with short autumns (Poudel et al. 2022). Another critical assumption is for the climatic limitations, where we presumed that cover crops are grown after non-irrigated winter wheat and thus neglect any other crops on which cover crops may follow (Heller et al. 2024). Finally, climate change could reduce the C sequestration potential due to more frequent unfavourable weather after main crop harvests (Lee et al. 2023).

Overall, better data on crop rotations, harvest and seeding times are required, as these strongly affect when and how long cover crops can grow, and thus their C input to soils (Gselman and Kramberger 2008). There is also a need for LTEs and new field trials in underrepresented regions in order to better elucidate the effects of cover crops on SOC accrual including its effect on subsoil C.

4.7 | Crop Residues

In our study, the new European EF used for crop residues is mainly based on cereal straw and thus highly relevant for European croplands. Yet, many other crop residues will not be well represented by this EF (Panagea et al. 2024). C sequestration in soils is only possible if additional crop residues can be left on the soil compared to current practice (including straw residue harvest and returning them to soils as part of farmyard manure). Thus, as for the area of implementation, only soils where crop residues are currently burned are considered. Because the straw in these new areas must be incorporated, additional GHG emissions from the use of a field cultivator lead to an increase of 37% compared to the baseline (Nikolaus and Lesschen 2024).

4.8 | Forage Legumes and Temporary Leys

The option to increase the share of forage legumes (grown for harvest of total above-ground biomass such as clover, clover mixtures, lucerne and vetch) and temporary leys which include legumes in crop rotations was chosen as a measure due to the acknowledged C accrual potential revealed by a strong base of available data that cover the majority of pedoclimatic conditions in Europe (Panagea et al. 2024). Indeed, SOC accrual is possible through an increased share of forage legumes and temporary leys, in addition to multiple other soil health benefits such as reduction of N fertiliser demand and reduced tillage needs (Kremen et al. 2012; Wezel et al. 2014; Garbach et al. 2017; Beillouin et al. 2019; Tamburini et al. 2020; Di Bene et al. 2022). Additionally, the potential to enhance SOC stocks through this measure aligns with the current priorities on the political agenda of the European Union (European Commission 2020). In Europe, protein crops such as forage legumes are grown on only 3% of arable land, yet they supply 30% of the EU's crop protein consumption as animal feed (Häusling 2011). To reduce the resulting import dependency, Europe is investing in policies boosting and reintroducing high-protein crops by "fostering EU-grown plant proteins" (European Commission 2018, 2020). A higher fodder production through implementation of this management option will increase EU protein output and can reduce imports (Leip et al. 2010).

Yet, defining the area of implementation for this measure was challenging since forage legumes can be grown on almost all arable land across Europe. An approach towards a feasible potential area of implementation involves creating a scenario in which land-use is optimised without drastic external consequences in other parts of the agri-food-production chain. Replacing green maize with forage legumes (e.g., alfalfa) or temporary leys could be conducted without changing animal numbers but would result in extensification, as less fodder per hectare would be grown for example, when compared to silage maize (Lehtilä et al. 2024). Thus, all areas currently used for green maize production were repurposed to introduce leguminous forage crops into the crop rotation. This scenario represents just one of many possible variations for introducing this measure into a crop rotation. The consequence of this choice is that in some areas the potential might be overestimated (areas with high share of green maize) or underestimated (areas where it could replace other crops than maize). If this forage crop is alfalfa, emissions could be reduced up to 40% due to reduced field operations (Nikolaus and Lesschen 2024).

4.9 | Woody Features

Agroforestry systems are championed to store additional C in biomass and soil not only per hectare, but also when implemented across Europe (Tables 5, 6) and can therefore become an active C sink if they are newly implemented (Drexler et al. 2021). This is reflected in the management option having the second highest C sequestration potential of all identified options when considering both SOC accrual and C stored in biomass. The new European EF for SOC (1.26) is valid for hedgerows and alley cropping systems alike and represents only the soil covered with woody vegetation. It comes with the limitation that most data derive from Western Europe, which increases the uncertainty of estimates for other areas. The EF cannot be and was not applied to soils under silvopasture and grassland management as the SOC is expected to remain stable if grasslands are the reference system (Panagea et al. 2024).

This measure is not only increasing SOC stocks but also storing additional C in the biomass. Therefore, it is coherent to include C in aboveground and belowground biomass in the C sequestration potential of the measure. In fact, this is the main effect representing about 90% of the C sequestered through this measure. In agroforestry systems there are many variables controlling C storage in biomass, for example, tree species, tree density, and percentage of trees included in hedges. All these variables can lead to varying C sequestration potentials. We followed the results from Drexler et al. (2021) for biomass suggesting an average C storage potential of hedgerows representative of the temperate climate zone, as this is currently the most comprehensive and representative study on this topic.

To implement this measure, a scenario was designed in line with the European Commission's biodiversity strategy to increase the share of high-diversity features in the agricultural landscape to 10% of all current agricultural land (European Commission 2020). In practice, even the conservative estimate of the management option is ambitious, as we assume that farmers will plant hedges instead of landscape features that are easier and cheaper to implement, such as buffer strips or rotational fallow land.

4.10 | Trade-Offs and Co-Benefits

Each agricultural management option comes with its own specific trade-offs and co-benefits which must be considered in the implementation strategies. For example, possible offsets to food production, reduction in GHG emissions or groundwater recharge. It is also often expected a positive impact of SOC accrual on many ecosystem services and positive effects on soil functions such as water infiltration rates, pollutant filtration or erosion control. Such trade-offs and co-benefits are briefly touched upon for each option below.

Non-inversion and zero tillage may lead to increased herbicide use and reduced fuel consumption, and the overall GHG emissions are expected to decrease due to avoided ploughing (Nikolaus and Lesschen 2024). The effect on N_2O emissions is site-specific and may negate the potential C sequestration benefits in the case of non-inversion tillage but probably not for zero tillage (Guenet et al. 2021; Li et al. 2021; Table S5, Table S6). Zero tillage reduces direct emissions by 2.8% compared to ploughing (Nikolaus and Lesschen 2024), though herbicide use may rise—with mixed findings across studies (Lal 2004; Hobbs and Govaerts 2010; Sainju et al. 2014; Sørensen et al. 2014; Troccoli et al. 2015; Dachraoui and Sombrero 2020). Non-inversion and zero tillage offer co-benefits beyond C storage, including improved soil water conservation (especially in dry regions), reduced erosion, better soil structure, enhanced soil biota, and potential economic gains (Mihovsky and Pachev 2012; Betancur-Corredor et al. 2022; Spiegel et al. 2025). However, there is a risk of increased soil compaction which in turn may lead to increases in N_2O emissions (Soane et al. 2012; Powlson et al. 2014).

Biochar provides several soil health benefits—such as better water infiltration and retention, lower soil bulk density, and improved nutrient availability—especially in semi-arid regions. These effects were minimal in temperate zones with mean annual temperatures below 9°C, where no yield improvements have been observed (Schmidt et al. 2021). Further, biochar may reduce N_2O emissions by up to 33%, aiding climate mitigation, though the duration of this effect varies across studies, lasting from one to at least three years (Hagemann et al. 2017; Verhoeven et al. 2017; Borchard et al. 2019; Joseph et al. 2021; Valkama et al. 2024). The key advantage of biochar is that, once applied, it provides long-term C storage and, unlike other practices, does not require continuous management. Consequently, biochar is particularly well aligned with the EU Carbon Removals and Carbon Farming Certification Regulation (European Commission 2024). However, as long as the energy sector is not decarbonised, a more efficient use of the pyrolisation of biomass could be to replace fossil C products with biochar (Azzi et al. 2019).

Expanded irrigation offers co-benefits such as increased crop yields, greater yield stability, and more opportunities to diversify cropping systems (Smith et al. 2013). Yet, water resources are limited and are already overexploited in some countries, and precipitation patterns are expected to change due to climate change effects (Trenberth 2011).

Non-leguminous cover crops can reduce nitrate leaching by about 56% in temperate regions, though they may increase N_2O emissions (Thapa et al. 2018; Lugato et al. 2018; Nikolaus and Lesschen 2024). Despite additional emissions from seeding and machinery use, overall GHG emissions are likely lower compared to no cover cropping (Nikolaus and Lesschen 2024; Table S5, Table S6) not taking into account possibly considerable emissions from additional area used for seed production and associated resources for growing and transporting seeds. In cold regions, frost-sensitive species can increase N_2O emissions, emphasising the need for regionally adapted mixtures minimising this risk (Kjær et al. 2026). Other co-benefits include enhanced biodiversity, better nitrogen availability for following crops, reduced erosion and nitrogen leaching, improved weed control and soil structure, and greater landscape attractiveness (Poeplau and Don 2015; Adetunji et al. 2020; Kim et al. 2020; Nouri et al. 2022).

Incorporating crop residues can reduce nitrate leaching by 14% through improved nitrogen retention, though overall GHG emissions may slightly increase without offsetting the C sequestration potential (Li et al. 2021; Nikolaus and Lesschen 2024). Co-benefits include better soil structure, reduced runoff and erosion, enhanced nutrient availability and quality, and increased soil biodiversity (Lehtinen et al. 2014; Tiefenbacher et al. 2021). However, stopping this practice, for example, to use this straw as feedstock for biochar production, will lead to the loss of these benefits (Spiegel et al. 2018).

Forage legumes and ley rotations including legumes come with trade-offs to consider, for example, in regions where green maize is used to produce electricity from biogas, where biomass remains essential for the biogas plant. More legumes in leys may also increase N_2O emissions in the boreal zone, stressing the importance of regionally adapted implementation strategies (Sturite et al. 2021). Yet, many co-benefits are linked to this management option, such as increases in the number of vertical biopores, a reduction in mineral N fertiliser, increases in biodiversity, improved soil protection (reduced erosion), and overall, an increase in soil health (Cooledge et al. 2022).

Agroforestry contributes to climate change mitigation by directly reducing N_2O emissions and indirectly lowering GHG emissions by up to 8% through reduced fertiliser use and smaller cultivated areas (Drexler and Don 2024; Nikolaus and Lesschen 2024). It also offers multiple co-benefits, including enhanced biodiversity, additional biomass production, microclimate regulation, improved soil water retention, and reduced erosion, runoff, and nutrient leaching (Montgomery et al. 2020; Drexler et al. 2021).

4.11 | Uncertainties

This work does not account for the effects of climate change, such as altered SOC mineralisation rates or shifts in the suitability of implementation areas due to changing water availability and temperatures as this would result in increased uncertainty. For example, European croplands that are already heavily affected by climate change show a diverse picture with some countries reporting SOC losses (54% of area) and some reporting SOC increases (46% area) (Harbo et al. 2026). Yet, it is important to mention that for example, with increasing temperature, SOC mineralisation rates increase and thus increased SOC losses can occur, while at the same time net primary productivity and thus C inputs may increase (Zhou et al. 2024). In addition, crop rotations may change as well, affecting C inputs further. However, the modelled contribution of climate change to observed trends in SOC stocks over the past 100 years appears to be relatively small yet not negligible (Poeplau and Dechow 2023; Keel et al. 2023). However, in LTEs, this modelled effect cannot be clearly attributed to rising temperatures but is instead driven by site-specific conditions, as demonstrated by Swiss LTEs data spanning the past 75 years (Keel et al. 2019).

Furthermore, a complete formal propagation of uncertainties or the calculation of confidence intervals is not feasible because robust and consistent information on input-layer–specific uncertainties is not available across all datasets used in this study. Under these conditions, any seemingly rigorous error calculation would risk being misleading, as it would imply a level of precision not supported by the underlying data.

However, the main sources of uncertainty are the EFs and the assumptions regarding implementation areas; variations in these parameters can substantially influence the results of this study.

The analysis of EFs reveals clear differences in uncertainty among management practices, as reflected by their standard deviations. In particular, zero tillage and woody features rank among the most influential measures while also exhibiting relatively high variability. The high relative uncertainty associated with EFs for tillage practices indicates that these measures do not consistently result in increased C accrual and must be implemented with careful consideration of climatic conditions, soil type, and site-specific management. In contrast, the other measures show more consistent increases in C accrual, suggesting that the estimated C sequestration potentials for tillage practices are comparatively less robust. To generate robust EFs requires numerous and identical studies across pedo-climatic regions. However, reality falls short of this ideal, requiring future improvements for increasing accuracy (Panagea et al. 2024). The study of Panagea et al. (2024) focuses on European-scale EFs, refining IPCC recommendations with region-specific insights and introducing management practices previously omitted. Yet, more LTEs are needed to enhance EF robustness. For cover crops, a higher share of fodder legumes in the rotation and for crop residues, the climatic zones were statistically significant but had unbalanced data distribution, affecting model reliability. Consequently, using the European average EFs was recommended for zero tillage, variability in EFs was driven by pedo-climatic conditions, interacting soil management practices, and methodological choices such as soil sampling depth, bulk density determination, and EF calculation approach. Mediterranean sites illustrate this complexity, showing both the highest and lowest EFs within the dataset. For example, a Spanish clay loam experiment reported an EF of 0.59 using a fixed-depth method but 0.97 when applying an equivalent soil mass approach, underscoring the strong influence of methodology on EF estimates. Another uncertainty with the EFs are synergistic effects, which are rarely studied. As a matter of fact, a robust quantification of how a combination of measures (e.g., regenerative agricultural practices) in different pedo-climatic regions will affect for example, GHG emissions and C stocks is often lacking (Olander et al. 2013; Amundson and Biardeau 2018; Bijttebier et al. 2018; Khangura et al. 2023). Yet, there is evidence that combinations of management measures can result in cumulative gains in SOC accrual (López i Losada et al. 2025) but more of this is needed to increase robustness.

Further, our assumptions regarding management options are open to criticism. For instance, the reference scenario for biochar—defined as no biochar application—may not be optimal. A more suitable reference could be the current practice of applying available biomass directly to the field, as this same biomass could alternatively be used as biochar feedstock. In addition, feedstock availability to produce biochar remains an open question. Another example illustrating increasing uncertainty is the estimated area of implementation for cover crops. For Germany, based on our assumptions, we identified an area that is 7.8% smaller than the estimate reported by Seitz et al. (2023) (2.174 million ha vs. 2.357 million ha, respectively). Direct comparisons are challenging, however, as few studies assess additional and realistically implementable areas using assumptions comparable to those applied in this study. In general, the assumptions for each and every measure were largely constrained by data availability at European scale, thus highlighting the need for more LTEs and additional data on European scale to develop more realistic and robust scenarios beyond what is currently possible.

Also, non-CO_2 GHG emissions may change if management changes and need to be better quantified for estimating the real impact of management on the GHG effect of agricultural soils. By including changes in N_2O emissions (Table S7), we cautiously estimated that an additional 11 Mt. CO_2e yr.$^{-1}$ can potentially be mitigated through overall reduction in N_2O emissions accounting for an additional 5% of the total GHG effect (Table S5, Table S6). This is highly uncertain, because existing N_2O emission data across the European pedo-climatic regions is still scarce and not robust (Nikolaus and Lesschen 2024). Especially for biochar, data from LTEs do not exist. Uncertainty increases significantly for all measures when including N_2O emissions, as the data used for this estimate lacks the robustness needed for reliable application at the European scale.

5 | Conclusions

We determined relative magnitudes and plausible ranges of potential C sequestration in Europe. We did find that soil health–oriented agricultural management offers substantial climate mitigation potential through C accrual, corresponding to 21%–33% of current European agricultural GHG emissions when subsoil C is included (agriculture and LULUCF sectors). This possible C accrual can only lead to C sequestration if it is larger than the loss of SOC under business-as-usual conditions, which is not accounted for in this study. The proposed changes in agricultural management aimed at sequestering C offer numerous positive side effects, co-benefits, but also trade-offs that need to be considered before implementation. Biochar shows the highest and most robust potential for soil C sequestration but remains underutilised in Europe due to high costs, limited production, and unresolved feedstock constraints. Yet, its key advantage is the provision of long-term C storage without the need for continuous management, unlike other practices. Agroforestry also shows a large and reliable C sequestration potential in almost all countries and the highest C sequestration rate per hectare, with most additional C stored in the biomass. At the same time, it has multiple positive co-benefits such as increasing biodiversity, significantly reducing N_2O emissions, and supplying additional woody biomass. Using this feedstock to produce biochar to increase SOC stocks is a synergistic effect that enhances the overall effectiveness of these management options. Other measures show much smaller and similar potentials. Finally, we emphasise that tillage-related measures are less reliable in increasing C accrual than all other measures. The success of C sequestration in European agriculture hinges on scaling up the area where agricultural management options are implemented. This needs political ambition and economic incentives, as these play a crucial role in turning potential C sequestration into realised outcomes. Increasing SOC is more than just climate change mitigation; it is crucial for sustainable agriculture and helps increase the resilience of agriculture to climate change.

Author Contributions

Felix Seidel: conceptualization, methodology, investigation, validation, formal analysis, visualization, project administration, writing – review and editing, writing – original draft, data curation. **Jorge Álvaro-Fuentes:** writing – review and editing, conceptualization. **Martin A. Bolinder:** writing – review and editing, conceptualization. **Claudia Di Bene:** conceptualization, writing – review and editing. **Mariangela Diacono:** conceptualization, writing – review and editing. **Eugenio Diaz-Pines:** conceptualization, writing – review and editing. **Sophia Götzinger:** writing – review and editing. **Thomas Kätterer:** conceptualization, writing – review and editing. **Sonja G. Keel:** conceptualization, writing – review and editing. **Katharina M. Keiblinger:** writing – review and editing, conceptualization. **Jens Leifeld:** conceptualization, writing – review and editing. **Jan Peter Lesschen:** conceptualization, writing – review and editing. **Ioanna Panagea:** conceptualization, writing – review and editing, methodology. **Daniel Rasse:** conceptualization, writing – review and editing. **Christoph Rosinger:** writing – review and editing. **Greet Ruysschaert:** conceptualization, writing – review and editing. **Florian Schneider:** conceptualization, methodology, software, data curation, visualization, writing – review and editing. **Daria Seitz:** conceptualization. **Heide Spiegel:** conceptualization, writing – review and editing. **Marjetka Suhadolc:** writing – review and editing, methodology. **Silvia Vanino:** writing – review and editing. **Axel Don:** conceptualization, methodology, supervision, writing – review and editing, funding acquisition, project administration.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at https://zenodo.org/records/14777801, reference number https://doi.org/10.5281/zenodo.14777801.

References

Adetunji, A. T., B. Ncube, R. Mulidzi, and F. B. Lewu. 2020. "Management Impact and Benefit of Cover Crops on Soil Quality: A Review." *Soil and Tillage Research* 204: 104717. https://doi.org/10.1016/j.still.2020.104717.

Agora Agriculture. 2024. "Agriculture, forestry and food in a climate neutral EU. The land use sectors as part of a sustainable food system and bioeconomy."

Amundson, R., and L. Biardeau. 2018. "Soil Carbon Sequestration Is an Elusive Climate Mitigation Tool." *Proceedings of the National Academy of Sciences* 115: 11652–11656. https://doi.org/10.1073/pnas.1815901115.

Azzi, E. S., E. Karltun, and C. Sundberg. 2019. "Prospective Life Cycle Assessment of Large-Scale Biochar Production and Use for Negative Emissions in Stockholm." *Environmental Science & Technology* 53: 8466–8476. https://doi.org/10.1021/acs.est.9b01615.

Beillouin, D., T. Ben-Ari, and D. Makowski. 2019. "Evidence Map of Crop Diversification Strategies at the Global Scale." *Environmental Research Letters* 14: 123001. https://doi.org/10.1088/1748-9326/ab4449.

Betancur-Corredor, B., B. Lang, and D. J. Russell. 2022. "Reducing Tillage Intensity Benefits the Soil micro- and Mesofauna in a Global meta-Analysis." *European Journal of Soil Science* 73: e13321. https://doi.org/10.1111/ejss.13321.

BFS. 2017. "Landwirtschaftsbetriebe: Bodenbedeckung im Winter und Bodenbearbeitung nach Grössenklasse LN."

Bianchi, A., T. Larmola, H. Kekkonen, S. Saarnio, and K. Lång. 2021. "Review of Greenhouse Gas Emissions From Rewetted Agricultural Soils." *Wetlands* 41: 108. https://doi.org/10.1007/s13157-021-01507-5.

Bijttebier, J., G. Ruysschaert, R. Hijbeek, et al. 2018. "Adoption of Non-Inversion Tillage Across Europe: Use of a Behavioural Approach in Understanding Decision Making of Farmers." *Land Use Policy* 78: 460–471. https://doi.org/10.1016/j.landusepol.2018.05.044.

Blanco-Canqui, H., C. Shapiro, P. Jasa, and J. Iqbal. 2021. "No-Till and Carbon Stocks: Is Deep Soil Sampling Necessary? Insights From Long-Term Experiments." *Soil and Tillage Research* 206: 104840. https://doi.org/10.1016/j.still.2020.104840.

Borchard, N., M. Schirrmann, M. L. Cayuela, et al. 2019. "Biochar, Soil and Land-Use Interactions That Reduce Nitrate Leaching and N_2O Emissions: A meta-Analysis." *Science of The Total Environment* 651: 2354–2364. https://doi.org/10.1016/j.scitotenv.2018.10.060.

Börjesson, G., M. A. Bolinder, H. Kirchmann, and T. Kätterer. 2018. "Organic Carbon Stocks in Topsoil and Subsoil in Long-Term Ley and Cereal Monoculture Rotations." *Biology and Fertility of Soils* 54: 549–558. https://doi.org/10.1007/s00374-018-1281-x.

Brun, P., N. E. Zimmermann, C. Hari, L. Pellissier, and D. N. Karger. 2022. "Global Climate-Related Predictors at Kilometer Resolution for the Past and Future." *Earth System Science Data* 14: 5573–5603. https://doi.org/10.5194/essd-14-5573-2022.

Büchi, L., F. Walder, S. Banerjee, et al. 2022. "Pedoclimatic Factors and Management Determine Soil Organic Carbon and Aggregation in Farmer Fields at a Regional Scale." *Geoderma* 409: 115632. https://doi.org/10.1016/j.geoderma.2021.115632.

Budai, A. E., D. P. Rasse, T. Cottis, et al. 2024. "Qualitative Evaluation of Nine Agricultural Methods for Increasing Soil Carbon Storage in Norway." *European Journal of Soil Science* 75: e13493. https://doi.org/10.1111/ejss.13493.

Bundesamt für Umwelt. 2021. "Rechtlicher Umgang mit Pflanzenkohle Gutachten im Auftrag des BAFU."

Chenu, C., D. A. Angers, P. Barré, D. Derrien, D. Arrouays, and J. Balesdent. 2019. "Increasing Organic Stocks in Agricultural Soils: Knowledge Gaps and Potential Innovations." *Soil and Tillage Research* 188: 41–52. https://doi.org/10.1016/j.still.2018.04.011.

COM. 2020. "EU Biodiversity Strategy for 2030: Bringing Nature Back Into Our Lives, Brussels."

Cooledge, E. C., D. R. Chadwick, L. M. J. Smith, J. R. Leake, and D. L. Jones. 2022. "Agronomic and Environmental Benefits of Reintroducing Herb- And Legume-Rich Multispecies Leys Into Arable Rotations: A Review." *Frontiers of Agricultural Science and Engineering* 9: 245–271. https://doi.org/10.15302/J-FASE-2021439.

Corine Land Cover, C.L.M.S. (CLMS). 2018. "Copernicus Land Monitoring Service CORINE Land Cover."

CRCF. 2022. "Commission Proposes Certification of Carbon Removals [WWW Document]. Eur. Comm. - Eur. Comm." Accessed May 14, 2025. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7156.

Dachraoui, M., and A. Sombrero. 2020. "Effect of Tillage Systems and Different Rates of Nitrogen Fertilisation on the Carbon Footprint of Irrigated Maize in a Semiarid Area of Castile and Leon, Spain." *Soil and Tillage Research* 196: 104472. https://doi.org/10.1016/j.still.2019.104472.

D'andrimont, R., J. Skoien, R. Koble, M. Yordanov, and J. Terres. 2023. *EU Landscape Feature Indicator Fact Sheet*. Vol. 2023, JRC136069. European Commission.

d'Andrimont, R., M. Yordanov, F. Sedano, et al. 2024. "Advances in LUCAS Copernicus 2022: Enhancing Earth Observations With Comprehensive In Situ Data on EU Land Cover and Use." *Earth System Science Data* 16: 5723–5735. https://doi.org/10.5194/essd-16-5723-2024.

Di Bene, C., M. Dolores Gómez-López, R. Francaviglia, et al. 2022. "Barriers and Opportunities for Sustainable Farming Practices and Crop Diversification Strategies in Mediterranean Cereal-Based Systems." *Frontiers in Environmental Science* 10: 861225. https://doi.org/10.3389/fenvs.2022.861225.

Don, A., F. Seidel, J. Leifeld, et al. 2024. "Carbon Sequestration in Soils and Climate Change Mitigation—Definitions and Pitfalls." *Global Change Biology* 30: e16983. https://doi.org/10.1111/gcb.16983.

Drexler, S., and A. Don. 2024. "Carbon Sequestration Potential in Hedgerow Soils: Results From 23 Sites in Germany." *Geoderma* 445: 116878. https://doi.org/10.1016/j.geoderma.2024.116878.

Drexler, S., A. Gensior, and A. Don. 2021. "Carbon Sequestration in Hedgerow Biomass and Soil in the Temperate Climate Zone." *Regional Environmental Change* 21: 74. https://doi.org/10.1007/s10113-021-01798-8.

Dyjakon, A., and D. García-Galindo. 2019. "Implementing Agricultural Pruning to Energy in Europe: Technical, Economic and Implementation Potentials [WWW Document]." Accessed December 8, 2024. https://www.mdpi.com/1996-1073/12/8/1513.

EBC. 2012. "Comparison of European Biochar Certificate Version 4. 8 and IBI Biochar Standards Version 2.0 European Biochar Certificate First Publication March 2012b. Www Eur.-Biochar Orgenhome IBI Biochar Stand First Publ May."

Emde, D., K. D. Hannam, I. Most, L. M. Nelson, and M. D. Jones. 2021. "Soil Organic Carbon in Irrigated Agricultural Systems: A meta-Analysis." *Global Change Biology* 27: 3898–3910. https://doi.org/10.1111/gcb.15680.

European Commission. 2018. "Report from the Commission to the Council and the European Parliament on THE Development of Plant Proteins in the European Union."

European Commission. 2020. "Farm to Fork Strategy for a Fair, Healthy and Environmentally-Friendly Food System."

European Commission. 2024. "REGULATION (EU) 2024/3012 Establishing a Union Certification Framework for Permanent Carbon Removals, Carbon Farming and Carbon Storage in Products". https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202403012.

European Commission. Directorate General for Climate Action, COWI, Ecologic Institute, IEEP. 2021. "Operationalising an EU Carbon Farming Initiative: Executive Summary. Publications Office, LU."

European Union. 2021. "Regulation (EU) 2021/2088 of the European Parliament and of the Council of 27 November 2019 on Sustainability-Related Disclosures in the Financial Services Sector."

EUROSTAT. 2020a. "Agricultural practices (EF_MP_PRAC)."

EUROSTAT. 2020b. "Plants Harvested Green and Fallow Land by NUTS 2 Regions (EF_LAC_GREENFAL)."

EUROSTAT. 2020c. "Soil Cover by NUTS2 Regions (EF_MP_SOIL)."

EUROSTAT. 2023. *Main Farm Land Use by NUTS 2 Regions (EF_LUS_MAIN)*. https://doi.org/10.2908/EF_LUS_MAIN.

EUROSTAT. 2024. "Farms and Hectares by Type of Crops, Utilised Agricultural Area, Economic Size and NUTS 2 Regions (EF_LUS_ALLCROPS)."

FAO. 2013. "AQUASTAT - FAO's Global Information System on Water and Agriculture [WWW Document]." Accessed February 17, 2025. https://www.fao.org/aquastat/en/geospatial-information/global-maps-irrigated-areas/latest-version.

FAOSTAT. 2023. "Land, Inputs and Sustainability / Land Use."

Fetting, C. 2020. "The European Green Deal. ESDN Report, ESDN Office, Vienna."

Fohrafellner, J., K. M. Keiblinger, S. Zechmeister-Boltenstern, R. Murugan, H. Spiegel, and E. Valkama. 2024. "Cover Crops Affect Pool Specific Soil Organic Carbon in Cropland – A meta-Analysis." *European Journal of Soil Science* 75: e13472. https://doi.org/10.1111/ejss.13472.

Froger, C., E. Tondini, D. Arrouays, et al. 2024. "Comparing LUCAS Soil and National Systems: Towards a Harmonized European Soil Monitoring Network." *Geoderma* 449: 117027. https://doi.org/10.1016/j.geoderma.2024.117027.

Garbach, K., J. C. Milder, F. A. J. DeClerck, M. Montenegro De Wit, L. Driscoll, and B. Gemmill-Herren. 2017. "Examining Multi-Functionality for Crop Yield and Ecosystem Services in Five Systems of Agroecological Intensification." *International Journal of Agricultural Sustainability* 15: 11–28. https://doi.org/10.1080/14735903.2016.1174810.

Giersbergen, Q., A. Barthelmes, C. Couwenberg John Fritz, K. Lång, N. Martin, and F. Tanneberger. 2024. "Identifying Hotspots of Greenhouse Gas Emissions From Drained Peatlands in the European Union." https://doi.org/10.21203/rs.3.rs-4629642/v1.

Gselman, A., and B. Kramberger. 2008. "Benefits of Winter Legume Cover Crops Require Early Sowing." *Australian Journal of Agricultural Research* 59: 1156–1163. https://doi.org/10.1071/AR08015.

Guenet, B., B. Gabrielle, C. Chenu, et al. 2021. "Can N_2O Emissions Offset the Benefits From Soil Organic Carbon Storage?" *Global Change Biology* 27: 237–256. https://doi.org/10.1111/gcb.15342.

Haddaway, N. R., K. Hedlund, L. E. Jackson, et al. 2017. "How Does Tillage Intensity Affect Soil Organic Carbon? A Systematic Review." *Environmental Evidence* 6: 30. https://doi.org/10.1186/s13750-017-0108-9.

Hagemann, N., J. Harter, R. Kaldamukova, et al. 2017. "Does Soil Aging Affect the N_2O Mitigation Potential of Biochar? A Combined Microcosm and Field Study." *GCB Bioenergy* 9: 953–964. https://doi.org/10.1111/gcbb.12390.

Hagemann, N., V. Kamra, and H.-P. Schmidt. 2024. "Production Quantities and C-Sink Potential of EBC-Certified Biochar in 2023." https://doi.org/10.5281/zenodo.10679330.

Harbo, L. S., J. E. Olesen, C. Lemming, B. T. Christensen, and L. Elsgaard. 2023. "Limitations of Farm Management Data in Analyses of Decadal Changes in SOC Stocks in the Danish Soil-Monitoring Network." *European Journal of Soil Science* 74: e13379. https://doi.org/10.1111/ejss.13379.

Harbo, L. S., E. Pihlap, G. Barančíková, A. Don, F. Schneider, and C. Poeplau. 2026. "Soil Organic Carbon Changes in Agricultural Areas of Europe—Synthesis of Repeated Regional Soil Surveys." *European Journal of Soil Science* 77: e70263. https://doi.org/10.1111/ejss.70263.

Häusling, M. 2011. "EU Protein Deficit: What Solution for a Long Standing Problem?".

He, M., X. Xiong, L. Wang, et al. 2021. "A Critical Review on Performance Indicators for Evaluating Soil Biota and Soil Health of Biochar-Amended Soils." *Journal of Hazardous Materials* 414: 125378. https://doi.org/10.1016/j.jhazmat.2021.125378.

Heller, O., C. D. Bene, P. Nino, et al. 2024. "Towards Enhanced Adoption of Soil-Improving Management Practices in Europe." *European Journal of Soil Science* 75: e13483. https://doi.org/10.1111/ejss.13483.

Hernanz, J. L., R. López, L. Navarrete, and V. Sánchez-Girón. 2002. "Long-Term Effects of Tillage Systems and Rotations on Soil Structural Stability and Organic Carbon Stratification in Semiarid Central Spain." *Soil and Tillage Research, Conservation Tillage and Stratification of Soil Properties* 66: 129–141. https://doi.org/10.1016/S0167-1987(02)00021-1.

Hijmans, R. J. 2025. "Terra: Spatial Data Analysis." https://doi.org/10.32614/CRAN.package.terra.

Hobbs, P. R., and B. Govaerts. 2010. "How Conservation Agriculture Can Contribute to Buffering Climate Change." In *Climate Change and Crop Production, CABI Climate Change Series*, 177–199. CABI. https://doi.org/10.1079/9781845936334.0177.

IPCC, E. C. Buendia, S. Guendehou, et al. 2019. "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [WWW Document]." Accessed January 8, 2024. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

Jeffery, S., D. Abalos, M. Prodana, et al. 2017. "Biochar Boosts Tropical but Not Temperate Crop Yields." *Environmental Research Letters* 12: 053001. https://doi.org/10.1088/1748-9326/aa67bd.

Jian, J., X. Du, M. S. Reiter, and R. D. Stewart. 2020. "A Meta-Analysis of Global Cropland Soil Carbon Changes due to Cover Cropping." *Soil Biology and Biochemistry* 143: 107735.

Johnston, A. E., P. R. Poulton, and K. Coleman. 2009. "Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes." *Advances in Agronomy* 101: 1–57.

Joseph, S., A. L. Cowie, L. Van Zwieten, et al. 2021. "How Biochar Works, and When It Doesn't: A Review of Mechanisms Controlling Soil and Plant Responses to Biochar." *GCB Bioenergy* 13: 1731–1764. https://doi.org/10.1111/gcbb.12885.

Kätterer, T., and M. A. Bolinder. 2024. "Response of Maize Yield to Changes in Soil Organic Matter in a Swedish Long-Term Experiment." *European Journal of Soil Science* 75: e13482. https://doi.org/10.1111/ejss.13482.

Kätterer, T., M. A. Bolinder, K. Berglund, and H. Kirchmann. 2012. "Strategies for Carbon Sequestration in Agricultural Soils in Northern Europe." *Acta Agriculturae Scandinavica Section A Animal Science* 62: 181–198. https://doi.org/10.1080/09064702.2013.779316.

Keel, S. G., T. Anken, L. Büchi, et al. 2019. "Loss of Soil Organic Carbon in Swiss Long-Term Agricultural Experiments Over a Wide Range of Management Practices." *Agriculture, Ecosystems and Environment* 286: 106654. https://doi.org/10.1016/j.agee.2019.106654.

Keel, S. G., D. Bretscher, J. Leifeld, A. von Ow, and C. Wüst-Galley. 2023. "Soil Carbon Sequestration Potential Bounded by Population Growth, Land Availability, Food Production, and Climate Change." *Carbon Management* 14: 2244456. https://doi.org/10.1080/17583004.2023.2244456.

Keesstra, S. D., C. Chenu, L. J. Munkholm, et al. 2024. "European Agricultural Soil Management: Towards Climate-Smart and Sustainability, Knowledge Needs and Research Approaches." *European Journal of Soil Science* 75: e13437. https://doi.org/10.1111/ejss.13437.

Khangura, R., D. Ferris, C. Wagg, and J. Bowyer. 2023. "Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health." *Sustainability* 15: 2338. https://doi.org/10.3390/su15032338.

Kim, N., M. C. Zabaloy, K. Guan, and M. B. Villamil. 2020. "Do Cover Crops Benefit Soil Microbiome? A meta-Analysis of Current Research." *Soil Biology and Biochemistry* 142: 107701. https://doi.org/10.1016/j.soilbio.2019.107701.

Kjær, S. T., R. Lang, T. Kätterer, and P. Dörsch. 2026. "Species Specific Effects of Cover Crops on Nitrous Oxide Emissions in Hemiboreal Cereal Production: The Importance of Freeze-Thaw Driven Emissions." *Agriculture, Ecosystems and Environment* 397: 110061. https://doi.org/10.1016/j.agee.2025.110061.

Kremen, C., A. Iles, and C. Bacon. 2012. "Diversified Farming Systems: An Agroecological, Systems-Based Alternative to Modern Industrial Agriculture." *Ecology and Society* 17: art44. https://doi.org/10.5751/ES-05103-170444.

Lal, R. 2004. "Carbon Emission From Farm Operations." *Environment International* 30: 981–990. https://doi.org/10.1016/j.envint.2004.03.005.

Lamb, W. F., T. Wiedmann, J. Pongratz, et al. 2021. "A Review of Trends and Drivers of Greenhouse Gas Emissions by Sector From 1990 to 2018." *Environmental Research Letters* 16: 073005. https://doi.org/10.1088/1748-9326/abee4e.

Lee, H., K. Calvin, D. Dasgupta, et al. 2023. *IPCC, 2023: Climate Change 2023: Synthesis Report, Summary for Policymakers. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by H. Lee and J. Romero. IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647.001.

Lehtilä, A., A. Taghizadeh-Toosi, M. Roitto, et al. 2024. "Cultivation of Forage Maize in Boreal Conditions – Assessment of Trade-Offs Between Increased Productivity and Environmental Impact." *Animal Feed Science and Technology* 309: 115878. https://doi.org/10.1016/j.anifeedsci.2024.115878.

Lehtinen, T., N. Schlatter, A. Baumgarten, et al. 2014. "Effect of Crop Residue Incorporation on Soil Organic Carbon and Greenhouse Gas Emissions in European Agricultural Soils." *Soil Use and Management* 30: 524–538. https://doi.org/10.1111/sum.12151.

Leifeld, J., B. Hardy, A. Budai, et al. 2024. "Final Report Work Package 3 – Biochar and Other Organic Amendments. Zenodo." https://doi.org/10.5281/zenodo.14046237.

Leip, A., F. Weiss, T. Wassenaar, et al. 2010. "Evaluation of the Livestock Sector's Contribution to the EU Greenhouse Gas Emissions (GGELS) Final Report. European Commission, Joint Research Centre."

Li, Z., R. Reichel, Z. Xu, H. Vereecken, and N. Brüggemann. 2021. "Return of Crop Residues to Arable Land Stimulates N_2O Emission but Mitigates NO_3–Leaching: A meta-Analysis." *Agronomy for Sustainable Development* 41: 66. https://doi.org/10.1007/s13593-021-00715-x.

Liang, Z., E. Ø. Mortensen, C. De Notaris, L. Elsgaard, and J. Rasmussen. 2022. "Subsoil Carbon Input by Cover Crops Depends on Management History." *Agriculture, Ecosystems and Environment* 326: 107800. https://doi.org/10.1016/j.agee.2021.107800.

Liu, X., A. Zhang, C. Ji, et al. 2013. "Biochar's Effect on Crop Productivity and the Dependence on Experimental Conditions—A meta-Analysis of Literature Data." *Plant and Soil* 373: 583–594. https://doi.org/10.1007/s11104-013-1806-x.

López i Losada, R., K. Hedlund, N. R. Haddaway, et al. 2025. "Synergistic Effects of Multiple "Good Agricultural Practices" for Promoting Organic Carbon in Soils: A Systematic Review of Long-Term Experiments." *Ambio* 54: 1715–1728. https://doi.org/10.1007/s13280-025-02188-8.

Lugato, E., F. Bampa, P. Panagos, L. Montanarella, and A. Jones. 2014. "Potential Carbon Sequestration of European Arable Soils Estimated by Modelling a Comprehensive Set of Management Practices." *Global Change Biology* 20: 3557–3567. https://doi.org/10.1111/gcb.12551.

Lugato, E., A. Leip, and A. Jones. 2018. "Mitigation Potential of Soil Carbon Management Overestimated by Neglecting N_2O Emissions." *Nature Climate Change* 8: 219–223. https://doi.org/10.1038/s41558-018-0087-z.

Lugato, E., L. Paniagua, A. Jones, W. de Vries, and A. Leip. 2017. "Complementing the Topsoil Information of the Land Use/Land Cover Area Frame Survey (LUCAS) With Modelled N_2O Emissions." *PLoS One* 12, no. 4: e0176111. https://doi.org/10.1371/journal.pone.0176111.

Merante, P., C. Dibari, R. Ferrise, et al. 2017. "Adopting Soil Organic Carbon Management Practices in Soils of Varying Quality: Implications and Perspectives in Europe." *Soil and Tillage Research* 165: 95–106. https://doi.org/10.1016/j.still.2016.08.001.

Meurer, K. H. E., N. R. Haddaway, M. A. Bolinder, and T. Kätterer. 2018. "Tillage Intensity Affects Total SOC Stocks in Boreo-Temperate Regions Only in the Topsoil—A Systematic Review Using an ESM Approach." *Earth Science Reviews* 177: 613–622. https://doi.org/10.1016/j.earscirev.2017.12.015.

Meurer, K. H. E., C. M. J. Hendriks, J. H. Faber, et al. 2024. "How Does National SOC Monitoring on Agricultural Soils Align With the EU Strategies? An Example Using Five Case Studies." *European Journal of Soil Science* 75: e13477. https://doi.org/10.1111/ejss.13477.

Mihovsky, T., and I. Pachev. 2012. Reduced Tillage Practices.

Minasny, B., B. P. Malone, A. B. McBratney, et al. 2017. "Soil carbon 4 per mille." *Geoderma* 292: 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002.

Monforti, F., E. Lugato, V. Motola, K. Bodis, N. Scarlat, and J.-F. Dallemand. 2015. "Optimal Energy Use of Agricultural Crop Residues Preserving Soil Organic Carbon Stocks in Europe." *Renewable and Sustainable Energy Reviews* 44: 519–529. https://doi.org/10.1016/j.rser.2014.12.033.

Montgomery, I., T. Caruso, and N. Reid. 2020. "Hedgerows as Ecosystems: Service Delivery, Management, and Restoration." *Annual Review of Ecology, Evolution, and Systematics* 51: 81–102. https://doi.org/10.1146/annurev-ecolsys-012120-100346.

Nikolaus, K., and J. P. Lesschen. 2024. "Assessment of SOC Sequestration Measures on Other GHG Emissions. Zenodo." https://doi.org/10.5281/ZENODO.14506063.

Nouri, A., S. Lukas, S. Singh, S. Singh, and S. Machado. 2022. "When Do Cover Crops Reduce Nitrate Leaching? A Global meta-Analysis." *Global Change Biology* 28: 4736–4749. https://doi.org/10.1111/gcb.16269.

Ogle, S. M., F. J. Breidt, and K. Paustian. 2005. "Agricultural Management Impacts on Soil Organic Carbon Storage Under Moist and Dry Climatic Conditions of Temperate and Tropical Regions." *Biogeochemistry* 72: 87–121. https://doi.org/10.1007/s10533-004-0360-2.

Olander, L., E. Wollenberg, F. Tubiello, and M. Herold. 2013. "Advancing Agricultural Greenhouse Gas Quantification*." *Environmental Research Letters* 8: 011002. https://doi.org/10.1088/1748-9326/8/1/011002.

Panagea, I., G. Blanchy, K. Keiblinger, et al. 2024. "Report on Emission Factors (Effects on SOC Stocks) of Each Agricultural Cropland Measure. Zenodo." https://doi.org/10.5281/ZENODO.14045964.

Panagea, I. S., P. Quataert, M. Alonso-Ayuso, et al. 2025. "Forage vs. Grain Legumes: Contrasting Effects on Soil Organic Carbon Stocks–Evidence From 30 European Field Experiments." *European Journal of Soil Science* 76: e70086. https://doi.org/10.1111/ejss.70086.

Panagos, P., P. Borrelli, A. Jones, and D. A. Robinson. 2024. "A 1 Billion Euro Mission: A Soil Deal for Europe." *European Journal of Soil Science* 75: e13466. https://doi.org/10.1111/ejss.13466.

Pebesma, E. 2018. "Simple Features for R: Standardized Support for Spatial Vector Data." *R Journal* 10: 439–446. https://doi.org/10.32614/RJ-2018-009.

Pebesma, E., and R. Bivand. 2023. *Spatial Data Science: With Applications in R*. Chapman and Hall/CRC. https://doi.org/10.1201/9780429459016.

Peralta, G., L. Di Paolo, I. Luotto, et al. 2022. *Global Soil Organic Carbon Sequestration Potential Map (GSOCseq v1.1) - Technical Manual*. FAO. https://doi.org/10.4060/cb2642en.

Poeplau, C., and R. Dechow. 2023. "The Legacy of One Hundred Years of Climate Change for Organic Carbon Stocks in Global Agricultural Topsoils." *Scientific Reports* 13: 7483. https://doi.org/10.1038/s41598-023-34753-0.

Poeplau, C., and A. Don. 2015. "Carbon Sequestration in Agricultural Soils via Cultivation of Cover Crops – A meta-Analysis." *Agriculture, Ecosystems and Environment* 200: 33–41. https://doi.org/10.1016/j.agee.2014.10.024.

Poggio, L., L. M. De Sousa, N. H. Batjes, et al. 2021. "SoilGrids 2.0: Producing Soil Information for the Globe With Quantified Spatial Uncertainty." *Soil* 7: 217–240. https://doi.org/10.5194/soil-7-217-2021.

Porre, R., L. B. Martinez-Garcia, E. Diaz-Pines, U. R. Esparza-Robles, and J. P. Lesschen. 2026. "Literature Review and Meta-Analysis on N_2O Emissions Related to Agricultural SOC-Sequestration Measures." Zenodo. https://doi.org/10.5281/zenodo.14633996.

Porwollik, V., S. Rolinski, J. Heinke, and C. Müller. 2019. "Generating a Rule-Based Global Gridded Tillage Dataset." *Earth System Science Data* 11: 823–843. https://doi.org/10.5194/essd-11-823-2019.

Poudel, P., J. Ødegaard, S. J. Mo, et al. 2022. "Italian Ryegrass, Perennial Ryegrass, and Meadow Fescue as Undersown Cover Crops in Spring Wheat and Barley: Results From a Mixed Methods Study in Norway." *Sustainability* 14: 13055. https://doi.org/10.3390/su142013055.

Powlson, D. S., C. M. Stirling, M. L. Jat, et al. 2014. "Limited Potential of No-Till Agriculture for Climate Change Mitigation." *Nature Climate Change* 4: 678–683. https://doi.org/10.1038/nclimate2292.

R Core Team. 2024. "R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing [WWW Document]." Accessed January 26, 2026. https://www.scirp.org/reference/referencespapers?referenceid=3887298.

Randerson, J. T., G. R. van der Werf, L. Giglio, G. J. Collatz, and P. S. Kasibhatla. 2017. "Global Fire Emissions Database, Version 4.1 (GFEDv4) (Version 4.1)." ORNL Distributed Active Archive Center. https://doi.org/10.3334/ORNLDAAC/1293.

Rodrigues, L., B. Hardy, B. Huyghebeart, et al. 2021. "Achievable Agricultural Soil Carbon Sequestration Across Europe From Country-Specific Estimates." *Global Change Biology* 27: 6363–6380. https://doi.org/10.1111/gcb.15897.

Rosinger, C., G. Bodner, L. G. Bernardini, et al. 2023. "Benchmarking Carbon Sequestration Potentials in Arable Soils by on-Farm Research on Innovative Pioneer Farms." *Plant and Soil* 488: 137–156. https://doi.org/10.1007/s11104-022-05626-8.

Rudis, B. 2025. "hrbrthemes: Additional Themes, Theme Components and Utilities for ggplot2."

Ruysschaert, G., I. Panagea, G. Blanchy, et al. 2023. "EJPSOIL CarboSeq Crop and Soil Management Database." https://doi.org/10.5281/ZENODO.8130195.

Sainju, U. M., J. L. Barsotti, and J. Wang. 2014. "Net Global Warming Potential and Greenhouse Gas Intensity Affected by Cropping Sequence and Nitrogen Fertilization." *Soil Science Society of America Journal* 78: 248–261. https://doi.org/10.2136/sssaj2013.08.0325.

Schmidt, H., C. Kammann, N. Hagemann, et al. 2021. "Biochar in Agriculture – A Systematic Review of 26 Global meta-Analyses." *GCB Bioenergy* 13: 1708–1730. https://doi.org/10.1111/gcbb.12889.

Seitz, D., L. M. Fischer, R. Dechow, M. Wiesmeier, and A. Don. 2023. "The Potential of Cover Crops to Increase Soil Organic Carbon Storage in German Croplands." *Plant and Soil* 488: 157–173. https://doi.org/10.1007/s11104-022-05438-w.

Siebert, S., V. Henrich, K. Frenken, and J. Burke. 2013. "Update of the Digital Global Map of Irrigation Areas to Version 5."

Silva, A. P. D., L. C. Babujia, J. C. Franchini, R. Ralisch, M. Hungria, and M. D. F. Guimarães. 2014. "Soil Structure and Its Influence on Microbial Biomass in Different Soil and Crop Management Systems." *Soil and Tillage Research* 142: 42–53. https://doi.org/10.1016/j.still.2014.04.006.

Skadell, L. E., F. Schneider, M. I. Gocke, et al. 2023. "Twenty Percent of Agricultural Management Effects on Organic Carbon Stocks Occur in Subsoils – Results of Ten Long-Term Experiments." *Agriculture, Ecosystems and Environment* 356: 108619. https://doi.org/10.1016/j.agee.2023.108619.

Smith, P., M. R. Ashmore, H. I. J. Black, et al. 2013. "REVIEW: The Role of Ecosystems and Their Management in Regulating Climate, and Soil, Water and Air Quality." *Journal of Applied Ecology* 50: 812–829. https://doi.org/10.1111/1365-2664.12016.

Soane, B. D., B. C. Ball, J. Arvidsson, G. Basch, F. Moreno, and J. Roger-Estrade. 2012. "No-Till in Northern, Western and South-Western Europe: A Review of Problems and Opportunities for Crop Production and the Environment." *Soil and Tillage Research* 118: 66–87. https://doi.org/10.1016/j.still.2011.10.015.

Sørensen, C. G., N. Halberg, F. W. Oudshoorn, B. M. Petersen, and R. Dalgaard. 2014. "Energy Inputs and GHG Emissions of Tillage Systems." *Biosystems Engineering* 120: 2–14. https://doi.org/10.1016/j.biosystemseng.2014.01.004.

Spiegel, H., T. Sandén, G. Dersch, A. Baumgarten, R. Gründling, and U. Franko. 2018. "Chapter 17 - Soil Organic Matter and Nutrient Dynamics Following Different Management of Crop Residues at Two Sites in Austria." In *Soil Management and Climate Change*, edited by M. Á. Muñoz and R. Zornoza, 253–265. Academic Press. https://doi.org/10.1016/B978-0-12-812128-3.00017-3.

Spiegel, H., T. Sandén, H. Sandén, S. Götzinger, J. Miloczki, and E. Kandeler. 2025. "Changes in Biological and Chemical Soil Properties in an Austrian Long-Term Tillage Experiment." *European Journal of Soil Science* 76: e70037. https://doi.org/10.1111/ejss.70037.

Sturite, I., S. Rivedal, and P. Dörsch. 2021. "Clover Increases N_2O Emissions in Boreal Leys During Winter." *Soil Biology and Biochemistry* 163: 108459. https://doi.org/10.1016/j.soilbio.2021.108459.

Tamburini, G., R. Bommarco, T. C. Wanger, et al. 2020. "Agricultural Diversification Promotes Multiple Ecosystem Services Without Compromising Yield." *Science Advances* 6: eaba1715. https://doi.org/10.1126/sciadv.aba1715.

Thapa, R., S. B. Mirsky, and K. L. Tully. 2018. "Cover Crops Reduce Nitrate Leaching in Agroecosystems:A Global Meta-Analysis." *Journal of Environmental Quality* 47: 1400–1411. https://doi.org/10.2134/jeq2018.03.0107.

Tiefenbacher, A., T. Sandén, H.-P. Haslmayr, J. Miloczki, W. Wenzel, and H. Spiegel. 2021. "Optimizing Carbon Sequestration in Croplands: A Synthesis." *Agronomy* 11: 882. https://doi.org/10.3390/agronomy11050882.

Trenberth, K. E. 2011. "Changes in Precipitation With Climate Change." *Climate Research* 47: 123–138. https://doi.org/10.3354/cr00953.

Troccoli, A., C. Maddaluno, M. Mucci, M. Russo, and M. Rinaldi. 2015. "Is It Appropriate to Support the Farmers for Adopting Conservation Agriculture? Economic and Environmental Impact Assessment." *Italian Journal of Agronomy* 10: 661. https://doi.org/10.4081/ija.2015.661.

Tubiello, F., R. Biancalani, M. Salvatore, S. Rossi, and G. Conchedda. 2016. "A Worldwide Assessment of Greenhouse Gas Emissions From Drained Organic Soils." *Sustainability* 8: 371. https://doi.org/10.3390/su8040371.

UNFCCC. 2024. "Greenhouse Gas Inventory Data - Flexible queries Annex I countries [WWW Document]." Accessed February 19, 2025. https://di.unfccc.int/flex_annex1.

Valkama, E., D. Tzemi, U. R. Esparza-Robles, A. Syp, A. O'Toole, and P. Maenhout. 2024. "Effectiveness of Soil Management Strategies for Mitigation of NO Emissions in European Arable Land: A meta-Analysis." *European Journal of Soil Science* 75: e13488. https://doi.org/10.1111/ejss.13488.

Vanwindekens, F., O. Heller, C. Di Bene, P. Nino, and B. Huyghebaert. 2022. "EJPSoil-iSoMPE. Innovative Soil Management Practices across Europe. Deliverable D4. Final report."

Varela, M. F., C. M. Scianca, M. A. Taboada, and G. Rubio. 2014. "Cover Crop Effects on Soybean Residue Decomposition and P Release in No-Tillage Systems of Argentina." *Soil and Tillage Research* 143: 59–66. https://doi.org/10.1016/j.still.2014.05.005.

Verhoeven, E., E. Pereira, C. Decock, E. Suddick, T. Angst, and J. Six. 2017. "Toward a Better Assessment of Biochar–Nitrous Oxide Mitigation Potential at the Field Scale." *Journal of Environmental Quality* 46: 237–246. https://doi.org/10.2134/jeq2016.10.0396.

Wang, J., Z. Xiong, and Y. Kuzyakov. 2016. "Biochar Stability in Soil: meta-Analysis of Decomposition and Priming Effects." *GCB Bioenergy* 8: 512–523. https://doi.org/10.1111/gcbb.12266.

Wezel, A., M. Casagrande, F. Celette, J.-F. Vian, A. Ferrer, and J. Peigné. 2014. "Agroecological practices for sustainable agriculture. A Review." *Agronomy for Sustainable Development* 34: 1–20. https://doi.org/10.1007/s13593-013-0180-7.

Wickham, H. 2016. *ggplot2, Use R!* Springer International Publishing. https://doi.org/10.1007/978-3-319-24277-4.

Zhou, Z., C. Ren, C. Wang, et al. 2024. "Global Turnover of Soil Mineral-Associated and Particulate Organic Carbon." *Nature Communications* 15: 5329. https://doi.org/10.1038/s41467-024-49743-7.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Total areas of implementation ranked by potential carbon accrual measure and country in thousand hectares. "0" refers to no potential area of implementation. **Table S2:** Overview of management options increasing carbon (C) accrual and the individual calculations to reach yearly C sequestration potential rates in carbon dioxide equivalents (CO_2e). **Table S3:** Total carbon sequestration potential ranked by measure and country in Mt. CO_2e without subsoil C. **Table S4:** Total carbon sequestration potential ranked by measure and country in Mt. CO_2e including subsoil C. **Table S5:** Annual carbon (C) sequestration potential and greenhouse gas (GHG) effects of agricultural management options across all European countries taking N_2O emission changes and subsoil C changes into account. Negative numbers denote a reduction in the climate mitigation benefit compared to the reference.* This value is not robust as long-term experimental data does not exist. **Table S6:** Carbon (C) sequestration potential and greenhouse gas (GHG) effect over 50 years per hectare of agricultural management option taking N_2O emission changes and subsoil C changes into account. * estimated over 100 years due to long-term stability (Leifeld et al. 2024). **Table S7** Change of N_2O emissions through changes in agricultural management. [1]Data from (Porre et al. 2026). [2]Data from Lugato et al. (2017). [3]Data from Valkama et al. (2024). A "+" indicates increase in emissions while "−" indicates a decrease in N_2O emissions. **Figure S1:** Area of implementation for agricultural measures leading to C accrual. **Figure S2:** Present share of agricultural land covered with high-diversity landscape features by country based on data from the LUCAS 2022 field survey (EUROSTAT, 2023; d'Andrimont et al. 2024). The Commission's biodiversity target is indicated with a dashed horizontal line. **Figure S3:** (a) In the ambitious scenario, only woody features on arable land (red bars) are increased to reach the 10% target on a national level. (b) In the conservative scenario, all landscape features (red, green and grey bars) are increased by a constant, country-specific factor to reach the 10% target on a national level.