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Carbon sequestration potential from sustainable management of arable land in the EU

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Abstract

Carbon sequestration in arable soils is gaining increasing attention in global policymaking initiatives for climate-change mitigation. Large-scale assessments of soil organic carbon development in arable land are affected by the scarcity of reliable time series of soil organic carbon monitoring data and often fail to replicate observed trends or appreciate any effects induced by changes in soil management. This study quantifies C loss from contemporary soil management on specialist crop farms in the EU and the potential societal benefits from C sequestration and avoided C loss due to improved management. Our analysis is based on an evidence pool of 214 independent long-term time series of soil organic carbon measurements spanning a wide range of climatic conditions and soil types, and considers the implementation of reduced tillage, organic amendments, soil cover during winter, and crop rotations. Overall, we estimate the potential for C sequestration from improved soil management on specialist crop farms, representing 40% of all the arable land in the EU, to be 48 ($\pm$ 15) million tonnes CO2 equivalents yearly, which corresponds to 17% ($\pm$ 8) of the target for additional carbon removals in the soil and forest sinks under the Fit for 55 package. In addition, our results show high spatial variability in C losses due to current soil management practices and potential C sequestration from improvements. The annual climate-change mitigation value per unit of land with improved management shows a four-fold variation across countries, with Finland exhibiting the highest value and Cyprus the lowest. This demonstrates that a C payment eco-scheme should be adjusted spatially to achieve cost-effective soil organic carbon sequestration in arable soils in the EU.

1. Introduction

Carbon sequestration in soils is gaining increasing attention in global policymaking initiatives for climate-change mitigation [1]. Arable soils in particular, which have lost 50%–70% of their Soil Organic Carbon (SOC) stocks existing before agriculture was established, are already actively managed and thus responsive to improvements [2]. Evidence from field experiments supports that practices for the sustainable management of arable soils (e.g. reduced tillage, organic amendments, soil cover, crop rotations) indeed contribute to SOC preservation and restoration in arable land [3, 4]. Beyond its significance for C sequestration, SOC is closely correlated with the ecosystem services that support agriculture, which highlights latent synergies from improving soil management for climate-change mitigation and sustainable food production [5].

Adoption costs of sustainable soil management often outweigh the present value of earnings that farmers would obtain from enhanced soil health, thus stressing the need for policy measures to promote carbon farming, i.e., management improvements for

C sequestration in soils [6, 7]. Yet, creating market-based incentives for carbon farming is challenging because SOC gains are difficult to measure [1]. This is detrimental to the cost-effectiveness of measures that are not necessarily placed where they would create the largest environmental improvement [8, 9]. Despite its potential benefits for society, policy promoting SOC in arable land shows pitfalls that, in part, can be explained by the lack of robust methods to assess SOC flows and C sequestration potentials from improving arable-land management in soils at regional, national or larger scales [10, 11].

Large-scale assessments of SOC development in response to management in arable land are affected by the scarcity of reliable time series of soil carbon monitoring data and often fail to replicate observed trends or appreciate any effects induced by changes in soil management [12]. Estimates of SOC development are most often based on either factors of SOC change derived statistically from a broad pool of agricultural experiments or process-based models [13]. Statistical factor-based approaches rarely discriminate in their pool of evidence against experiments that are too short or that measure differences as a single point in time relative to a control [3, 14], and very few process-based models validate SOC trends adequately [15]. In consequence, carbon storage in agriculture constitutes a major blind spot in inventories of domestic GHG emissions in the EU [12].

A challenge therefore remains in discerning the effects of different suites of management on SOC development across large geospatial scales [10]. A recent review and meta-analysis of independent long-term time series of SOC measurements in field experiments across a wide span of climatic conditions and soil types addressed the drawbacks associated with the evidence pool of existing factor-based approaches [16]. Building on this analysis, our work aims to support the spatial prioritisation of a payment eco-scheme for carbon farming in soils by providing an EU-wide assessment of the climate-change mitigation benefits of improved arable-land management based on long-term time series data. Our account of potential management improvements is benchmarked to observed practices from a 2016 Eurostat survey. Given the substantial influence that the EU's common agricultural policy (CAP) framework exerts on farmers´ decisions [17], we consider that the findings from the survey are fairly representative throughout the whole CAP period (2014–2022). The following research questions guide our study:

- Where in the EU has arable-land management during the 2014–2022 CAP period resulted in SOC losses?
- What is the marginal economic benefit to society of improved management in terms of C sequestration potential for climate-change mitigation?
- What would be the maximum value of a payment eco-scheme for carbon farming by region and for the EU?

Our estimate of SOC stock development is based on rates of net SOC change for different management suites comprising reduced tillage, organic amendments, crop rotations and soil cover from López i Losada, Hedlund [16, 18]. This approach is thus based on long-term experimental evidence covering a wide range of management norms, climatic conditions and soil characteristics that can be found across Europe. In addition, it considers the combined effects of practices that are not mutually exclusive (e.g. reduced tillage and organic amendments) and, indeed, often assumed to yield linearly additive gains in SOC [19, 20]. Our study thus contributes to the assessment of SOC gains from improved management across farming regions in the EU, which has been identified as a key research gap to support policymaking concerned with the sustainable management of soils [10].

2. Methods

This study quantifies climate-change mitigation benefits to society from SOC gains from generalised implementation of good soil management practices (defined here as reduced tillage, organic amendments, crop rotations, and soil cover during winter) in intensive arable land across NUTS2 regions in the EU. First, we determine current coverage of good practices across NUTS2 regions based on farm statistics. To estimate regional SOC development, we use the average SOC content in arable land within each region together with net rates of SOC change from management. The net rates of SOC change are based on meta-analysis results by López i Losada, Hedlund [16] and constant across regions when expressed as a proportion of SOC content. We calculate the potential for C sequestration from improved management as the difference between SOC development when good practices are implemented in all arable land of a given region and their current adoption levels. The remainder of this section describes the method more in detail.

Net rates of SOC change due to management in this study are based on estimated averages (along their 95% confidence intervals) for intensive arable land in Europe and North America [16]. Our analysis is restricted to arable land on crop specialist farms (CSFs), given that the evidence pool of 214 time data series by López i Losada, Hedlund [16] is representative of mineral soils in crop rotation systems without perennial grasses that are typical for these farms. CSFs (i.e. one of 23 farm types from a typology employed by Eurostat) are defined as those obtaining at least two thirds of their annualised income from cereals, oilseeds, root crops and industrial crops such as tobacco or cotton, and account for 40% of the arable land in

Table 1. Eurostat data categories considered across each type of good practice for soil. Source: Eurostat [21].

Type of good practice	Eurostat data
Reduced tillage	Reduced tillage—no tillage
Soil cover during winter	Winter crop—intermediate crop—crop residues—perennial crop
Organic amendments	Crop residues—intermediate crop—manure application[a]
Crop rotation	Crop rotation

[a] Manure application on CSFs is estimated based on livestock presence and its distribution among farm types within the region. Further details are provided in this section and the supplementary data.

the EU [21]. The remaining arable land is used heterogeneously, although typically in farms with more diverse production activities and cropping patterns, often including high shares of arable grasses for grazing livestock.

2.1. Arable-land management in the EU

Regionalised information at NUTS2 level on farm characteristics across farm types, including the adoption rate of several arable-land management practices, is provided by Eurostat [21]. This data was gathered through a farm survey in 2016 and is the most recent data available across the EU. Regional averages of arable-land management in CSFs are taken to be representative of conventional practices given the very small number of CSFs dedicated to organic production. Information on soil management from Eurostat is further aggregated to calculate adoption levels of four types of practices providing soil benefits, namely reduced tillage, soil cover during winter, organic amendments, and crop rotation (table 1).

Given that manure production and application data is not published by Eurostat, adoption rates of organic amendments combine data on crop residues and intermediate crops with an estimate of arable land with manure application on CSFs based on livestock presence and its distribution among farm types within the regions. First, manure production is estimated by combining livestock statistics in 2020 and national estimates of manure excretion rates in kg N per livestock type [22]. Arable land with manure application on CSFs is then estimated by considering statistics on manure management systems in 2020 from the National Inventory Reports of GHG emissions and their N volatilisation losses according to IPCC 2006 guidelines. Livestock presence across farm types is rather heterogeneous and particularly scarce in intensive arable farming. We assume that livestock-oriented farmers will spread up to 170 kg N ha^{-1} of manure on their arable land as a measure to dispose of it cost-effectively, which is the limit established for nitrate vulnerable zones in the Water Framework Directive. Given that manure transportation is costly, trade is low between regions and farm types with manure above that limit are assumed to distribute the excess within the same region among farms where manure is scarce [23]. We consider that these farms apply manure at a rate of 30 kg N ha^{-1}, which corresponds to the average found across long-term experiments with manure application [16]. While both N and C play important roles in plant-soil dynamics, C application levels or C:N ratios in manure were usually not recorded in the long-term experiments that support this study [24]. Detailed mathematical expressions used to calculate adoption levels of manure amendments are described in the Appendix.

Our analysis is limited to EU Member States, though it excludes Ireland because we were unable to trace land and livestock statistics throughout the substantial reconfiguration undergone by its NUTS2 regions. We also exclude overseas territories, given concerns that their climatic conditions are outside the validity range of the evidence base used in this study, and NUTS2 regions with less than 1000 ha arable land (and in consequence, Malta) because most of their data on soil management and livestock statistics is confidential. This analysis considers the 2010 classification of NUTS2 regions, while livestock statistics reported using the 2016 classification were adjusted based on equivalences found in López-Cobo [25]. An expert survey by Heller, Bene [26] was used to complete missing data in Eurostat on soil cover for Spanish regions.

2.2. Estimating net SOC stock change from management practices

Estimates of SOC stock development from management are based on a meta-analysis by López i Losada, Hedlund [16] of 214 long-term time series from field experiments spanning a wide range of climatic and soil conditions that are representative of management on CSFs in the EU. Net change rates of SOC obtained in that study for different adoption levels of good practices for soil represent a log-linear fit of the time series data, which are simplified here with a first-order Taylor polynomial approximation of the exponential function that is adequate for small values of $a^{*}t$ [27]:

$$\mathrm{SOC}_j\,(t) = (1 + a * t) * \mathrm{SOC}_{0,j} \qquad (1)$$

where $\mathrm{SOC}_{0,j}$ represents initial SOC stock obtained as an average for arable land in region j from the LUCAS soil database [28], a is the estimated parameter for the yearly net rate of change based on long-term time series from field experiments, and t is time (in years from 0, the starting time when SOC_j is equal to SOC_0). While the validity of this approximation diminishes over time as the term t increases, our study is limited to near-term estimation of yearly C sequestration, which we calculate for $t = 1$. The difference between $SOC_j(t = 1)$ and $SOC_{0,j}$ represents thus the yearly gain (or loss) of SOC that may be expected on average when maintaining management conditions over many years across large geo-spatial scales, although SOC variability due to exogenous factors (e.g., weather and soil characteristics) make annual measurements of SOC changes from management unreliable [29].

Rates of net SOC change estimated in the meta-analysis for an increasing number of good practices were interpolated for an index of good practice that is defined regionally as an average adoption level across the four types of good practices considered in this study. This approach assumes that all individual practices contribute similarly to SOC development, which is supported by results from the meta-analysis showing stronger effects on SOC from increasing the number of good practices applied simultaneously than from changing some good practices for others (supplementary data figure A1).

We consider that significant C loss (gain) occurs below (above) the value of the index of good practice for which the interpolated upper (lower) limit of the 95% confidence interval of the net rate is zero (supplementary data figure A2). Analogously, we differentiated between non-significant C gain and non-significant C loss at the value of the index of good practice for which the interpolated mean of the net rate is zero.

Regional SOC potential gains from improved management were obtained for an index of good practice of 100%, i.e. when the four types of good practices are adopted in all the arable land in the region, and benchmarked to SOC change under current practices. Our analysis of potential SOC gains under best soil management practices thus differentiated between avoided C loss under current management (if any) and C sequestration according to definitions established by Don *et al* [30].

Lastly, we estimated the economic value to society of avoided C loss and C sequestration potential based on the average market price of European Carbon Permits in 2023, which is 83.66 EUR per tonne CO2-eq. This considers equal marginal cost of abatement in all sectors of the economy, which is necessary for reducing emissions cost-effectively across sectors in the EU.

3. Results

3.1. Soil management in intensive arable land

The results show significant C loss due to contemporary arable-land management during the previous CAP period in 71 out of 194 NUTS2 regions, while none exhibit significant C sequestration (table 2). Contemporary management led to a yearly total loss in SOC stocks in CSFs across all regions of 13 (± 15) million tonne CO2-eq, though differential values for C sequestration/loss for a given management suite occur due to the variability of SOC stocks in arable land across EU Member States (see equation (1)). Overall, countries and regions in higher latitudes exhibit greater C sequestration/loss from management, which is connected to higher initial SOC stocks in arable land (figures 1–3).

All regions present some level of soil management corresponding to applying at least one good practice fully across all arable land on CSFs (figure 1). However, the adoption levels of the different types of good practices considered in this study vary substantially across regions (supplementary data figure A3). Some regions show high levels of implementation of some practices, but very few regions consistently exhibit high adoption levels across all types. Most regions show high adoption levels of crop rotations, whereas organic amendments and reduced tillage show contrasting spatial patterns across the EU.

3.2. Potential SOC change from management improvement

The largest potential C sequestration per unit of land from improved management is found in Finland, Estonia and Latvia, while the largest C losses from contemporary management are found in Latvia and Sweden. C loss in CSFs due to arable-land management in the evaluated CAP period is largest in countries with large SOC stocks and comparatively low index of good practice scores, and is significant in Finland, Latvia, Sweden, Slovenia, Hungary, Romania, Poland, Greece and Lithuania. Other countries such as the Netherlands, Belgium, and France show insignificant C loss, indicating that SOC loss due to arable-land management is a regional problem. In contrast, potential C sequestration from improved management is significant across all countries and shows a four-fold variation across Member States, with Finland exhibiting the largest potential and Cyprus the lowest (figure 2). In addition, our estimates of value show greater variation across countries than across regions within the same country (appendix figure A4).

Overall, the potential for C sequestration from improved soil management is estimated to be 48 (± 15) million tonnes CO2-eq yearly. Together with avoided C losses, this yields a potential of 62 (± 30) million tonnes CO2-eq yearly that corresponds to 17% (± 8%) of the target for additional carbon removals in the soil and forest sinks under the Fit for 55 package. The lower bound of this estimate is conservative, as it considers minimum C loss from current practices and minimum C sequestration from improved management. The upper bound is a

Table 2. C loss or gain in crop specialist farms (CSFs) due to arable-land management represented as an index of good practice (IGP) during the 2014–2022 CAP period across NUTS2 regions.

IGP	IGP-predicted C loss/C gain	NUTS2 regions		Arable land in CSFs	
		n	%	M ha	%
Above 82.2	Significant gain	0	0.0	0.0	0.0
Between 72.4 and 82.2	Non-significant gain	10	5.2	0.5	1.2
Between 50.0 and 72.4	Non-significant loss	113	58.2	20.4	52.5
Under 50.0	Significant loss	71	36.6	18.0	46.3

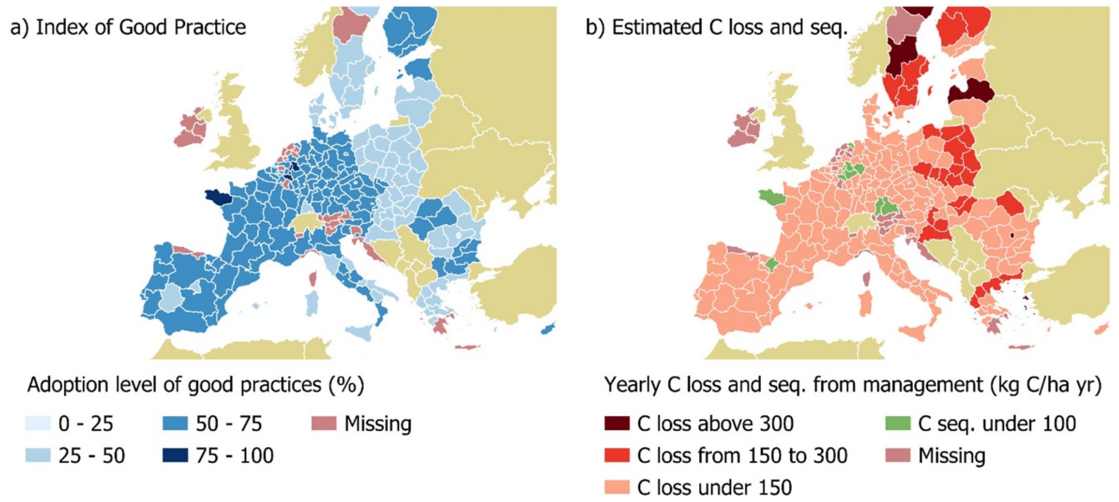

Figure 1. Index of good practice (a) and estimated C loss (b) across NUTS2 regions in the EU. Regions where arable land in crop specialist farms is less than 1000 ha and Ireland are classified as missing.

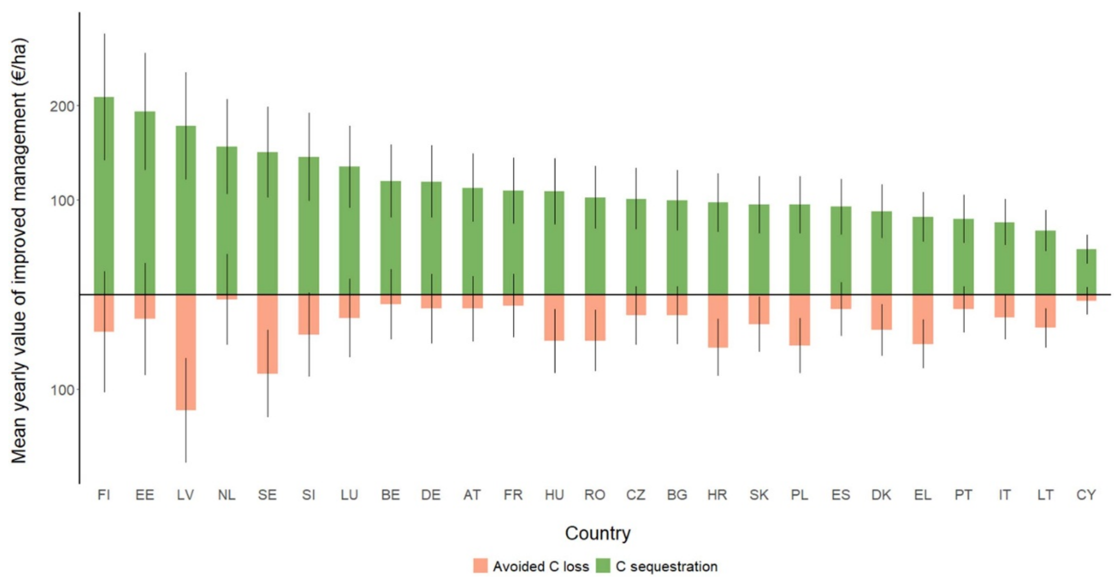

Figure 2. Value of management improvements per unit of land in 25 EU countries. Malta and Ireland are excluded from our analysis. Adapted from [31]. CC BY 4.0.

highball estimate, as it considers maximum C loss from current practices and maximum C sequestration from improved management.

3.3. Budgeting a carbon-farming eco-scheme

Our estimates on SOC gains and societal benefits can be interpreted as an upper level of the

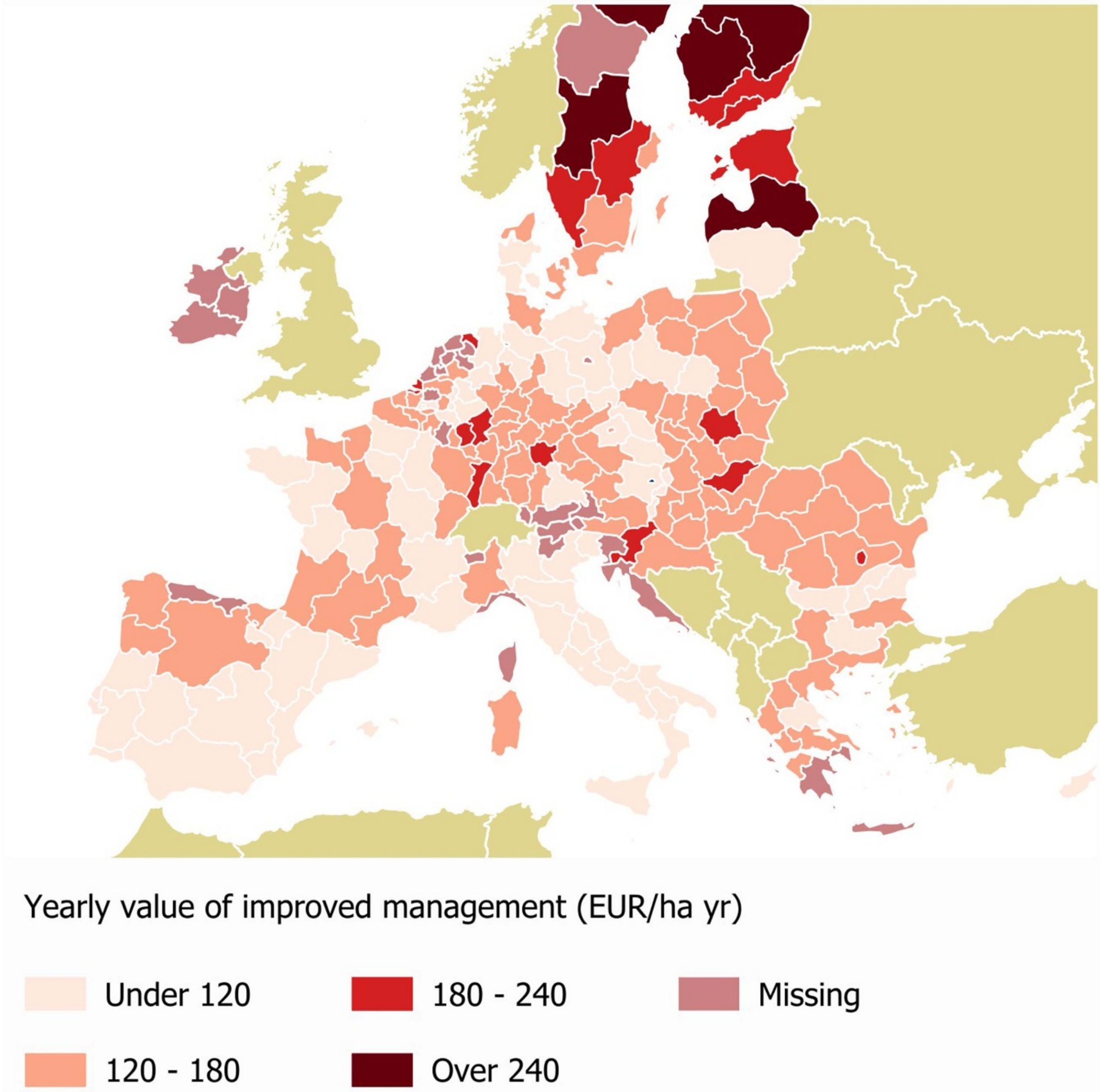

Figure 3. Annual value of management improvements across NUTS2 regions in the EU.

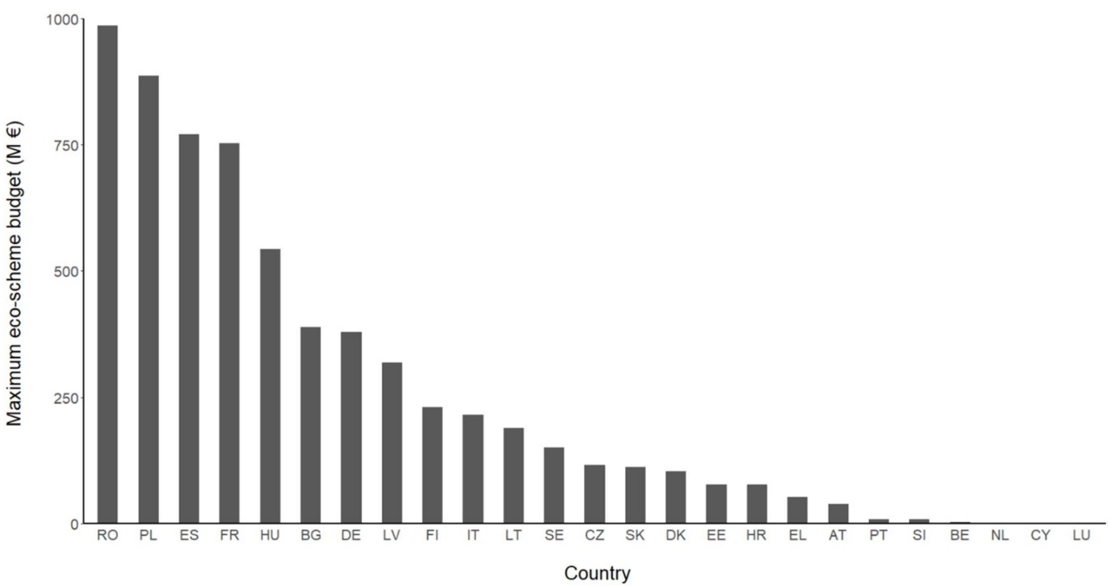

Figure 4. Annual potential benefit from management improvements across 25 EU Member States. Malta and Ireland are excluded from our analysis.

implementation budget for a payment eco-scheme for carbon farming based on modelled climate-change mitigation benefits. Under this eco-scheme, CSFs would be offered a hectare-based payment according to the societal value of the yearly mean estimate of C sequestration and avoided C losses obtained in this study from improved arable-land management. Naturally, farmers would only be expected to adopt improvement measures if their costs were lower than the payment.

Assuming that the average observed price of CO2-eq in the EU-ETS 2023 reflects the benefits of emission reduction and thus determines the payment to farmers, the maximum potential budgetary outlay for this eco-scheme across the entire EU would be 6.4 billion EUR. This would cover payments to all CSFs for the climate-change mitigation benefits from reducing tillage, applying organic amendments, covering soil in sensitive periods, and rotating crops in all their arable land. This level would comprise payments to farmers for both C sequestration (5 billion EUR) and avoided C loss (1.4 billion EUR). Five countries (i.e. Romania, Poland, Spain, France and Hungary) account for 62% of the maximum budget (figure 4). While these countries show lower potential for C sequestration per unit of land compared to others such as Finland, Latvia, Estonia, and Sweden (figure 3), they account for 60% of the arable land in CSFs (and 50% of the arable land overall) in the EU [21].

4. Discussion

4.1. C loss from contemporary soil management

This study values recent C losses from arable-land management and potential C sequestration from improvements in soil management on CSFs across Europe as a climate-change mitigation measure. Overall, our analysis shows substantial C losses in mineral soils in CSFs in the EU representing roughly one fifth of the 70 million tonnes CO2-eq that cropland in the EU is losing yearly according to a coarse estimate by Bellassen *et al* [12]. Although their estimate accounts for all arable land in the EU and is therefore not directly comparable to ours, arable land outside of CSFs (i.e. ∼60% of the total) is less likely to lose SOC stocks due to less intensive practices, high shares of arable grasses in crop rotations and access to manure [32]. Both Bellassen *et al* [12] and our study contrast with official inventory reporting of limited C sequestration in croplands in the EU [33].

High spatial variability across regions and countries in our results indicates that C loss due to contemporary arable-land management is a regional problem. Organic amendments and reduced tillage are the two most absent practices that could reduce C loss in soils. While manure spreading is the largest contributor to organic amendments ahead of crop residues and cover crops, its implementation could only be calculated indirectly through livestock statistics and assuming profit-maximising decision-making by farmers. Our results show low manure availability in CSFs, which usually have little if any livestock in their proximity [23]. Conversely, uniform distribution of manure regionally would achieve sufficient use of organic amendments in roughly half of the regions (appendix figure A5). In this regard, an eco-scheme payment for carbon farming could create an economic incentive to distribute manure more effectively for C sequestration and soil health. However, our study does not consider transportation distances and subsequent costs and GHG emissions, which are critical aspects affecting feasibility and overall climate-change mitigation potential of manure redistribution [23].

This study assumes that all CSFs in a region behave similarly and close to the mean index of good practice for arable-land management because variability and concatenation of practices within a region is largely unknown. Net SOC change rates are relatively linear in the domain of the index of good practice in most regions—i.e. 25% to 75%—meaning that it would be unlikely for non-normal distributions of good practices regionally to substantially affect our results. In addition, the meta-analysis that derived the net SOC change rates used in this study does not contemplate effects on SOC from gradual changes for each type of good practice (e.g., different manure application rates or fractions of residues left in the soil), given that it lays focus on the effects of combined practices in management suites. At the same time, survey data on management from Eurostat did not record incremental differences across any of the practices in focus. López i Losada *et al* [16] offer detailed descriptions of the management in the included field studies, which are indicative of the type of practices that are the most representative for the net SOC change rates used in our study. With better information on concatenation of practices that may be available for some regions, estimates can be refined with information from the meta-analysis on change rates for specific management suites.

4.2. Societal benefit from SOC gains due to improved management

Our study shows that SOC levels and current practices drive potential marginal benefits from improving arable-land management. This is because higher SOC levels exacerbate C sequestration or losses from a given management suite, and current lack of good management is a measure of additionality, i.e. it ensures that farmers in a region are not paid for something that most were already doing [7]. While information on contemporary arable-land management comes from a 2016 Eurostat survey, Heller *et al* [26] found adoption levels of sustainable soil management practices generally similar to, though to some extent higher than, those reflected in the 2016 Eurostat survey. SOC stocks are in turn primarily driven across wide-ranging geospatial scales by the influence of climatic conditions on soil dynamics [29]. Overall, potential benefits per unit of arable land are largest in regions with low implementation of sustainable soil management practices and comparatively high SOC stocks.

Our choice of valuation method is centred on the public good generated by improved arable land management in terms of increased C stored in soils (or reduced C loss) as a climate-change mitigation measure. Although ecosystem services affecting yields and yield security may also be enhanced, these benefit primarily farmers´ incomes and their contribution to food security is challenging to quantify [6, 34, 35]. In addition, the influence of future climate change on soil dynamics and C sequestration from improved management is clearly not captured in the long-term field experiments that underpin this work [36]. Although outside the scope of our study, climate change poses a threat to carbon stocks in soils and highlights the relevance of integrating dynamic soil modelling with a wide span of long-term time series data for validation [15].

The reference value for C sequestration in soils from the European Carbon Credits system considers SOC gains as negative emissions, which should remain stored for decades to compensate the effects of GHG emissions into the atmosphere [37]. This analogy, while common [38, 39], has also drawn criticism given the reversibility of SOC gains that could come, e.g., from a reversal in management or different soil dynamics in future warmer climates [37, 40], and led Günther *et al* [37] to question the Commission´s proposal to include soil carbon in the Carbon Removal Certification Framework. However, we believe that the CAP, considering its pledge to never become less environmentally ambitious, offers a long-term commitment to keep incentives promoting sustainable soil management in place. Improved soil health and its positive effect on future income security also provide a strong incentive, though likely insufficient on its own, for farmers to favour sustainable soil management [6].

Long-term time series allow estimating C loss and C sequestration resulting from management choices without an arbitrary counterfactual benchmark [41, 42]. Thus, we disentangle the polluter and provider effects, which enables policymaking to consider them separately, for instance by devising instruments to pay farmers for C sequestration while taxing them for C losses following a 'polluter pays, provider gets' principle. This would, in turn, enhance accountability of farmers in case stored C is re-emitted due to a backward change in management [7].

4.3. Implications for a carbon-farming payment eco-scheme

This study provides scientific input for policymaking to conceptualise a carbon-farming payment eco-scheme targeting CSFs based on modelled outcomes by valuing societal benefits across the EU [43]. The lowest economic benefit per unit of land from improvements in soil management are found in Mediterranean countries, with eastern and northern countries exhibiting values up to four times higher. This is a relevant finding in light of the development of National Strategic Plans as part of the new CAP 2023 structure conceived for performance-based governance [44]. The large spatial variability found in our results demonstrates the potential to enhance cost-effectiveness of a carbon-farming eco-scheme by adjusting payments spatially (e.g. region or country level) to better match expected outcomes. Basing payments on (modelled) marginal benefits for climate-change mitigation rather than management costs to the farmer would therefore guarantee cost-effective C sequestration across arable land in the EU. In contrast, this approach would also compensate some farmers beyond their marginal implementation costs, which could have undesired societal consequences for income redistribution.

The latest reform of the CAP for the 2023–27 period formulates conditionalities on soil cover during sensitive periods, crop rotations, and tillage for farmland to be eligible for direct payments. A recent proposal by the European Commission to relax conditionality requirements on soil cover and crop rotations (COM/2024/139) suggests lack of broad farmer support for the current form of the CAP and highlights current challenges in sustainable soil governance. Although the uptake of the payment eco-scheme is not considered in this study and could vary widely due to regional differences in implementation costs to farmers, we estimate a maximum budget, based on the value of emission reduction, of 6.4 billion EUR, which is equivalent to 39% of the entire CAP budget allocated to environmental and climate objectives. If the payment eco-scheme was to be included in this budget, it would require substantial funding expansion or incur large opportunity costs for other environmental measures outside of CSFs or that relate to environmental objectives other than climate-change mitigation. Conversely, the maximum budget for the payment eco-scheme represents 17% of the CAP funds allocated to income support. This indicates that the loss of direct payments by farmers not fulfilling soil management conditionalities is substantially larger than the societal benefit of climate-change mitigation generated by the improvements. Interestingly, our findings could motivate a reformulation of the conditionalities on soil management so that they only affect a fraction of the direct payments received in CSFs. This could contribute to preserving trust from stakeholders and society, and thereby to the repurposing of the CAP towards environmental objectives [17, 45, 46].

Measuring SOC gains from management improvements is challenging because exogenous factors (i.e. climatic variability and field characteristics) preclude observing trends induced from management in the short term [14, 29]. Environmental outcomes from a carbon farming eco-scheme could in practice only be validated after many years in large-scale sampling efforts, thus motivating our modelling approach on expected regional outcomes supported with evidence from long-term field experiments [43]. Potential uncertainties about the estimation of C sequestration could furthermore motivate reducing the payment levels in the eco-scheme with a risk premium.

Our modelling of the societal benefits from improved management is limited to climate-change mitigation from SOC gains. Yet shifts in soil management can bring about contrasting short- and long-term effects on yields, fertiliser needs and operational requirements that are substantial and constitute societal costs and benefits that we do not consider [47–49]. In addition, C sequestration rates due to enhanced management should eventually start to decrease until SOC levels eventually plateau, thus causing societal value from management improvements to decrease over time [50]. The time horizon for SOC change -which was outside the scope of the meta-analysis [16]—is a sensitive parameter in dynamic SOC modelling and commonly assumed to range between 20 and 100 years [13, 51–53]. Noticeably, the lower end of this range already suits a global agenda with ambitious climate-change mitigation targets before 2050 [54].

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.15023792.

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Author contributions

All authors conceptualized the study. RLL designed the methodology with input from all authors. RLL performed the analysis. RLL wrote the manuscript, and all authors contributed with editing and revisions.

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