Soil carbon, the blind spot of European national greenhouse gas inventories

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Title: Soil carbon, the blind spot of European national greenhouse gas inventories

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Abstract:

Soil carbon is currently being monitored in European national greenhouse gas inventories. Reviewing their data and methods, we find that unreported losses could be around 70 MtCO2 yr-1 in croplands and unreported gains could be around 15 MtCO2 yr-1 in grasslands and 45 MtCO2 yr-1 in forests. The share of EU forest area for which soil carbon is being accurately reported is at most 33%, and more likely close to 24%. Accuracy is even worse for grasslands and croplands. A widespread adoption of key carbon farming practices (peatland restoration, agroforestry, substituting maize with grass) could remove an additional 150-350 MtCO2 yr-1. Yet, if effective policies lead to realizing this potential, current GHG inventories would not capture their climate mitigation benefits.

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The Intergovernmental Panel on Climate Change (IPCC) estimates that in order to keep global warming below +1.5°C compared to the pre-industrial period, achieving global carbon neutrality by 2050 will be necessary[1]. Carbon neutrality mostly requires dramatic reductions in CO_2 emissions from fossil fuels as well as emissions of other greenhouse gases. But to balance residual emissions, a substantial increase in carbon storage will also be needed through changes in land use and the diffusion of climate smart agricultural and forestry practices. The EU is targeting to balance 500-600 MtCO2e yr^{-1} of its residual emissions with carbon storage, 50-85% of which is expected to come from soils and biomass[2].

The well-monitored forest biomass sink has been declining since 2013 (Figure 1). This is increasing the expectation on European soils to make up for the difference in meeting the overall carbon storage target of 500-600 MtCO2e yr^{-1}. Provided that the forest biomass sink does not fall further than the current 284 MtCO2e yr^{-1}, soils would be expected to store up to 260 $MtCO_2$ yr^{-1}. This is ambitious but not wholly unreasonable as existing assessments put the soil carbon storage potential in Europe at around an additional 150-350 $MtCO_2$ yr^{-1} for mineral and organic soils combined (see section 1 below). However, we show here that even if climate-smart agricultural and forest practices were being upscaled, their benefits would not be captured by the monitoring system intended to track progress towards the EU climate neutrality target. Despite this bleak picture, we also argue that minor adjustments in the monitoring rules and incentives, combined with a higher accessibility of existing data, could rapidly improve the ability of national greenhouse gas inventories to reflect actual changes in soil carbon storage.

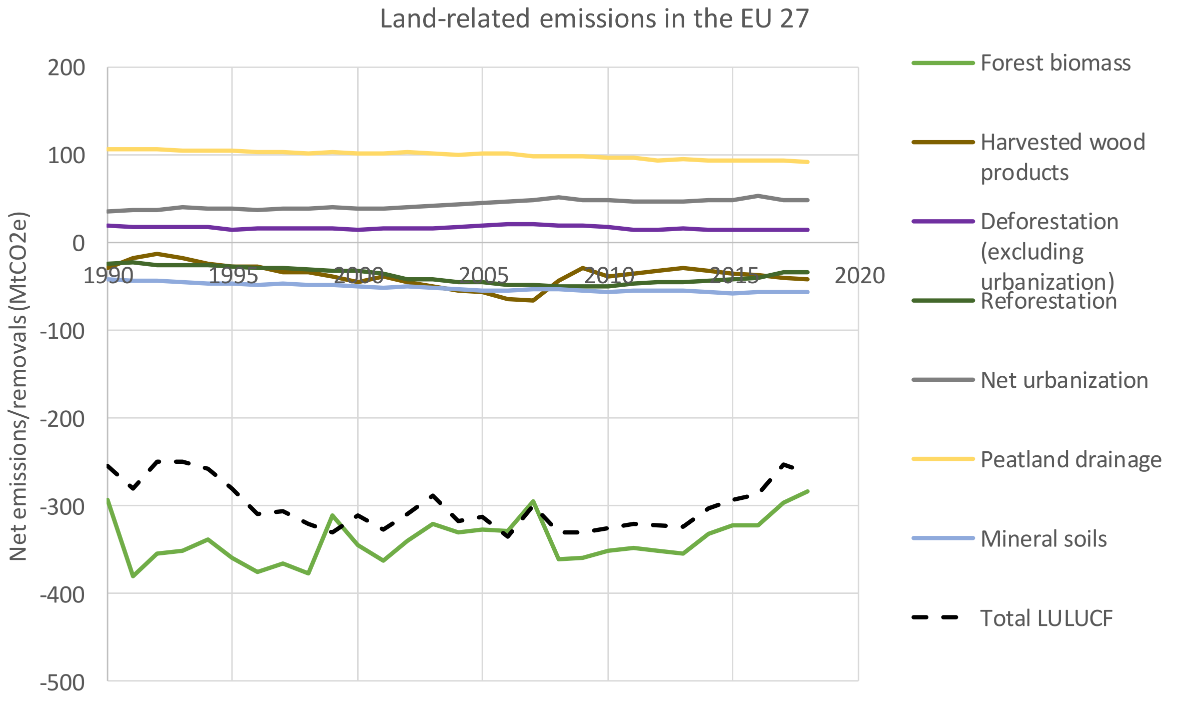

Figure 1. Land-related emissions in the EU 27 as reported in national greenhouse gas inventories. A negative value indicates a net carbon storage. Source: authors' calculations based on 2020 national greenhouse gas inventories (see SM 1.1 for details).

Soil carbon, a substantial mitigation potential in the EU

According to the few existing large-scale assessments in the EU, the soil carbon storage potential could add up to 150-350 $MtCO_2$ yr^{-1}, relying on four key practices: agroforestry, cover crops, substituting fodder crops (eg. maize) with grass, and peatland restoration (Table 1). An additional storage of 250-350 $MtCO_2$ yr^{-1} could be obtained from land-use changes, but these are already properly monitored in national GHG inventories and their economic feasibility is seldom assessed.

Agroforestry. The sequestration potential of arable agroforestry has been estimated at 0.8 tCO_2 ha^{-1} yr^{-1} in the soil and 3.3 tCO_2 ha^{-1} yr^{-1} in the biomass, leading to a national potential of 34 M tCO_2 yr^{-1} in France at a price of 250 € tCO_2e^{-1} [3]. A coarse upscaling proportional to cropland area puts the European soil storage potential at 60 $MtCO_2$ yr^{-1} (Table 1). Current agroforested arable areas only amount to 0.4 Mha, that is 0.3% of the cropland area in the EU[4].

Cover crops. Introducing cover crops and avoiding bare soils between harvest and seeding is boosting removals by 1.1 tCO_2 ha^{-1} yr^{-1} [3] and their area have been rapidly growing from 6% to 8% of EU arable land between 2010 and 2016. With 23-30% of bare soil during the winter, there is still a substantial untapped potential, estimated at 45 $MtCO_2$ yr^{-1} at EU level by Lugato et al.[5].

Substituting maize with grass. Pellerin et al.[3] estimates the national storage potential of this practice at 5 M tCO_2 yr^{-1} in France at a price of 250 € $tCO2e^{-1}$. The EU level potential of a similar practice, consisting in increasing areas cultivated with ley/alfalfa, has been estimated at 45 M tCO_2 yr^{-1} [5].

Peatland restoration. While peatland restoration does not allow to restore a positive carbon storage dynamic in the short term, it quickly reduces or stops the considerable CO_2 emissions from peatland drainage that would otherwise go on for decades. Depending on climate, land-use and the extent of degradation, peatland restoration can avoid emissions between 2 and 34 tCO_2 ha^{-1} yr^{-1} [3,6]. The EU potential for reducing emissions through peatland restoration has been estimated at around 109 $MtCO_2$ yr^{-1} [7].

Other practices. No/low-tillage practices are not considered because the most recent meta-analysis conclude that, in the temperate context, they mostly redistribute soil organic carbon over the soil profile, with little to no increase in total soil organic carbon over the entire soil profile[8,9]. Increased nitrogen fertilization in grassland is not considered either because its soil carbon benefits are offset by fertilizer-induced emissions in grassland[3]. Other practices have been shown to store carbon in the soil – e.g. crop residues returning, hedges, exogenous organic matter input - but their potential at large scale is likely limited[3,5].

	Current area (Mha)	Carbon sequestration potential in the soil (MtCO2/yr)					
Management practices		(3) upscaled		(5)	(7)	Minimum	Maximum
		Min (25€/tCO2)	Max (250 €/tCO2)				
Arable agroforestry	0.4	0.1	60			0	60
Cover crops	7.5	68	94	46		46	94
Grass/Maize substitution	not applicable	5	25	46		5	46
Wetland restoration	negligible				109	109	109
All residues left on field	negligible			26		26	26
Total						*186*	*334*
Land-use changes		(11)		(5)	(10)		
		Min (25€/tCO2)	Max (250 €/tCO2)				
Afforestation		0	29		111	0	111
Conversion to grassland				266		266	266
Total						*266*	*377*

Table 1. Estimates of soil sequestration potentials at EU level. In the case of Pellerin et al.[3] which assess potentials at the national level in France, original figures are increased proportionally to the area of arable land (for agroforestry and cover crops) and to number of cattle heads for grass/maize substitution. The resulting figures are relevant to the EU 27, whereas Lugato et al.[5] and Greifswald Mire Centre[7] still cover the United Kingdom. For afforestation[10,11], original figures do not separate soil from biomass: the soil potential is obtained based on the 11% share of soil in total storage for land converted to forest land in the European inventory.

[Note: the excel version of this table can be found in sheet "estimates" of SM file "21-06-30 - Soil_carbon_in_inventories.xlsx]

Regarding forest soils, existing scientific evidence only provides one clear recommendation: avoiding losses that have been documented to take place when whole-tree harvesting – including remnants and stumps – is practiced[12,13]. Fortunately, this type of harvesting remains rare in the EU. Nitrogen addition or the introduction of nitrogen-fixing species are the only practices which have been consistently shown to increase soil carbon storage, but the extent to which this increase offsets the associated fertilizer-induced emissions remains to be assessed[13]. The impact of other practices such as leaving harvest residues on site, extending rotation length, limiting soil disturbance and replacing clear-cut harvesting by partial harvesting are likely to be beneficial but limited. Further research is needed to obtain robust estimates of the effect of these practices on soil carbon, and derive clear policy recommendations[13].

A blind spot in national GHG inventories

Assuming that these climate-smart agricultural and forest practices were being upscaled, would the EU be able to report the climate mitigation benefits in its GHG inventory? To answer this question, we review the reported trends over the past 30 years as well as the methods and reliability of each of the 27 national GHG inventories.

Surprising stability and astonishing drivers in reported soil storage. At European scale, mineral soils were reported to be storing 55 $MtCO_2\ yr^{-1}$ in 2018, while drained organic soils were emitting 96 $MtCO_2\ yr^{-1}$ (Figure 1). The relative stability of these reported fluxes over the past 29 years is already somewhat surprising: has nothing changed in European soils since 1990? Diving into regional and national estimates renders the picture even more surprising. Carbon storage in mineral arable soils is reported to have increased from 4 $MtCO_2\ yr^{-1}$ in 1990 to 10 $MtCO_2\ yr^{-1}$ in 2018, largely driven by the rise of reduced-tillage practices in France (Atlantic region) and of organic farming in Italy (Mediterranean region) according to the relevant national inventory reports. Yet, reduced-tillage practices have been demonstrated to have little to no impact on soil carbon in temperate regions[8,9,14] and organic farming is more likely displacing storage through manure than actually triggering additional soil carbon storage when land-use changes (eg. conversions from cropland to grassland) have already been accounted for[15]. Moreover, the additional 2.1 Mha of cover crops in 2016 compared to 2010 should be adding a sustained 2.3 $MtCO_2\ yr^{-1}$ to the EU total over that period. Instead, they are neither mentioned in national GHG inventories nor visible in the EU tally which decreases by 2 $MtCO_2\ yr^{-1}$ over the same period (Figure 2). In order to understand these apparent paradoxes, we estimate the share of EU mineral soils which are monitored with unreliable methods and the CO_2 fluxes likely missed out.

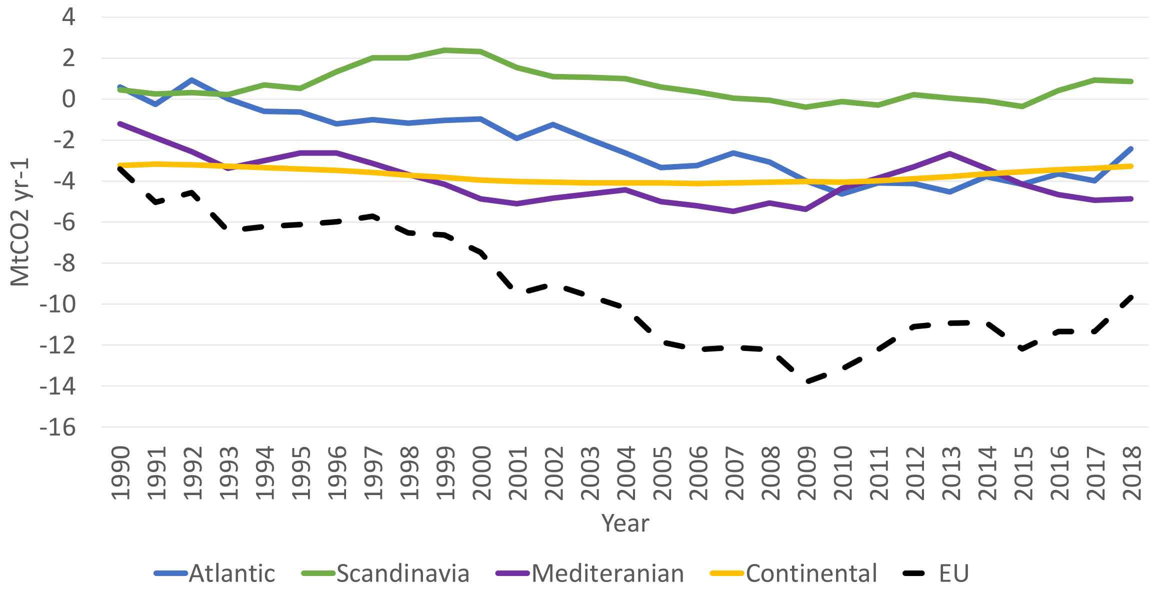

Figure 2. Net carbon stock changes in EU arable (cropland remaining cropland) mineral soils. A negative value indicates a net carbon storage. Source: 2020 national greenhouse gas inventories (see SM 1.1 for details).

Monitoring methods and their reliability. The IPCC classifies monitoring methods into three “tiers”, with increasing ability to capture national and sub-national specificities but also increasing complexity, cost, and difficulty to verify. For land conversions, emissions are properly reported by all member states as even IPCC Tier 1 methods are reasonably accurate in this respect. Therefore, we focus here on the main “land remaining land” categories, hereafter named cropland, grassland and forests. 95 % of these categories are reported as mineral soils – generally defined as soils with less than 12% organic carbon.

For mineral soils, most countries using Tier 1 do not report changes in practices, which equates to no monitoring: soil carbon is assumed to be stable. Tier 2 generally consists in monitoring the areas concerned by a set of practices, and multiplying area changes with a mix of default or country-specific emission factors. To the extent that the most relevant practices are being monitored, Tier 2 methods can be expected to be accurate at national level. Tier 3 methods cover two very different approaches. Measurement-based methods mobilize repeated soil inventories for which soil samples are being collected over hundreds of sites. In model-based methods, a process-based model (mostly involving half-decay factors and carbon transfers between different organic matter pools such as Yasso, C-Tool, …) simulates soil carbon changes based on variable inputs such as weather data, soil type, harvest statistics, … Models are often put forward as an efficient alternative to soil inventories for accurate reporting. This strategy is implemented by Finland, Austria and Ireland for forests, and by Finland, Sweden and Denmark for cropland (see SM 1.2). Unfortunately, most of these models are not able to reproduce recent trends at regional or national scale (see SM 1.3).

In the following section, two indicators are used to determine how many member states and how much European area are properly monitoring soil carbon:

- The method type: on the one hand, because the Tier 1 method is generally associated with reports of unchanged management practices, it is obviously too coarse. On the other hand, only soil inventories are obviously accurate because they actually measure soil carbon changes. Indeed, many Tier 2 methods are restricted to the distinction between annual and perennial crops, a typology which fails to capture key carbon storage practices. As for Tier 3 approaches based on modelling, they are usually not properly validated (see SM 1.3).

Accordingly, the lower bound for the area “properly monitored” is considered to be the area subject to repeated and representative soil inventories.

- The variability of reported carbon stock changes: carbon stocks in mineral soils have likely been subject to substantial variations over three decades, driven by changes in weather, yield, practices, … The reporting of an almost constant value over 1990-2018 is therefore a sign that carbon stock changes are not being monitored with precision. In several countries using accurate methods such as soil inventories or detailed Tier 2 approaches, we note that the standard deviation of reported SOC changes is higher than 0.01 tC ha^{-1} over 1990-2018. We therefore use this threshold as an indicator that soil carbon is possibly – but not necessarily –being properly monitored, the upper bound for the area “properly monitored”.

67-88% of EU land area missed out by GHG inventories. Current reporting completely ignores carbon stock changes in an estimated 5% of EU cropland area (Tier 1 method with no reported change in management practices, see Table 2). Based on the proxies for proper monitoring defined above, the share of EU cropland area which is being properly reported is estimated to be at most 37%, and more likely close to 1%. Indeed, the implied emission factors exhibit a standard deviation higher than 0.01 tC/ha over 1990-2018 – a likely necessary but not sufficient indicator of accurate reporting – in 11 member states adding up to 37% of EU cropland area, and only Belgium is actually reporting soil carbon changes based on a soil inventory for this land category.

The reporting gaps are even larger for grassland and forest soils: Tier 1 reporting rises to 32% and 53% respectively, and only 8 and 3 member states report a substantial standard deviation in their implied emission factor. However, two large member states, Sweden and Germany, base their reporting on a soil inventory for forest soils, representing one fourth of the EU forest area. Overall, a substantial variation in reported carbon stocks takes place in only 33% of these major land areas, and only 12 % are subject to a soil inventory.

	Total area of mineral soils (kha)	Tier 1 with no reported management changes		Reporting type Measurement-based (Tier 3, soil inventory)		Modelling-based (Tier 3, model)		Substantial temporal variation in IEF (SD > 0.01 tC/ha)	
		# of MS	Share of total area	# of MS	Share of total area	# of MS	Share of total area	# of MS	Share of total area
Cropland remaining cropland	109,922	5/27	5%	1/27	1%	3/27	7%	11/27	37%
Grassland remaining grassland	62,050	12/27	33%	2/27	1%	1/27	0%	8/27	28%
Forest remaining forest	145,481	19/27	52%	2/27	24%	3/27	14%	3/27	33%
Total	317,453		32%		12%		9%		33%

Table 2. Reporting methods for soils in European GHG inventories (2020 submissions). Adding Tier 2 reporting type allows the numbers to sum up to 27 member states. Calculations and details per country are available in SM 1.2.

[Note: the excel version of this table can be found in sheet “reporting quality” of SM file “21-06-30 - Soil_carbon_in_inventories.xlsx]

Reporting shortfalls for organic soils. Overall, the current reporting of organic soils is more accurate, although the reported figures are incomplete or imprecise in several member states. Regarding activity data, Barthelmes[6] identified substantial gaps in the reported areas of drained peatlands for 5 member states based on the 2017 inventories. But most of these gaps have been addressed since then: in the 2020 submissions, Romania was the only member state with a sizeable (> 200 kha) unreported drained peatland area (there was still a gap of more than 1 Mha in UK, not anymore in the EU).

Regarding emission factors, many member states are still using Tier 1 approaches to estimate emissions from drained organic soils. This generates substantial uncertainty. For example, Estonia uses an average emission factor of 1.3 tC ha^{-1} yr^{-1} for drained forested peatlands, derived from the IPCC default values for the boreal zone. Whether “boreal” is the correct zone for Estonia is a matter of debate, but the temperate zone would increase Estonian emissions by approximately 0.6 $MtCO_2$ yr^{-1}. Ultimately, the only way to settle the debate is to invest in the development of a country-specific measurement-based emission factor (Tier 2 approach). In addition, 50-70% of member states with drained organic soils do not estimate all sources of emissions (CH_4, N_2O and off-site emissions from dissolved organic carbon). In the member states where these omissions occur, emissions from drained peatland may be underestimated by up to 20%[16].

Large soil carbon gains and losses likely go unreported. In order to estimate the magnitude of unreported soil carbon gains and losses as a result of the current pitfalls in GHG inventories, we compare the reported amounts to estimates based on upscaled per hectare averages from the scientific literature. Table 3 compiles recent scientific estimates for different land-uses in European or comparable (temperate) areas. Only estimates based on proper soil inventories involving at least 50 sample locations per land use category are retained (eg. UK, Belgium, grassland in New Zealand). Forests and grasslands are currently storing soil carbon, likely because some of them are still transitioning from former cropland use, but also related to environmental changes which have been boosting vegetation growth and hence organic inputs to soils[17,18]. To the contrary, croplands are losing carbon, possibly because some are still transitioning from former grassland use[19], but there could be other explanations such as the stagnation of crop yield since 1990 or rising temperatures[20,21]. Recent increases in cover crop areas may mitigate these losses but the temporal and spatial resolution of these studies is too coarse to ascertain this.

From\To	Forest	Cropland	Grassland	Peatland
Forest	-0.17 [-0.41 ; 0][(a)]	Over 20 years: 2,31 ± 1,50 Over 100 years: 0,47 ± 0,29	0	0
Cropland	Over 20 years: -0,77 ± 0,36 Over 100 years: -0,80 ± 0,37	0.17 [-0.16 ; 0.5] [(b)]	Over 20 years: -0,92 ± 0,25 Over 100 years: -0,59 ± 0,11	0
Grassland	0	Over 20 years: 2,08 ± 0,26 Over 100 years: 0,42 ± 0,05	-0.11[-0.17 ; 0.03]	0
Peatland	3 ± 2[(c)]	3 ± 2	3 ± 2	-0.4 ± 0.2

Table 3. Average soil carbon changes in the EU (tC ha^{-1} yr^{-1}, adapted from Pellerin et al.[3]). A negative value indicates a net carbon storage. The list of publications reviewed for this compilation and their estimates is provided in SM 1.4. (a) Pellerin et al.[3] does not provide an uncertainty range for forest soils. 0 is the value reported by Emmett[22] based on the UK soil inventory and 0.41 is the value reported by Grüneberg[23] based on the German soil inventory. (b) Pellerin et al.[3] does not provide an uncertainty range. The range is taken from Ciais et al.[24] which also averages at –0.17 tC ha^{-1} yr^{-1} and is quoted by Pellerin et al.[3]. (c) Based on IPCC[25,16] estimates that emissions from drained agricultural soils average at 10 tC_{eq} ha^{-1} yr^{-1}.

Multiplying these figures by the area of mineral soils in each land category gives a sense of what current GHG inventories may be missing at EU level: cropland soils could be currently emitting 70 $MtCO_2$ yr^{-1} whereas inventories report a net sequestration of 3 $MtCO_2$ yr^{-1}, grassland soils could be storing 25 $MtCO_2$ yr^{-1} whereas inventories report a net sequestration of 10 $MtCO_2$ yr^{-1} and forest soils could be storing twice the reported 43 $MtCO_2$ yr^{-1} (Figure 3). The obvious pitfall of such coarse upscaling is that they rely on soil inventory repetitions in very few and mostly oceanic countries (Belgium, UK, Germany, Denmark, see SM 1.4 for details) which may not be representative of current trends in the entire EU. Given the shortage of data however, there is no obvious other way of obtaining more representative and up-to-date estimates.

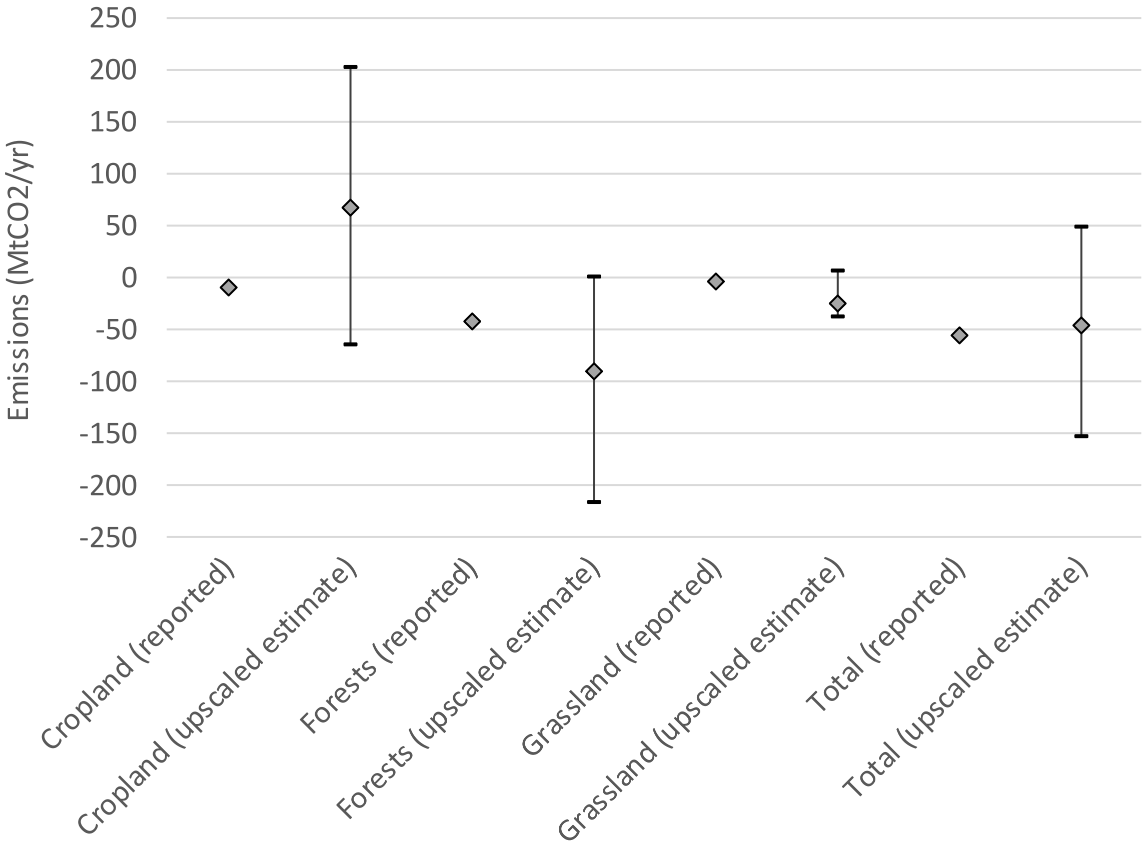

Figure 3. Reported vs estimated soil carbon changes in the EU 27. Reported values are taken from GHG inventories (year 2018). Upscaled estimates are obtained from Table 3, multiplying the central estimates and the confidence intervals by the areas reported in GHG inventories (year 2018). A negative value indicates a net carbon storage.

In addition, one cannot exclude that the emissions and removals currently measured by soil inventories have partly been reported in past GHG inventories as resulting from land-use changes. Indeed, most member states assume that all emissions and removals from land-use changes are compressed during the first 20 years following change, whereas in practice they spread over around 50-100 years. There again, the shortage of data makes it difficult to tell apart the share of the legacy effects of past land-use changes which are included in the average implied emission factors from Table 3 and have been reported, albeit too early, in GHG inventories.

Challenges to monitoring soil carbon at national level

This alarming picture of the inaccuracy and imprecision of reported soil carbon changes is not caused by a lack of competence in reporting agencies. Instead, two key explanations are more likely: soil data is expensive and scarce, and regulatory incentives to improve soil carbon monitoring are weak.

Soil data is scarce and expensive. Most member states do not regularly monitor their soils through a soil inventory. Belgium, one of the few member states which had been conducting a regular soil inventory since 1990 has interrupted it in 2006. In France, the first re-measurement campaign (2016-2027) is still underway. At EU level, the LUCAS soil survey has been implemented at regular intervals since 2009 but its quality, representativeness and resolution have been questioned. The LUCAS remeasurement campaign since 2018 should provide estimates at EU level. Based on it, Fernández-Ugalde et al.[26] is consistent with the general trends in European soils from the scientific literature but falls short of providing figures on stock changes, as bulk density was not measured in 2009 and 2015 (only changes in concentration are estimated, expressed in gC/kg soil/yr).

The reason for this paucity of soil data is that it is expensive to come by. To track and understand changes in soil carbon stocks in different soils, climate conditions and under different management regimes, one must have repeated field trials or campaigns with relevant spatial resolution, including soil sampling and lab testing, and soil and land use mapping on the ground and from alternative sources such as remote sensing and administrative systems[27]. In France for example, a soil inventory including regular soil measurements at a reasonable spatial resolution has recently been estimated to cost between 2 and 6.5 million euros per year[28]. In Finland, it has been estimated at 0.4 million euros per year for forests only[29]. A coarse upscaling proportional to land area puts the figure at 15-55 million euros per year for the EU. This is clearly within the reach of the EU and its member states, but not necessarily easy to come by for national ministries in charge of the environment.

Limited climate policy attention to soils until now. One only minds what one cares about. Another key explanation for the inadequacy of current soil carbon monitoring is the shortfall of incentives, both at country and landowner levels, to protect and enhance soil carbon stocks. No policy tool is primarily aiming at storing carbon in soils[3]. Which is not saying that landowners are totally deprived of incentives to store carbon in soils:

- Some policy tools with other primary objectives such as the cover crops mandated by the Nitrates directive or Common Agricultural Policy subsidies for agroforestry indirectly provide incentives to store carbon in soils;

- The ancillary internal benefits of high soil carbon stocks such as higher fertility and water retention are sometimes sufficient to convince farmers to implement soil carbon enhancing practices;

- Several member states have encouraged the development of carbon standards aimed at channelling private corporate social responsibility money towards soil carbon sequestration (eg. Finland, Belgium, Sweden, France, … see Cevallos et al.[30])

However, these minor or indirect sources of incentive or constraint are not sufficient to drive widespread adoption of best management practices such as cover crops, agroforestry, or peatland restoration.

A focus on the LULUCF Regulation (2018/841) dedicated to the monitoring and accounting of emissions and sequestration from the land sector leads to the same conclusion:

- its requirement (article 7 and article 18) that soil carbon in key “managed land” categories be monitored using at least a Tier2 approach is not fully implemented and, as we have argued, likely insufficient to ensure proper monitoring;

- the country-level incentive for increasing soil carbon storage is diluted by LULUCF-specific accounting rules designed to factor out natural effects and limit windfall credits such as caps, forest reference levels and limited flexibilities;

- to the contrary of the EU Emissions Trading Scheme which directly provides incentives to firms, the incentives from LULUCF regulation only apply to member states which largely fail to pass them on to land owners and land managers through national legislation.

Practical suggestions for proper soil carbon monitoring

Having identified these problems, we argue that minor adjustments in the monitoring rules and incentives, combined with a higher accessibility of existing data, could rapidly improve the ability of national greenhouse gas inventories to reflect actual changes in soil carbon storage.

Monitoring rules. As a revision of the LULUCF regulation has been proposed by the European Commission on July 14th 2021, an opportunity is opening to improve monitoring rules (several improvements, such as the abandonment of forest reference levels, are already in the proposal). As argued, when it comes to soil C monitoring, the only accurate methods at national level are currently Tier 2 and measurement-based Tier 3 approaches. A revised regulation could make them mandatory for large land-use categories. Of course, Tier 2 approaches based on key practices should ensure that the most important practices (in terms of spatial extent and impact on SOC) such as agroforestry, cover crops, peatland drainage or restoration, and temporary grass are captured. A major challenge for many countries resides in the proper monitoring of changes in activity (land use and management changes, see Figure S 1).

Changes in SOC stocks can be either measured directly or estimated for properly-validated prediction models. Directly measuring SOC changes at European level will either require that more European countries maintain a representative national soil inventory or that the LUCAS survey is better exploited. Properly validated models would both require a substantial breakthrough in scientific understanding of soil carbon dynamics[27] and making soil carbon data more easily accessible (eg. freely downloadable with English metadata). A system which combines a model – for annual variability – with a decadal data constraint from a repeated and representative soil inventory is also an interesting solution: this is what Canada and other countries have implemented for forest biomass.

In particular, peatlands and former (drained) peatlands are intensive carbon landscapes with significant potential for avoided emissions, not to mention longer term potential for significant carbon sequestration. Therefore, in countries where peatlands are reasonably expected to be a key soil category (i.e. exempting Greece, Cyprus, Malta, …), a regular peatland inventory should be implemented to assess peatland area and its evolution. Including some soil carbon measurements in these inventories would allow the estimation of refined country-specific emission factors and possibly prepare the ground for a monitoring system based on actual soil measurements for all land uses.

Peer- and non-peer review. While the aforementioned precisions in monitoring rules would help, one could argue that they are already embedded – albeit more or less explicitly – in the IPCC guidelines[31]. For example, models are required to “effectively simulate measured trends” which, as demonstrated above, is either not documented or not the case. Yet, many UNFCCC reviewers fail to notice the problem, and when they do (eg. UNFCCC[32]), countries do not necessarily correct the model or change the monitoring approach (e.g. reverting to Tier 2). The UNFCCC designed an online training on reviewing Tier 3 approaches to address this pitfall, but without success. To address this problem, the UNFCCC or the EU could require reviewers and member states to answer a set of explicit questions such as: “If a modelled Tier 3 approach is used for soil carbon, how has the validity of the model been demonstrated at the national scale?”. Increased participation of scientists in the review of GHG inventories could also help as current reviewers are mostly peers, that is inventory compilers from other countries.

Materiality. Allocating resources in proportion to the size of emissions sources and the level of uncertainty through materiality provisions would incentivise inventory compilers to focus on what matters. For example, peatlands in Greece are much less significant and offers much lower mitigation potential as in Sweden. This would suggest allowing the use of a lower tier or exemption for Greece when it comes to peatland monitoring. The UNFCCC guidelines already relax the reporting requirements for “non-key categories” and allows to neglect sources smaller than 500 ktCO_2e/yr and 0.05% of national emissions[33], but only up to a cumulative 0.1% of national emissions which makes the provision mostly useless. This cumulative threshold could be raised to 2%, and the provision could be extended to the review process, by prioritizing action on errors that likely exceed a certain threshold. Also, when it comes to soil, the determination of key categories should go beyond the use of Tier 1 estimates: it should also be based on comparisons with neighbouring countries which are actually monitoring mineral soils.

Facilitate the accessibility and use of existing data and tools. The “Land Use/Cover Area frame statistical Survey Soil” or simply LUCAS is an EU-wide soil inventory which is repeated every 3-7 years depending on budget allocation and practical feasibility. After its third campaign in 2018, up to 45.000 samples have been taken and analysed, most of them recurring. In the 2009-2012 campaign, a limited range of parameters where measured, and hence absolute soil carbon (in weight) could not be derived, but this has later changed. As of now the resulting inventory of spatially explicit soil data on key parameters including organic soils holds valuable information that could complement national data, serve as basis for improved national or regional soil maps, or provide benchmarks. As more measurement cycles are completed before 2030 (and possibly more sample sites and parameters covered), the soil database could also support regional emission factor development, separate organic soil or peatland reference data sets, or even EU level soil carbon modelling valuable for future reviews, baselines or natural disturbance issues.

Sample size is a key element to assess whether LUCAS could, in time, replace existing national soil inventories for national-level estimates such as GHG inventories. The current sample size of LUCAS is comparable to existing soil inventories, with variability between member states (Table S 1). This comparison shows that the use of LUCAS for national-level estimates is realistic, especially considering the possibility to use points from neighbouring countries with similar characteristics.

The land parcel information system (LPIS) maintained for Common Agricultural Policy reporting and compliance purposes, can also be used to estimate area changes between land uses, at least for changes related to cropland and grassland. Various remote sensing data and products can be used for the same purpose. Depending on remote sensing products, it may be possible to obtain activity data on subcategories (e.g. cover crops, hedges, …). Depending on national circumstances, LPIS may also be used for activity data on subcategories (e.g. agroforestry, hedges, …) or as data for verification, control or as supplementary data source. Where a given practice can reasonably occur only if subsidized (e.g. afforestation in Denmark), the Integrated Administration and Control System (IACS) can be used for activity data on this practice.

All these datasets already exist but are not systematically used in GHG inventories. They may not always be adequate, but accessibility and ease-of-use are important barriers. For example, by providing freely downloadable deforestation maps and estimates, Hansen et al.[34] has greatly improved the deforestation estimates submitted by tropical countries to the UNFCCC. Replicating this success for the aforementioned data sources could rapidly improve reported estimates.

Bottom-up data harvest. Many initiatives and projects across the EU, such as the *Label Bas Carbone* in France or *MoorFutures* in Germany, produce own measured data or local proxies for emissions at project level. Some EU countries have established procedures or forms for sharing project level data. Ensuring that these “bottom-up” programmes include incentives for actual measurements and subsequent sharing of data could also complement research and government driven programmes in the gathering of soil carbon data.

Concluding remarks

Most soil carbon stock changes in European soils are currently not being monitored, which is the most important blind spot of land-related climate policy. If soil carbon was properly monitored all over the EU, new emissions on the order of 70 $MtCO_2$ yr^{-1} could appear in croplands, and new removals on the same order of magnitude could appear in grasslands and forests. It may seem that these omitted fluxes balance one another but they are only orders of magnitude: when actually measured, they will likely reveal tens of $MtCO_2$ yr^{-1} to be added or subtracted to the EU GHG budget.

The drivers of these large numbers are likely a combination of legacy from past land-use changes (eg. grassland/forest conversions into cropland) and environmental changes (eg. increased organic inputs to forest soils as a result of CO_2 fertilization, nitrogen deposition, yield stagnation in cropland, …). But as long as soil carbon is not properly monitored, we will not be able to identify the priority areas where new removals can be targeted and incentivised.

Drained organic soils are also a large source of emissions, reported at 100 $MtCO_2$ yr^{-1} in GHG inventories. They are better monitored than mineral soils, although substantial improvements are also desirable which would likely increase the current estimate. Interestingly, these total emissions are comparable to the carbon stock changes likely occurring in mineral soils, but they are concentrated on 5 % of the land.

Based on available projections, the EU soil carbon balance is not predicted to deteriorate as a result of climate change[35–37] although these projections are very uncertain and not unanimous[38]. One of the main factors is the balance between rising C inputs and rising decomposition driven by higher temperatures. The amount of soil organic carbon is in constant dynamic equilibrium between the carbon inputs from crops residues and organic fertilizers on the one hand, and losses of carbon caused by the decomposition of soil organic matter on the other hand. To determine in which direction the scale tilts and, as a consequence, whether the EU and other regions are really moving towards carbon neutrality, improving how soil carbon is monitored in GHG inventories is becoming crucial. The Horizon Europe research programme has identified “A soil deal for Europe” as one of its five “Missions” over 2021-2027. A reliable soil carbon monitoring system should be one of the concrete outputs on which the success of the Mission is assessed.

Although this Perspective is focused on the EU, many other countries have pledged to reach carbon neutrality around 2050. And yet, their reporting of soil carbon stock changes could also suffer from similar deficiencies. Repeated soil inventories are also missing in most countries[27], not to mention the countries which do not even submit yearly GHG inventories to the UNFCCC. Our conclusions and recommendations could therefore extend much beyond the EU.

Competing interest statement

The authors declare no competing interest.

Data availability statement

The raw data underlying all tables and figures in the manuscript are provided in the supplementary materials as spreadsheets.

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Author contribution statement

VB designed the study and wrote the first draft. VB and TK collected and analysed the data from greenhouse gas inventories. DA coordinated the compilation of average soil carbon changes (Table 3). DA and AO reviewed and revised the manuscript.

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1. Supplementary information

1.1. Emissions and removals for EU land areas

See 21-06-28 - Carbon stock change in all MS.xlsx

1.2. Reporting methods in EU GHG inventories

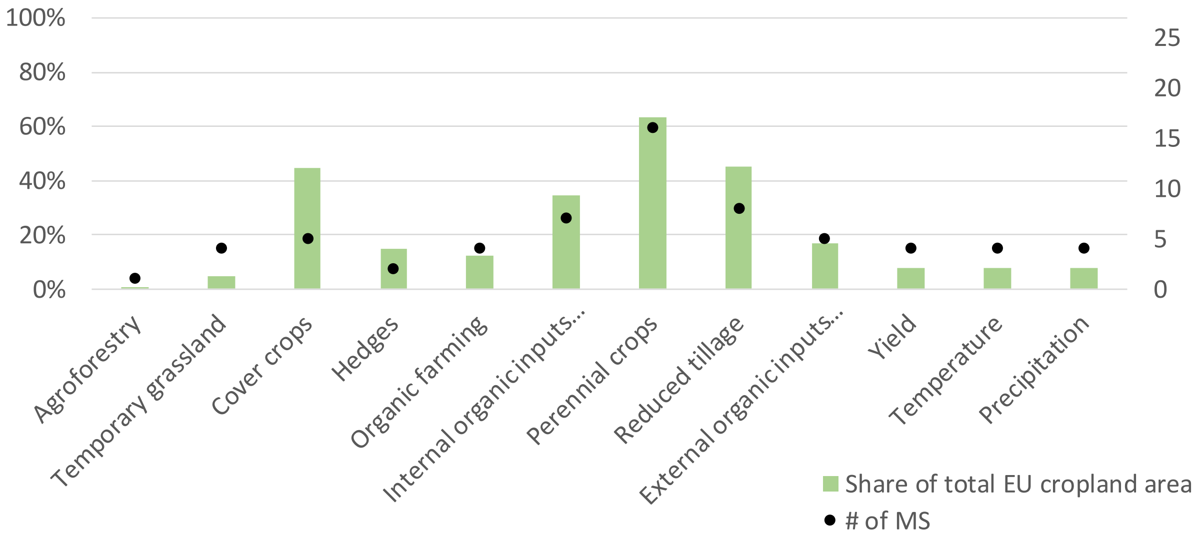

Figure S 1. Practices and effects captured by the 2020 GHG inventories for cropland. An inventory is considered to be capturing the practice (agroforestry, …) or effect (yield, …) if a change in activity data for the practice or in the value of the effect is expected to result in a change of reported emissions. The share of total EU cropland area corresponds to the summed cropland area of countries whose inventory captures the practice over the total EU cropland area.

See 21-06-30 - Soil_carbon_in_inventories.xlsx for details.

1.3. Validation of soil models used in GHG inventories

Validation data is provided in the GHG inventories (National Inventory Reports) for only one models out of the six currently used in European GHG inventories. This is the case for forests in Austria (Yasso07). If one includes National Forest Accounting Plans which require the use of a model for projected changes in soil carbon in forests, one can add the example of Sweden which reports validation data of its Q model.

In Austria (Figure S 2), simulated regional changes are equally distributed above and below zero, whereas measured changes all point to decreases in soil carbon stocks. Whereas a valid model would be expected to produce approximately aligned points close to the first bisector, Figure S 2 shows a large pack with no correlation between simulations and measurements. In Sweden (Figure S 3), measured soil carbon changes (black) are 2-3 times lower than inventory and FRL simulations (blue, Q model) in level, and inconsistent trend (simulations are stable whereas sequestration is increasing in measurements).

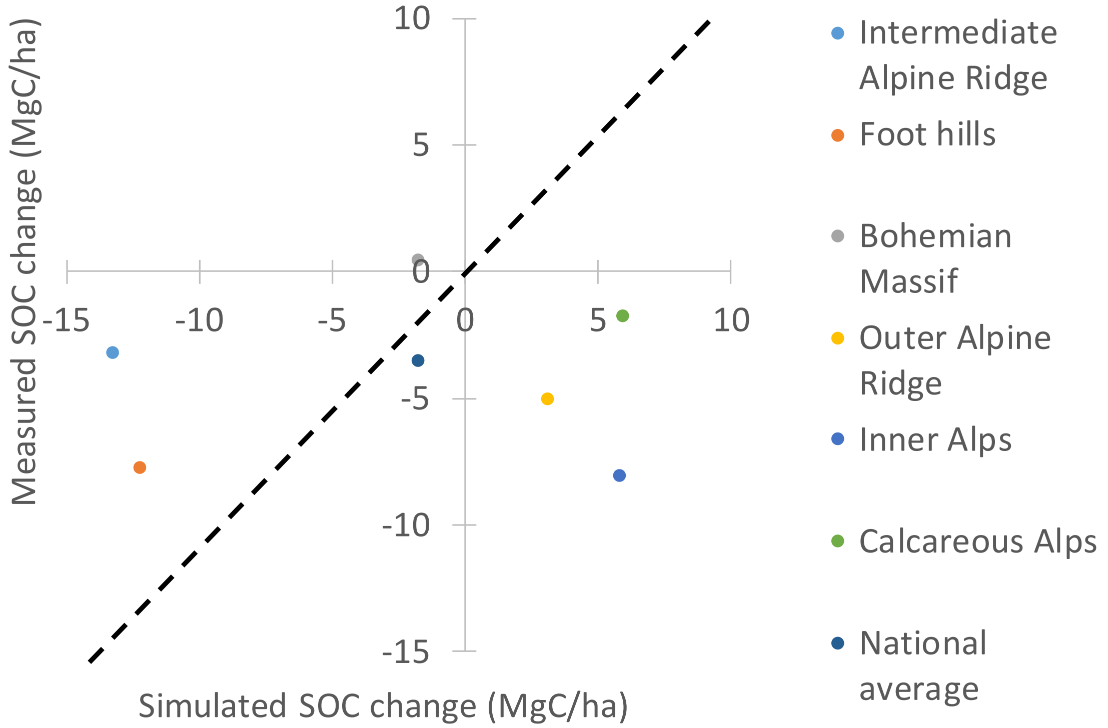

Figure S 2. Comparison of measured and simulated forest soil carbon changes in Austria. The soil carbon change of the Austrian Forest Soil Inventory (1989) versus Biosoil (2006) against simulated data with Yasso07 in the same time span (data source: Austrian NFAP[1], figure 15)

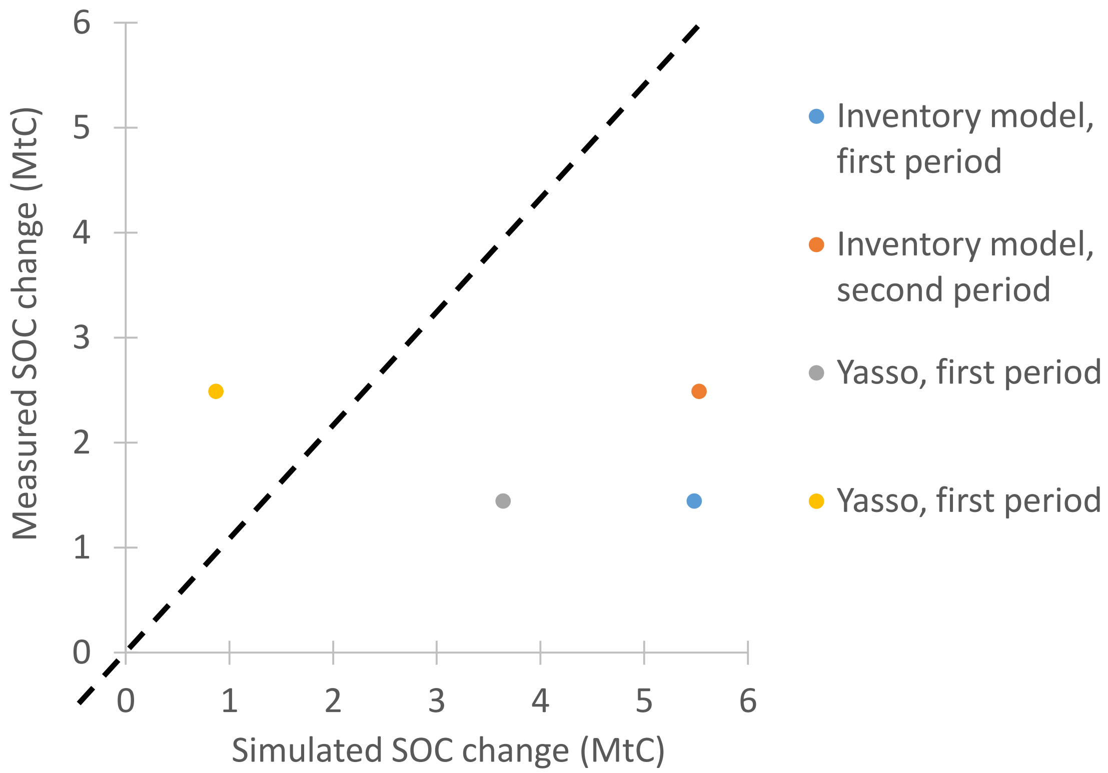

Figure S 3. Comparison of measured and simulated forest soil carbon changes in Sweden (data source: Swedish NFAP[2], figure 5)

The reason for these serious mismatches may simply be that current knowledge of soil carbon processes is not sufficient to design process-based models suited to simulate soil carbon changes at national level. Indeed, while several models have been validated for biomass changes in forests or crop yield in agriculture, most soil carbon models remain unable to reproduce soil carbon change data[eg. 3]. In all cases, these examples question the relevance of using process-based models for soil carbon reporting and emphasizes the necessity of regular soil inventories to accurately capture decadal changes in soil carbon stocks.

1.4. Compilation of soil carbon change estimates at large scales from soil inventories

See 21-06-30_compil_articles_SOC_change.xlsx

1.5. Sample size of a few existing soil inventories

Table S 1. Sample size (number of sites, with often 4-5 measurements per site) of a few existing soil inventories

Member State	LUCAS sample size in 2015[4]	Sample size of the National inventory[a]
France	3050	2158[5]
Belgium	146	629[6]
Denmark	222	336-590[7]
UK	744	256-591[8]

1.6. Current trends in what the EU and its Member states are currently reporting

Overall, reported changes in soil carbon – excluding land-use changes – are small: emissions decreased by 29 $MtCO_2\ yr^{-1}$ between 1990 and 2018 (Table S 1). In particular, reported changes in soil carbon have contributed little to the 18.9% decrease in the reported total LULUCF sink between 2013 and 2018.

Table S 3. Changes in soil carbon in the EU 27, excluding land-use changes[b]

	1990	2013	2018	2018 - 2013		
	MtCO2e	MtCO2e	MtCO2e	MtCO2e	% of total decrease	% of 2013
Forest mineral soils	-39	-41	-43	-1.7	-2.8%	0.5%
Cropland mineral soils	-3	-11	-10	1.2	2.0%	-0.4%
Grassland mineral soils	1	-3	-3	-0.5	-0.8%	0.2%
Organic soils	111	99	96	-2.5	-4.1%	0.8%
Total	70	45	41	-3.5	-5.7%	1.1%
Total LULUCF	-255	-324	-263	61.3	100%	-18.9%

In order to disentangle EU-wide trends for each land category, member states are grouped into four clusters, based on the largest biogeographical zone[9] in their territory: Atlantic, Scandinavian, Mediterranean, Continental (Table S 2).

[a] When the sample size varies between measurement campaigns, a range is provided.

[b] This table focuses on soil carbon in "land remaining land" categories, thereby excluding land-use changes and changes in biomass.

Table S 4. Country groupings according to the biogeographical zones

Atlantic	Mediterranean	Scandinavian	Continental
Ireland	Spain	Sweden	Poland
France	Portugal	Finland	Czechia
Belgium	Italy	Estonia	Slovakia
Netherlands	Greece	Latvia	Slovenia
Luxemburg	Malta	Lithuania	Hungary
Denmark	Cyprus		Romania
	Croatia		Germany
			Austria
			Bulgaria

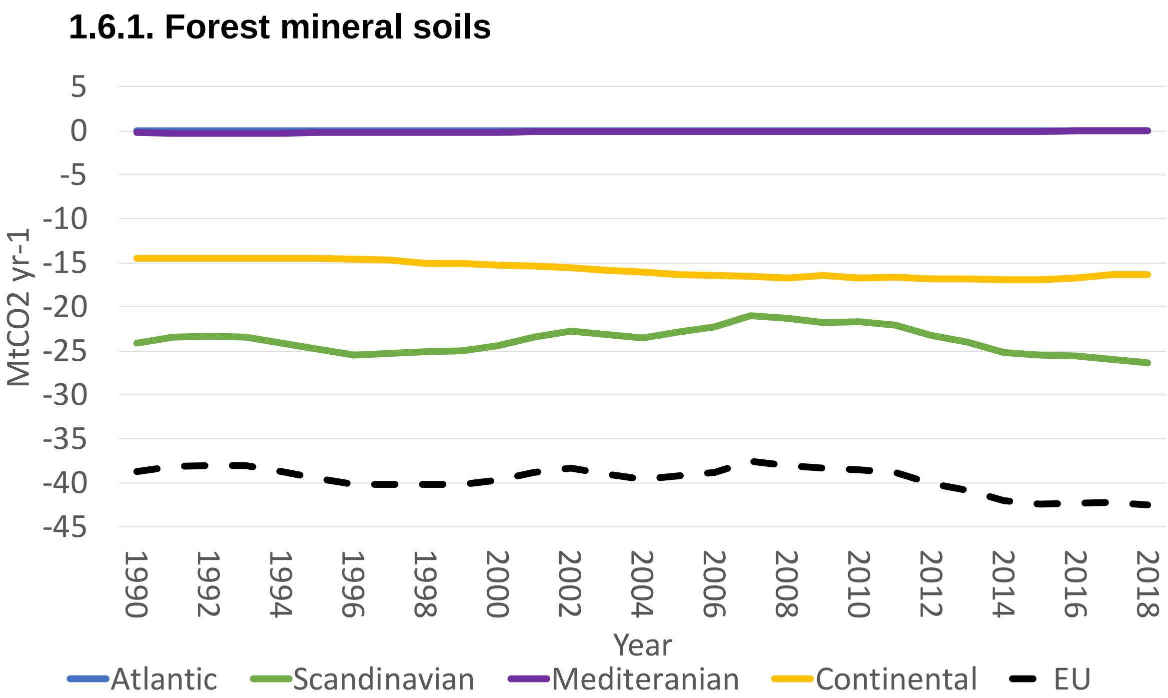

Figure S 4. Soil carbon changes in forest mineral soils (EU 27). Source: 2020 national greenhouse gas inventories (see SM 1.1 for details).

In countries which report soil carbon changes in forest mineral soils, the net sink has remained stable since 1990, around 40 $MtCO_2$ yr^{-1}. It is dominated by Scandinavian countries, both in level and trend. This dominance is likely an artefact stemming from the overall poor reporting of this category: Finland and Sweden are the only two member states using a Tier 3 approach for forest soils.

The sink has been slightly increased in recent years, from 39 $MtCO_2$ yr^{-1} in 2011 to 43 $MtCO_2$ yr^{-1} in 2018, largely driven by Sweden. The Swedish National Inventory report does not explain the drivers of this reported increase in removals.

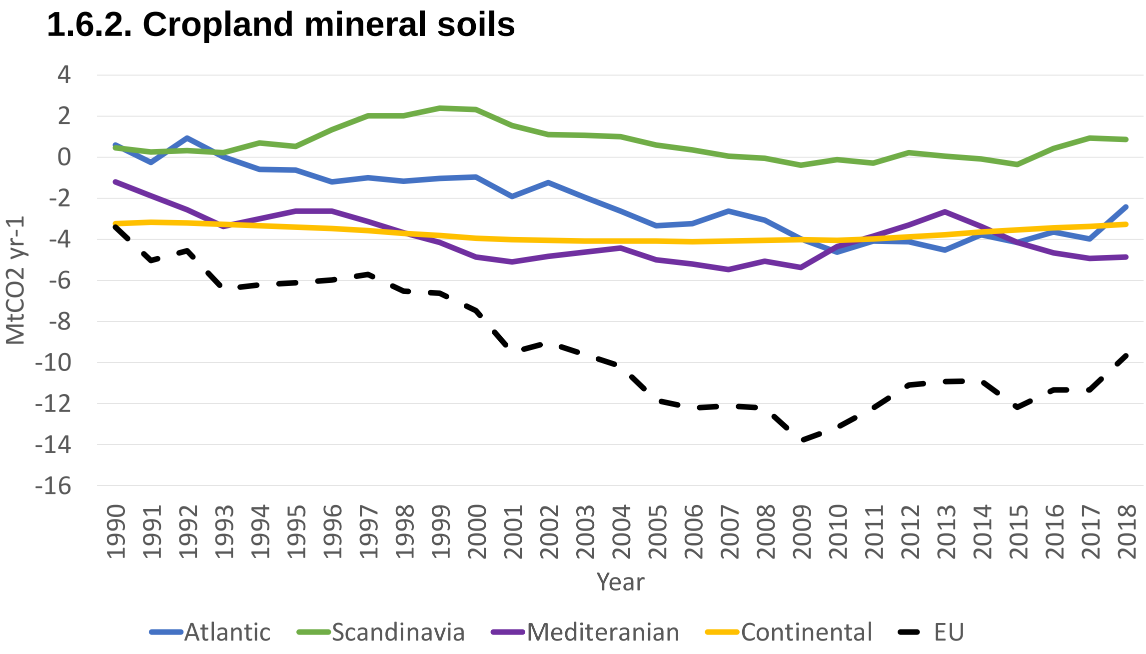

Figure S 5. Soil carbon changes in cropland mineral soils (EU 27). Source: 2020 national greenhouse gas inventories (see SM 1.1 for details).

In countries which report soil carbon changes in cropland mineral soils, the net sink has increased from 3 $MtCO_2$ yr^{-1} in 1990 to 9 $MtCO_2$ yr^{-1} in 2018, with a peak 13 $MtCO_2$ yr^{-1} in 2009. All regions contribute to the level except Scandinavia, but the trend is largely driven by the Atlantic region and more specifically France. According to the French NIR, a switch from classical tillage to simplified or no-till techniques for around 30 % of cropland area is driving this reported increased sink over the long term. The short-term variations of the reported sink for the Atlantic region are driven by Denmark which uses a Tier 3 modelling approach for reporting.

In the Mediterranean region, Italy and Spain are driving an increasing sink from 1 $MtCO_2$ yr^{-1} in 1990 to 5 $MtCO_2$ yr^{-1} in 2018. In Italy, this sink is driven by the increasing share of organic farming in perennial crops, while changes of management in annual crops (organic, conventional, set aside, …) create the short-term variability. In Spain, the reported increase in the sink is driven by an increased area of perennial crops, in which the share of soil conservation practices (limited tillage, set-aside and cover crops) is also increasing. In the Scandinavian region, the reported source of 2 $MtCO_2$ yr^{-1} at the end of the 1990s is driven by Sweden. Sweden also uses a Tier 3 modelling approach for reporting. However, the Swedish NIR does not explain the reasons for the reported changes in soil carbon emissions/removals. The carbon stock changes in the Continental region are more or less stable.

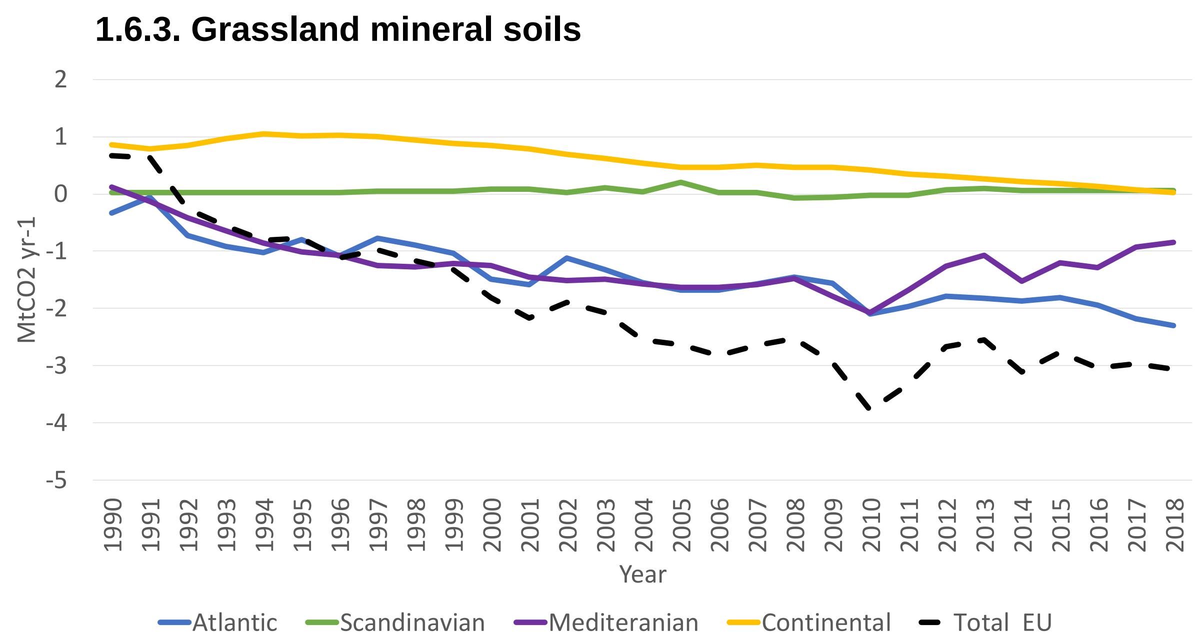

Figure S 6. Soil carbon changes in grassland mineral soils (EU 27). Source: 2020 national greenhouse gas inventories (see SM 1.1 for details).

In countries which report soil carbon changes in grassland mineral soils, the balance shifted from net emissions of 1 MtCO2e in 1990 to a net sink of 3 $MtCO_2\ yr^{-1}$ in 2018. Both level and trend are mostly driven by the Atlantic and Mediterranean regions.

In the Atlantic region, the increasing trend is driven by Ireland where grasslands “not in use” have been expanding at the expense of improved grasslands.

In the Mediterranean region, Italy has followed a parabolic trend with a peak in 2006, partly offset by a net sink taking off in Portugal at the same period, ending up at comparable levels, around 0.4 $MtCO_2\ yr^{-1}$ each, in 2018. The Italian curve results from the opposite influences of an increasing share of organic farming in grassland and an overall decrease in grassland area. In Portugal, the increased removals are caused by two projects funded by the Portuguese Carbon Fund, consisting of boosting grass productivity by sowing grassland with a highly biodiverse seed mix including a substantial share of legumes.

1.6.4. Drained organic soils

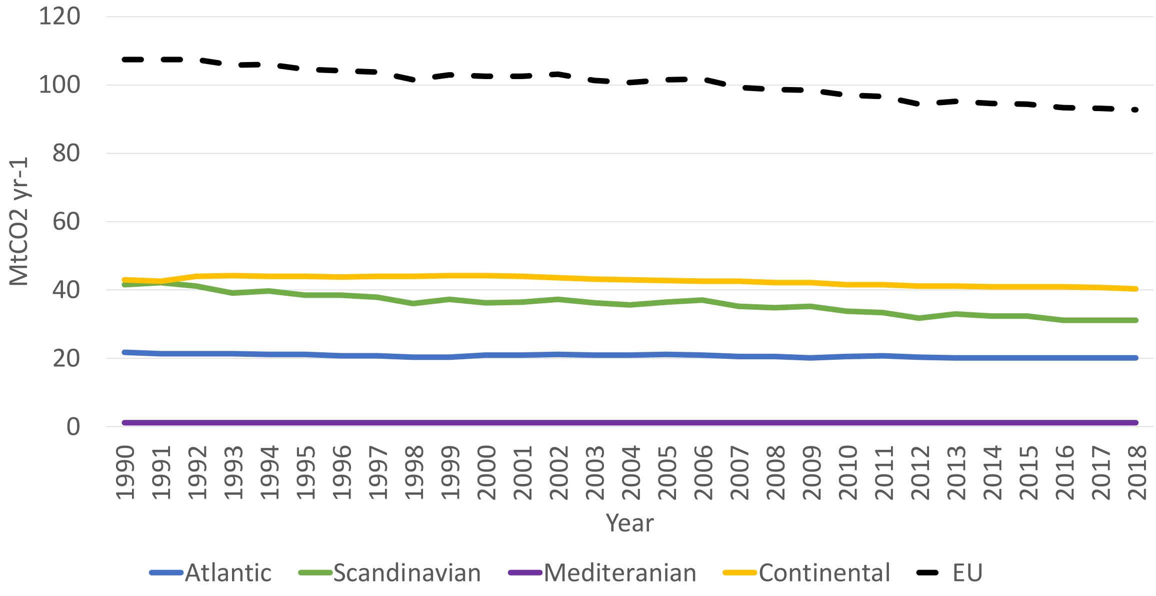

Figure S 7. Soil carbon changes in organic soils (mostly peatland drainage, EU 27). Source: authors' calculations based on 2020 national greenhouse gas inventories (summing up organic soils in all land categories and CRF table 4(II) dedicated to drainage, see SM 1.1 for details).

CO_2 emissions from drained peatlands have been decreasing from 111 $MtCO_2\ yr^{-1}$ in 1990 to 96 $MtCO_2\ yr^{-1}$ in 2018. All regions substantially contribute to the level, but the decreasing trend is driven by Scandinavia. Within Scandinavia, the bulk of the decrease takes place in Finland, where outflow (heterotrophic respiration) is assumed to be constant whereas the inflow from root turnover is increasing in proportion to tree biomass.

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