Towards climate-smart sustainable management of agricultural soils

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Synthesis on estimates of achievable soil carbon sequestration on agricultural land across Europe

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ABSTRACT

This synthesis identifies the available knowledge of achievable carbon sequestration in mineral soils and GHGs mitigation in organic soils in agricultural land, including pasture/grassland across Europe. The inventory of past and current studies on carbon sequestration and GHGs mitigation measures in agricultural soils and the methodology used for the assessment were considered from 25 Member states (MS) across Europe. The stocktake shows that availability of datasets concerning soil carbon sequestration (SCS) is variable among Europe. While northern Europe and central Europe is relatively well studied, there is a lack of studies comprising parts of Southern, Southeaster and Western Europe. Further, it can be concluded that at present country-based knowledge and engagement is still poor; very few countries have an idea on their national-wide achievable carbon sequestration potential. The presented national SCS potentials (MS n=13) do however point towards important contributions to mitigate climate change by covering considerable shares of national greenhouse gas emissions from the agricultural sector in the range of of 0.1-27 %, underpinning the importance of further investigations. In contrast to mineral soils, effective mitigation measures for organic soils while maintaining industrial agricultural production are still in its infancy. Very few mitigation options exist to mitigate GHG emissions without compromising agricultural production. Most GHG mitigation practices reported by the MS involve the restoration of organic soils, which means a complete abandonment of land from any agricultural use. Only one contribution (NL) reports possible mitigation potentials, which are based on specific water management measures (water level fixation). Nevertheless, there is an increasing awareness of the need of mitigation measures reflected by the several ongoing research projects on peatland management.

Table of contents

List of Tables

List of Figures

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N° 862695

List of acronyms and abbreviations

AGS	Agroscope
CRA-W	Centre Wallon de Recherches Agronomiques
CUE	carbon use efficiency
EA	Emissions from the agricultural sector
EZ	Environmental Zones:

ALN	Alpine North
ALS	Alpine South
ANA	Anatolian
ATC	Atlantic Central
ATN	Atlantic North
BOR	Boral
CON	Continental
LUS	Lusitanian
NEM	Nemoral
MDM	Mediterranean mountains
MDN	Mediterranean North
MDS	Mediterranean South
PAN	Panonian

GHG	Greenhouse gas
GL	Grey Literature
IPCC	Intergovernmental Panel on Climate Change
LTE	Long-term Experiment
MS	Member states
NIR	National Inventory Report
PSL	Published Scientific Literature
QS	Question
SCS	Soil Carbon Sequestration
SOC	Soil organic Carbon

1. Executive summary

This document summarizes the stocktaking activities for Europe led by Agroscope (AGS) and (CRA-W) in collaboration with 23 of the EJP SOIL consortium members. The goal of T2.4.3. is stocktaking and synthesis on available knowledge of achievable carbon sequestration in mineral soils and greenhouse gas (GHG) mitigation in organic soils in agricultural land, including pasture/grassland across Europe. All kind of information such as data, reports, scientific papers, including commercial and grey literature for each participating country were collected. The inventory of past and current studies on soil carbon sequestration (SCS) and GHGs mitigation measures in agricultural soils and the methodology used for the assessment were also considered. All participating MS (n=25) returned their country specific information. The stocktake shows that availability of datasets concerning SCS is variable among Europe. While northern Europe and central Europe is relatively well studied, there is a lack of studies comprising parts of Southern, Southeaster and Western Europe. There is however a clear increase in interest for topics covering SCS for climate change mitigation in the last two decades. A total of 111 ongoing projects have been reported dealing with SCS and GHG mitigation measures. However, at present country based knowledge and engagement is still poor. The stocktake shows only half of the participating MS (BE, CH, DE, DK, ES, FR, IR, IT, NL, NO, PO, SW, UK) have an idea on their national-wide achievable carbon sequestration potential. Information provided is mostly based on rough estimates without consideration of technical and socio-economic feasibilities (i.e. availability and suitability of land, costs or profits for farmers and the willingness of implementation by farmers), which are key for sustainable implementation. Climate change is usually not included, although it is known that it will have an important impact on carbon stocks. The presented national SCS potentials (n=13) do however point towards important contributions to mitigate climate change by covering considerable shares of national greenhouse gas emissions from the agricultural sector in the range of 0.1-27 %, underpinning the importance of further investigations.

In contrast to mineral soils, effective mitigation measures for organic soils while maintaining agricultural production are hardly known. Very few options exist to mitigate GHG emissions without compromising intensive agricultural production. Most GHG mitigation practices reported by the MS involve the restoration of organic soils, which implies abandonment of land from most agricultural uses. Only one contribution (NL) reports possible mitigation potentials, which are based on specific water management measures. Nevertheless, there is an increasing awareness of the need of mitigation measures reflected by the several ongoing research projects on peatland management.

2. Introduction and goal of T2.4.3

In the context of climate change and rising atmospheric CO_2 concentrations, the role of soils in the global carbon cycle has been increasingly acknowledged. Depending on land use and management, soils can act as both a source and a sink for CO_2 (Lal, 2004). Soils are the largest terrestrial pool of organic carbon with global soil organic carbon (SOC) stocks of 863 Pg C, 1,824 Pg C, and 3,012 Pg C in the upper 0.3 m, 1 m, and 2 m respectively (Sanderman et al., 2017). Several long-term soil-monitoring networks and data from long-term experiments (LTEs), in a considerable number of European countries, show that soil carbon in many agricultural soils is decreasing (Bellamy et al., 2005; Heikkinen et al., 2013; Keel et al., 2019; Sleutel et al., 2007; Taghizadeh-Toosi et al., 2014). However, there is a general agreement that selected agricultural practices could have a significant positive impact on soil carbon sequestration (SCS), with further benefits for soil fertility and ecosystem services (e.g. water infiltration and -holding capacity, provision of food and ecological resilience). Hence, since the last two decades, agricultural practices have been increasingly endorsed as an option to remove CO_2 from the atmosphere to mitigate climate change and a growing number of literature reviews show that specific agricultural measures can increase SCS (Lal, 2004; Smith et al., 2007, 2005). However, an increase in soil organic matter does not necessarily imply carbon (C) to be sequestered from the atmosphere. Within the EJP SOIL SCS is defined as “the process of transferring CO_2 from the atmosphere into the soil of a land unit, through plants, plant residues and other organic solids which are stored or retained in the unit as part of the soil organic matter for a given time period” (Olson et al., 2014).

LTEs and modelling are general approaches to estimate the potential of C-sequestration of agricultural land. To quote some examples for Europe: First estimates of agricultural SCS potentials in Europe were given by Smith et al., (1998, 1996) based on several LTEs in Europe. Freibauer et al., (2004) conducted an update by combining other estimates by Batjes, (1996), Nabuurs et al., (1999), Smith et al., (2000 a,b), and Vleeshouwers and Verhagen, (2002) also taking into account the available surface of agricultural land and its suitability for implementation of those management options. Further estimates at the pan-European level were given by Lugato et al., (2014) using the CENTURY agroecosystem model for a set of management practices under different scenarios. Despite all these efforts, there is still an incomplete understanding of how SCS is influenced by climate, by land use and –management and by pedo-climatic factors(Chenu et al., 2019; Smith et al., 2020; Stockmann et al., 2013).

In contrast to mineral soils, effective mitigation measures for organic soils while maintaining intensive agricultural production are much less studied. Organic soils in peatlands are one of the most important terrestrial carbon sinks, storing as much carbon as all terrestrial biomass worldwide. When drained for agriculture, they are a substantial source of greenhouse gases (GHG) due to the degradation of organic matter that is exposed to oxygen in the air. In the last decades, peatlands have been suffering degradation mainly through drainage for agriculture, forestry and peat extraction (Joosten and Clarke, 2002). Rewetting and restoration of cropped organic soils is one important option to mitigate GHG emissions, with great potentials. Globally ~1.91 (0.31–3.38) Gt CO_2-eq. yr^{-1} could be saved by peatland restoration (Leifeld and Menichetti, 2018). An alternative way of using converted wet and rewetted peatlands for agriculture is paludiculture, which however comes at the expense of losing land for intensive food production (Leifeld and Menichetti, 2018).

In summary, it can be concluded that there are still essential knowledge gaps comprising the effectiveness and feasibility of mitigation options for both mineral and organic soils. Moreover, country-specific knowledge and data sets are hitherto insufficiently exploited and used for implementing mitigation projects in practice. With this stocktake we aim to provide a better overview on the available knowledge of achievable SCS potentials in mineral soils in agricultural land, including pasture/grassland across Europe, under different farming systems, soil types and pedo-climatic conditions as well as on GHG mitigation measures for managed organic soils. We present an overview of estimates on carbon sequestration (mineral soils) and greenhouse gas mitigation potentials (organic soils) and measures for agricultural soils. An overview of the share of land for which such information is available is given and finally we present the most urgent knowledge gaps regarding methodological approaches, soil or management types and geographical regions.

3. Methodology and data source

The stocktaking of achievable soil carbon sequestration is based on three pillars:

- Project organization, providing an overview of the published potentials including methods used, data coverage etc., and providing an overview of personnel and institutions involved.
- Project organization. AGS and CRAW identified the main experts to be approached by the various consortium members, with the help of information delivered by the project coordinator.
- To achieve the main scientific goal a questionnaire was developed by the subtask leaders and provided to experts of each MS who helped in gathering the information available on the internet or provided non-public reports and information to the subtask leaders from AGS and CRA-W (see list of MS experts and contacts in Annex D).

The questionnaire was divided in two parts: a) the request for providing information on the achievable SCS in mineral soils and b) the request for providing information on the potential for reducing GHG emissions from managed organic soils. (See Annex E for complete questionnaire) to which the results are assigned accordingly. Together with the literature and the questionnaire, the partners delivered a summary in text format with a maximum of three pages excluding references, which included the information on state-of-the-art knowledge on the achievable SCS in mineral soils in agricultural land, including pasture/grassland across Europe, under different farming systems, soil types and pedo-climatic conditions as well as on GHGs mitigation measures for managed organic soils. The contributions were gathered between June and the end of August 2020. Each contribution (questionnaire, summary and literature) was reviewed and analysed by the task leaders. Documents submitted by the MS that did not fulfil our criteria (e.g. studies not from the country, C-sequestration potentials of other land uses like forest) were excluded. Although implementation of climate change mitigation measures and agricultural practices is often a result of socio-economic decisions, SCS varies depending on different soil types and climate.

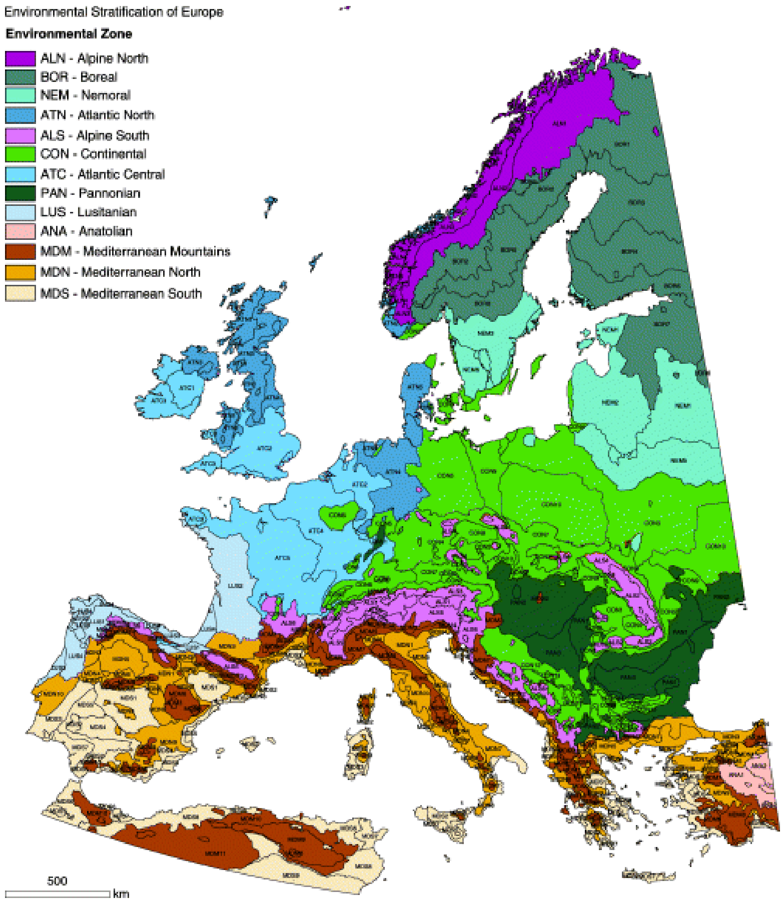

__Figure 1__ The Environmental Stratification of Europe in 84 strata. Where the size of the stratum permits, the individual strata are labelled within the main Environmental Zones. The stratification extends from 11° W to 32° E and from 34° N to 72° N. (Metzger et al., 2005).

The data was therefore primarily organized in respect to the boundaries of the Environmental Zones (EZ) as defined by Metzger et al., (2005) (default EJP SOIL) (Fig. 1). Additionally, results were also presented individually per MS where relevant. However, it is important to notice that implementation of agricultural mitigation measures is often guided by political, socio-economic and organizational considerations rather than by eco-physiological framework conditions. Consequently, the distribution of mitigation projects does not necessarily reflect the geographical variability of biophysical SCS potentials.

4. Results and discussion

4.1 Data and data coverage

The results presented here have to be taken with caution, as quality of the individual contributions was highly variable.

All participating MS (n= 25) returned their country specific information. These covered all EZ. For mineral soils, 156 contributions were considered for the stocktake. Out of them 80 % are published scientific literature and 20 % are grey literature (reports, presentations) (Fig. 2). Regarding the organic soils only 21 studies were considered with a share of 67 % published scientific literature and 33 % grey literature. All the literature dates from the years 2000-2021. More than 85 % of the articles were written in the period 2011-2021, reflecting the increase of interest in SCS over the last decade (Fig. 2). The lists of references for mineral and organic soils, respectively, grouped by MS are included in the Appendix A and B. In total 111 ongoing and planned research projects all over Europe were mentioned as being relevant for SCS and GHG-mitigation in agricultural soils (List in Appendix C).

The following results are presented separately for the mineral soils and organic soils, organized according to the questions posed to the MS’s.

4.2 Mineral soils

SCS in mineral soils are covered by 156 contributions. The data density per EZ (studies per 10’000km2) was visualized on a map, counting the studies per EZ (Fig. 3). The area of the EZ was normalized by the agricultural area including arable land, permanent crops, grassland and heterogeneous agricultural areas. The agricultural area was extracted from raster data of the CORINE land cover (CLC) inventory of Europe 2018 using ArcGIS and overlaid with the EZ by Metzger et al. (2005). Looking at the distribution per EZ the, Alpin North (ALN), Nemoral (NEM) and Boreal (BOR) zones are best covered by studies while Mediterranean Mountains (MDM), Atlantic North (ATN), Lusitania (LUS), and pannonian

(PAN) (with decreasing density) are relatively poorly studied. The Atlantic Central zone (ATC) and the Continental zone CON, covering the greatest share of agricultural area are moderately to well studied.

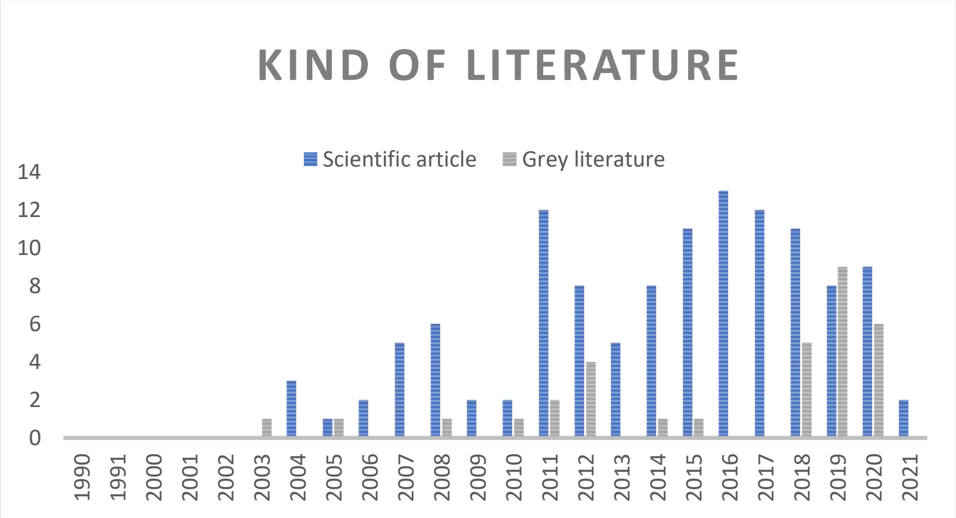

Figure 2 *Type of literature considering SCS and distribution from 1990-2021.*

In total 38 different measures were identified and studied to evaluate SCS on mineral soils. To allow a quantitative evaluation of the results, the measures that were reported to have an effect on SCS have been summarized into five main groups: 1) land use (excl. forest), 2) soil protective measures, 3) tillage, 4) fertilizers and soil amendments, and 5) other. Under land use, we include all measures that imply a long-term change in the coverage of the land, which cannot be quickly reversed. Soil protective measures include all types of farming practices targeting or favouring soil protection such as permanent soil cover, crop rotation, crop residue management, other include agroforestry, organic farming etc. (see Table 1 for complete information). No-till practices, which generally fall into the soil protective category, were counted separately because of their great number. “Other” contain all measures, which do not fit into the defined groups.

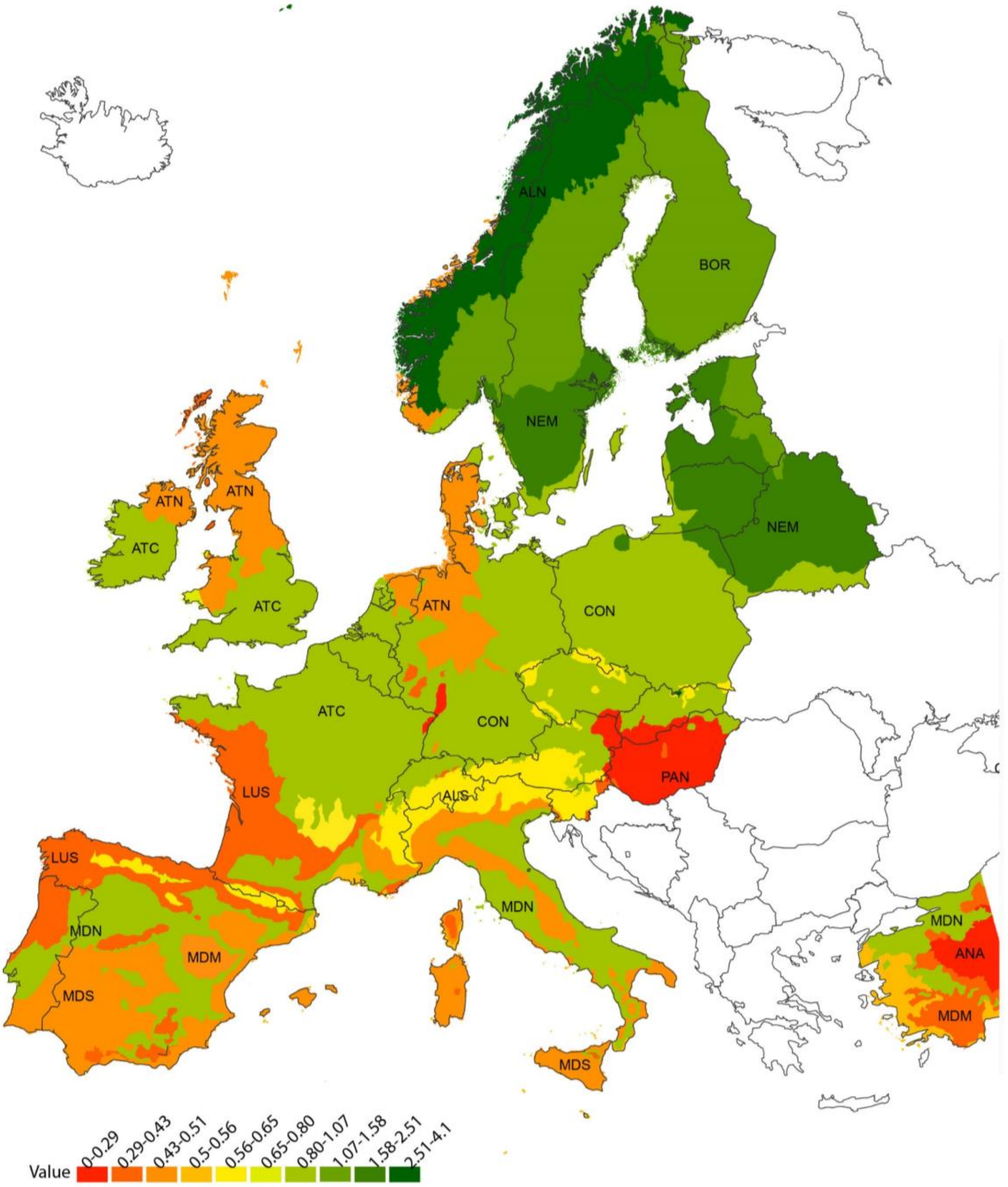

Figure 3 *Data density (Studies per 10'000km2) for each environmental zone (EZ) across Europe, normalized by its agricultural area. Value unit: Alpine North (ALN), Boral (BOR), Nemoral (NEM), Atlantic North (ATN), Alpine South (ALS), Continental (CON), Atlantic Central (ATC), Panonian (PAN), Lusitanian (LUS) Anatolian (ANA), Mediterranean mountains (MDM), Mediterranean North (MDN), Mediterranean South (MDS). EZ according to Metzger et al., 2005.*

Table 1 *Agricultural measures to improve SCS in mineral soils mentioned in the stocktake.*

Measures	**Total number of studies**
1 Land use:	**40**
Permanent grassland	11
Conversion to grassland	10
Sown biodiverse permanent grasslands	2
Perennials	5
Agroforestry	10
Shrub encroachment	2
2 Soil protective measures:	**83**
Mulching	1
Ley farming	9
Cover crops	16
Catch crop	6
Improved crop rotation	16
Specific crops	1
Crop residue management	24
Grass residue management	1
Reduction of grassland renovation	5
Erosion control measures	1
3 Tillage:	82
No-till	36
Conservation tillage (minimum tillage, reduced tillage)	31
Non inversion tillage	10
Dual layer tillage	2
Deep ploughing	2
4 Fertilizers and amendments:	69
Mineral fertilizers	16
Manure application	31
Amendments:	
Mycorrhiza-inoculated compost	1
Compost of organic waste	10
Liming	3
Sewage sludge	1
Biochar	4
Biochar-blended compost	1
5 Other measures:	19
Managed field margins	2

Irrigation	2
Improved grazing management	2
Organic farming	5
Above and below ground biomass maize	1
Hedges	1
Extensive grassland management	1
Restauration of organic soils	1
Crops with improved N efficiency	1
Energy crops	3

4.2.1 Question 1 (Q1): Are there any quantitative estimations of the achievable carbon sequestration under different soil management in your country (finished or ongoing studies)?

In total 43 contributions were submitted of which 23 are scientific published articles, and 20 are national reports. Thirteen countries assessed the achievable SCS in agricultural soils at the national scale (BE, CH, DK, ES, FR, IT, IR, NL, NO, PL, PT, SE, UK), and three countries presented data for specific regions (BE, DE, IT). The potentials have been reported either as total potentials Tg C yr^{-1} or Tg CO2 yr^{-1} or as annual rates Mg C ha^{-1} yr^{-1} and are summarized in Table 2. In order to realistically indicate the achievable SCS it is first essential to determine where and on which area a particular measure can be implemented. Further, costs and practical applicability of the measures should be considered. Studies considering all these conditions are scarce. Only one country (France) includes the additional costs for farmers and shows that in general the implementation of practices that sequester carbon results in a cost for the farmers (Pellerin et al., 2019). All other countries only include broad estimates of the areas on which measures technically can be applied without consideration of other factors (i.e., socio-economic parameters). Climate change has been considered by Italy and Poland only. The study of Mondini et al., (2012) clearly shows the importance of including climate change scenarios, because the response to compost application in Italy was only 0.13 t C ha^{-1}yr^{-1} when considering climate change, which was three times lower than values (0.42 ha^{-1}yr^{-1}) estimated by Smith et al. (2008) and Freibauer et al., (2004), where climate change was not accounted for. Contrasting methodologies were applied by the different countries (for example, sampling depths ranging from 10 to 100 cm were considered), making the comparison of SCS potentials from one country to another difficult. For this reason, the shares (%) of the potentials to the yearly total domestic emissions from the agricultural sector (EA) were calculated when possible (Figure 4 and Table 2). EA was taken from the national GHG inventory reports (NIR) of each country submitted in 2020 *(*National Inventory Submissions 2020 | UNFCCC*)*.

The total potential of each country for climate change mitigation varies greatly, ranging from 0.1 % to 28.5 % of EA (Fig. 3). ***It is however important to note that estimations are reported for a certain soil depth, area and time period and cannot be compared directly to each other (see Table 2 for details and references)****.*

France, Italy, Poland and Spain report relatively high potentials of **5.8 (30 yrs.), 2.1(100 yrs.), 1.6 (20 yrs.), Tg C yr^{-1}** and **2.9 (100 yrs.) Tg C yr^{-1},** respectively**.** For France the potential corresponds to 27.2 % of EA, which is to be achieved by a combination of measures including agroforestry (Table 2). When different acceptable costs are considered (e.g., 55 € T^{-1} CO_2 eq), the potential is reduced by 50%. This potential is however associated with very high annual costs in the order of 2.3 billion euros. The reported potential for **Italy** could offset 25% of the EA by applying compost of organic waste to all the arable land in the country. For **Spain,** the potential covers 27 % of their EA, which is to be attained by the implementation of no-till. For **Poland**, this corresponds to 18 % of the EA, which is to be achieved by combining reduced tillage, crops residues and manure. It should be noted that this potential is only achieved if the total crop area of Poland is considered, which might not be realistic. A combination of cover crops, agroforestry, rewetting of drained organic soils and afforestation of set aside arable land would reduce 25.5 % of the national EA of **Sweden. Norway** reports biochar as the measure with the greatest potential (**0.245 Tg C yr^{-1} (100 yrs.)**) for storing carbon in Norwegian soil in a long-term perspective, which would offset 20 % of their GHG from the agricultural sector. However, it has to be noted that the production of biochar would rely on 50 % of the available biomass residues at the national scale and would therefore compete with other uses for this feedstock. Outstanding potentials for land use and land use changes are given by **UK** with **2.39 Tg C yr^{-1} (30 yrs.)** and by **Switzerland 0.245 Tg C yr^{-1} (20 yrs.)** covering 21 % and 16 % of their respective EA. **Belgium** would achieve a potential of **0.26 Tg C yr^{-1} (20 yrs.)** on cropland, which could offset 9.6 % of the EA by a combination of measures including forest recover (Table 2). **Ireland** reports maximal potential of 0.11 Tg C yr^{-1} (9 yrs.) for a combination of reduced tillage and crop residue management (van Groenigen et al., 2011), offsetting 2.2 % of the domestic EA. The sum of all the reported potentials would amount **18 Tg C yr^{-1}**, which would offset 15.5 % of the total **European EA** (Table 2, Fig. 4).

The results show that only half of the MS participating have explored their national-wide achievable soil carbon sequestration potential. Some of the reported potentials however show potentially important contributions of SCS to mitigate climate change covering up to 27 % of the annual domestic GHG emissions. The high span going from 0.1% to 27% and the variety of measures and combinations used to estimate these potentials (Fig. 4), shows that the estimates still come with high uncertainties and unexplored alternative measures.

Information provided is mostly based on rough estimates, often without consideration of technical and socio-economic feasibilities (i.e. availability and suitability of land, costs or profits for farmers and the willingness of implementation by farmers), which are key controlling factors for sustainable implementation. Methodological heterogeneity further limits country-to-country comparison. Even though, guidelines for the technical assessment of carbon stock changes at various complexity levels (tiers 1-3) exist, a standard protocol to indicate the practical- achievable soil carbon sequestration is still missing. Please see section 4.5 General knowledge gaps and hot topics for further discussion of uncertainties and methodological challenges.

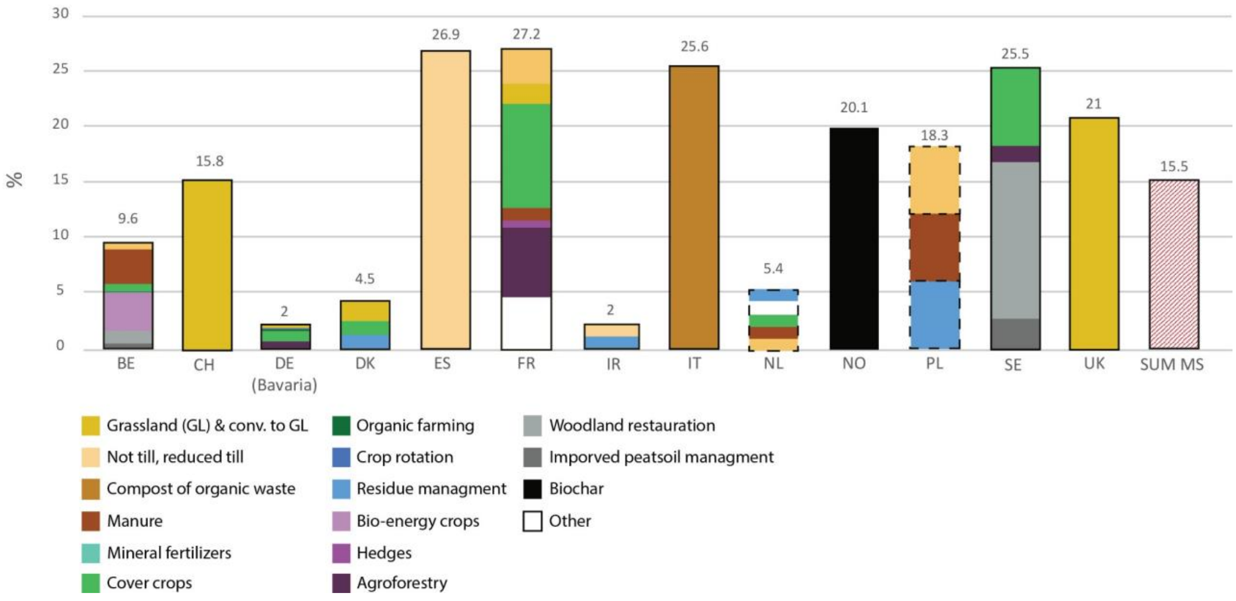

Figure 4 *Share of potentials to the annual total emissions from the agricultural sector for each country and share of measures involved. Dashed squares indicated unknown proportion of measures. Selection of maximum potential per country—additional potentials of countries are included in Table 2.*

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Table 2 *Achievable domestic soil carbon sequestration (SCS) and reduction potential of the total emissions from the agricultural sector (EA) reported by the MS. PSL = Published scientific Literature, GL= Grey Literature.*

Country	Spatial Scale	Area (ha) of applied measure	Temp. Scale	Measure	SCS-Potential Tg C/yr.	Percentage of total EA (%)	Total annual EA (Tg C)	Methods:	Reference:
Belgium	Regional (Flanders)	-	**15**	Permanent grassland, compost application, green manuring and management of crop residues (cereals)	**0.05**	**1.8**	**2.7**	Scenario analysis comparing change in an agricultural measure to 'business as usual' calculating SCS potential over period 2016-2030.	D'Hose and Ruysschaert, 2017 (GL)
	Regional (Flanders)	-	12	Green manuring, crop residue management, temporary pastures, organic farming and compost application	0.06	**2.2**	2.7	Increase of effective Organic carbon in the ''current'' (2002) and baseline (1990) year were calculated. (sampling depth:24 cm)	**Sleutel et al., 2007** (PSL)
	National	458807	20	Bio-energy crops, farmyard manure, woodland restauration, no-till, cover crops, improved management of farmed peat soils, organic farming	0.2589	**9.6**	2.7	Estimates are based on literature values and assumptions on the area the practice can be applied.	**Dendoncker et al., 2004**
Denmark	National	2310000	26	cover crops, crops residue management, conversion to grassland	0.136	**4.5**	3.0	Modelling with C-Tool (Soil depth: 100 cm)	Taghizadeh-Toosi and Olesen, 2016 (PSL)
France	National	28500000	30	Cover crops, reduced till, organic manures conversion to grassland, hedges, reduction of mowing, grass cover in vineyards, intra plot agroforestry	**5.7 (30 cm)** 8.15 (100 cm)	**27.2** (39)	20.4	Modelling (Soil depth: 100 cm) with the STICS and Pasim models	**(Pellerin et al., 2019** (GL, English)
Germany	Regional (Bavaria)	3315800	-	Agroforestry, conversion to grassland, cover crops, improved crop rotation, organic farming	0.3-0.4	**1.6-2.02**	17.3	Estimate based on literature values and assumptions on the area the practices can be applied.	**Wiesmeier et al., 2020** (PSL)
Ireland	National		10	Winter cover crops 0.51 Mg ha^{-1} yr^{-1}, winter cover crops combined with min. tillage 0.74 Mg ha^{-1} yr^{-1}	0.08 – 0.1	**1.3 – 1.6**	5.2	Flux measurements in combination with modelling and LTE's. (Soil depth: 15 cm)	(Lanigan et al., 2012) (GL)
	National	351000	9	Reduced tillage (0.18-1 Mg ha^{-1} yr^{-1}), crops residue management (0.44-0.6 Mg ha^{-1} yr^{-1}).	0.11	**2.2**	5.2	Field experiments and modelling Roth and cohort model (Soil depth: 60 cm)	**van Groenigen et al., 2011** (PSL)

	National	450,000	10	Improved management of grassland	**0.07**	1.3	5.2	Field experiments and modelling Roth and cohort model (Soil depth: 60 cm)	(Lanigan et al., 2018) (GL)
Italy	National	16284166	100	Compost of organic waste	2.1	**25.6**	8.2	Modelling with RothC. 12 climate scenarios	Mondini et al., 2012 (PSL)
	Regional (Foggia, Apulia Region)	505400	20	Compost of organic waste	0.031	**0.38**	8.2	Modelling with RothC10N and management scenarios	Bleuler et al., 2017 (PSL)
	Regional (Manfredonia, Apulia Region)	35454	20	Crop residues incorporation and water management	0.002 – 0.02	**0.02-0.25**	8.2	Modelling with RothC10N and management scenarios	Di Bene et al., 2016 (PLS)
Netherlands	National	-	20	Cover crops, managing field margins, No-till, non-inversion till, green manure, crop residue management, slurry, reduction of grassland renovation	0.27	**5.4**	4.9	Modelling with MITERRA-NL	**Lesschen et al., 2012** (GL Dutch)
	National	298253	30	Improved crop rotation	0.245	**4.9**	4.9	Modelling with NDICEA version 6.2.1	**Koopmans et al., 2019** (GL Dutch)
	National	298253		Reduction of grassland renovation	0.031	**0.6**	4.9	"	«
Norway	National	84000	100	Biochar	0.245	**20.1**	1.2	Estimate based on literature. Cover crops on 60 % of crop area.	**Rasse et al., 2019** (GL)
	National	22400	100	Cover crops	0.057	**4.7**	1.2	Based on meta-analysis results by (Lehmann and Joseph, 2015)	**Bøe et al., 2019** (GL)
Poland	National	10400000	20	Reduced tillage, crops residues, manure	1.6	**18.3**	9	Modelling: DNDC model	**Faber and Jarosz, 2018** ((PSL, Polish)
Portugal	National	-	10	Sown biodiverse permanent pastures rich in legumes (SBPPR) (1.76 Mg ha^{-1} yr^{-1}). No Area indicated.	-		1.9	Modelling (soil depth 10 cm)	**Teixeira et al., 2011** (PSL)
Spain	National	7650588		No-till	2.9	**26.9**	10.8	Modelling Century and RothC, using C emission-sequestration rates coefficients of the IPCC.	**Moreno-García et al., 2020** (PSL)
Sweden	National	1792000	30	Perennials, grassland, cover crops or catch crops	0.324	**15.5**	1.9	SOC change factors based on Swedish long-term trials	**Wikström, 2019** (GL, Swedish)

	National	610000	25	Cover crops, agroforestry, afforestation of set aside land, rewetting of organic soils	0.5	**25.5**	1.9	-	Karlsson et al., 2020 (GL. Swedish)
Switzerland	National	920000	20	Grasslands	0.258 (max)	**15.8**	1.6	Estimate based on literature values and assumptions on the area these practices can be applied	**Beuttler et al., 2019** (GL, English)
	National	10000	20	Deep ploughing	0.021	**1.3**	1.6	"	Beuttler et al. 2019 (GL, English)
	National	8230	40	No-till	0.0027	**0.2**	1.6	Estimate based on literature values. No-till	**Leifeld et al., 2003** (GL, English
UK	National	-	30	Grassland remaining grassland and cropland converted to grassland	2.39	**21**	11.2	UK Greenhouse Gas Inventory, 1990 to 2018	Brown et al., 2020 (GL)
Europe					Sum of all countries: 18	**15.5**	118.2	EU Emissions from agricultural Sector: 426. 473 Mt of CO2equivalent	EAA report 2020

4.2.2 Measures and land use Q1

Soil protective measures have the highest occurrence in the reports of MS, representing 37 % of all reported measures (Fig. 5). This group of measures includes, in decreasing order of importance: crop residue management (n=9), cover crops (n=9), and improved crop rotation (n=2). With 27%, land use-(change) is the second most mentioned group of measure, followed by tillage with 19%.
The total achievable SCS is commonly estimated by combining measures from all groups. Estimates of the achievable C-sequestration using just one single measure were provided for no-till (ES, DE, CH), cover cops (SE), perennial crops (SE) and biochar (NO).

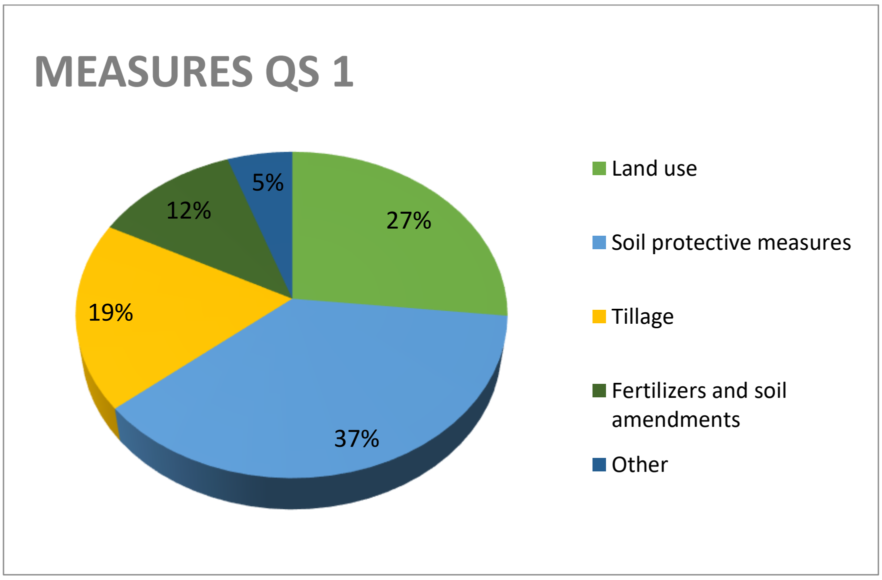

***Figure 5** Share of measures mentioned for national estimates of SCS. Question 1 (Qs1).*

4.2.3 Methods Q1:

The time periods considered in the studies ranged from 9 to 40 years and averaged 20 years. In total seven studies report time period of less than 20 years. By definition, SCS related to a change in farming practices lasts only for a certain period, until soil carbon stocks reach a new steady state. The IPCC therefore recommends a time horizon of at least 20 years for estimates of SCS potentials. Findings from multiple experiments at Rothamsted (Hertfordshire, UK), however, show how rates of SCS can vary through time over the entire duration of long-term experiments (Poulton et al., 2018a) and that soils may reach a new C equilibrium only around 100 years after a land use change (Smith, 2014). The increase in soil carbon storage is not linear and secondly its rate decreases over time. This means that potentials as annual rates (Tg C year^{-1}) will be larger if only calculated for a short period (e.g. 10 or 20 years) and will decrease if calculated for a longer period (e.g. 100 years). This should be taken into account when comparing the reported potentials.

The most common approaches used to estimate the potential of SCS for agricultural land are modelling (for detailed information see the review of models by Campbell and Paustian, (2015), calibration of SOC stock change factors from local long-term experiments, scenario analysis, or application of SCS rates from the literature.

Norway, Switzerland and Belgium applied SCS rates from the literature to their agricultural areas. Sweden used SOC change factors based on long-term trials and Flanders calculated the increase of effective organic carbon in the ‘‘current’’ (2002) and baseline (1990) year. A variety of modelling approaches were used by DK, DE, ES, FR, IT, NL, PL and UK. The models mentioned are:

- **The MITERRA-NL** is an adapted model for Dutch specific data based on the European MITERRA-EU Model (Lesschen et al., 2012). C-dynamics under conversion of land use is modelled based on a Tier 2 approach according to IPCC guidelines.

- The **C-TOOL Model** was developed to enable simulations of the medium- to long-term changes in SOC in the profile (0-100 cm) of temperate mineral soils under agricultural management and was improved with specific data for Denmark (Taghizadeh-Toosi et al., 2014). C-TOOL applies a less complex structure, compared with other models, which facilitates more straightforward calibration. It requires only a few inputs (i.e., average monthly air temperature, soil clay content, initial soil C: N ratio and C inputs to the soil from plants and other sources).

- A combination of the **CENTRURY** and **RothC** model was used to calculate SCS under regional land use in Spain (Moreno-García et al., 2020). C emission-sequestration of available SCS studies comprising Spanish regions as well as coefficients from the Intergovernmental Panel on Climate Change (IPCC) were included.

- **RothC model** and its modified version **RothC10N** were used to calculate SCS in Italy at different spatio-temporal scale (Farina et al., 2018). These models require few easily available inputs (e.g., average monthly air temperature, precipitation, evapotranspiration, soil clay content, initial SOC, and C inputs to the soil from plants or other sources). RothC was used to perform a spatially explicit simulation of the potential increase in C storage in compost-amended agricultural soils at the national scale under a changing climate, while RothC10N to simulate

SOC dynamics at regional level under semiarid conditions in Southern Italy (i.e., Foggia Province and Manfredonia District).

- **The EPIC model** was used to estimate the CO_2-mitigation potential in the federal state of Baden-Württemberg (SW-Germany) comparing conventional and zero tillage and taking into account C losses through soil erosion(Gaiser et al., 2008). The adjusted net CO_2-mitigation rates of zero tillage, subtracting the reduced carbon losses through soil erosion, were estimated. In Italy, the EPIC model was used to estimate soil carbon dynamics at field level in a representative rainfed cereal system as influenced by climate change and contrasting tillage (Iocola et al., 2017).

- **The DNDC model** Denitrification - Decomposition (DNDC) model (version 9.2; http://www.dndc.sr.unhu.edu) is used to estimate changes of SOC in Poland (Faber and Jarosz, 2018). DNDC consists of six sub models for simulating the soil climate, plant growth, decomposition, nitrification, denitrification and fermentation. To simulate SOC changes in agricultural land, DNDC requires a number of input parameters including daily meteorological data (air temperature and precipitation), soil properties (bulk density and initial SOC context), and management practices (crop rotation, fertilization and manure application). DNDC has been tested against numerous field data sets of long-term change SOC and N_2O emissions at a regional and national scale worldwide.

- **The ICBM** (The Introductory Carbon Balance Model) was developed in Sweden. It is a dynamic model, which describes and predicts soil C dynamics in agricultural soils. It is a simple two-pool model (one young and one old C pool) (Andrén and Kätterer, 1997). It was developed with the aim as being a “minimum model” which includes only processes that are necessary and relatively well known in the way it can be understood and used by nonprofessionals. ICBM has been successfully applied to many LTE’s in different environments. An extended version ICBM/2 exists where two young pools, representing aboveground plant litter and roots are considered.

- The two models **PaSim** and **STICS** were used for the study of France (Pellerin et al., 2019). PaSim is an ecosystem model simulating pasture. It is able to simulate annual dry matter production of mixed perennial meadows under cutting and fertilization in association to the carbon, nitrogen, energy and water balances of the atmosphere-plant-soil system. It contains four submodels for plant growth, microclimate, soil biology and soil physics and reflects carbon- and nitrogen fluxes as well as water and energy dynamics (Riedo et al.1998). STICS is a crop model developed at INRAE in France since 1996. Driven by climatic data, it simulates growth of various crops and soil water and nitrogen balances. It is able to calculate agricultural variables such as input consumption and yield and environmental variable such as water and nitrogen losses (Brisson et al., 2003).

4.2.4 Question 2 (Q2): Are there any estimated C sequestration rates for different management practices derived from field studies in your country (finished or ongoing studies)?

In total 110 contributions, comprising local or regional field studies were submitted of which 100 are scientific published articles, two are PhD thesis and 10 are national reports.

4.2.5 Measures Q2

The share of measures mentioned for the field studies slightly differs from the measures used to estimate nationwide carbon sequestration. Most experiments include measures from the tillage group (31 %) followed by fertilizers and amendments group (28 %) and soil protective measures group (25 %) (Fig. 6). The most studied measures from the soil protective measures groups are crops residue management (n=15), improved crop rotation (n=14) and cover crops (=8). From the fertilizers group, manure application represents the largest share appearing in 30 studies. Soil protective measures, fertilizers or amendments are mostly combined. Land use cover 9% of the studies, pointing to a minor role when it comes to local and regional field experiments.

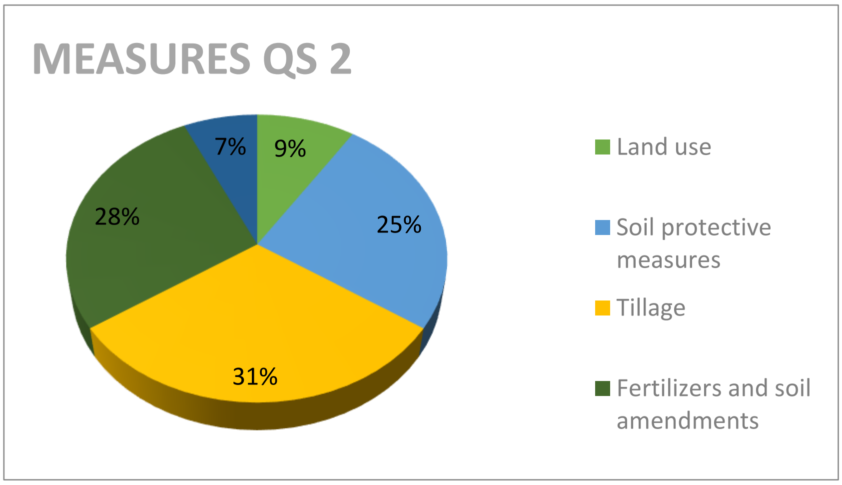

Figure 6 *Share of measures mentioned for national estimates of SCS. Question 2 (Qs2).*

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4.2.6 Methods for quantifying changes in C stocks (Q2)

Three main points are essential when quantifying soil stock changes by comparing measurements taken at two or more points in time and by comparing different measures or land uses (Powlson et al., 2011, Smith et al., 2019):

1.) Top and subsoil should be sampled considering that measures can have opposite effects depending on the soil depth. For instance, the common positive effect of no-till on soil C content measured in the topsoil may not be apparent when measuring to 60 cm depth; also, crops with deep root systems require deep soil sampling (Haddaway et al., 2017; Smith et al., 2020).
2.) Any account for changes in soil bulk density should be considered when sampling whole soil profiles by using the equivalent soil mass or equivalent soil depth approach.
3.) The quantification of the grain size of fine earth (<2 mm) and quantification of the coarse mineral (>2 mm) fractions of the soil.

The IPCC recommends sampling to a minimum depth of 30 cm, which is not in accordance to the requirements listed above. The stocktake shows that 22 % of the studies consider less than 30 cm, 19 % sample precisely to 30 cm, 28 % sample deeper than 30 cm and 20 % do not mention the soil depth studied.

With regard to the tillage studies (reduced, minimum and no-till) which report soil depth, 16 % consider topsoils down to less than 30 cm and 22 % precisely to 30 cm. For tillage experiments that account for the whole soil profile (eight studies), two studies include the equivalent soil mass approach.

Two out of nine studies report an increase in SCS using no-till (Farina et al., 2018, Lopez-Bellido et al., 2019) while seven state that there is no effect on C stocks when considering the whole soil profile (Anken et al., 2004; D'Hose et al., 2016; Dimassi et al., 2013; Hermle et al., 2008; Martínez et al., 2016; Meurer et al., 2018; Willekens et al., 2014). The two studies reporting an increase in SCS, however, refer to Mediterranean conditions and should be considered since the effect of no-till practices depend on pedo-climatic conditions (Chenu et al., 2019). In general, the rates provided by the MS for Manure, Mineral fertilizers, No-till, Cover Crops and Residue management (Fig.7) are comparable to values reported for meta-analysis of international and global studies (e.g. Freibauer et al., 2004; Poeplau and Don, 2015; P. Smith et al., 2000; Vleeshouwers and Verhagen, 2002).

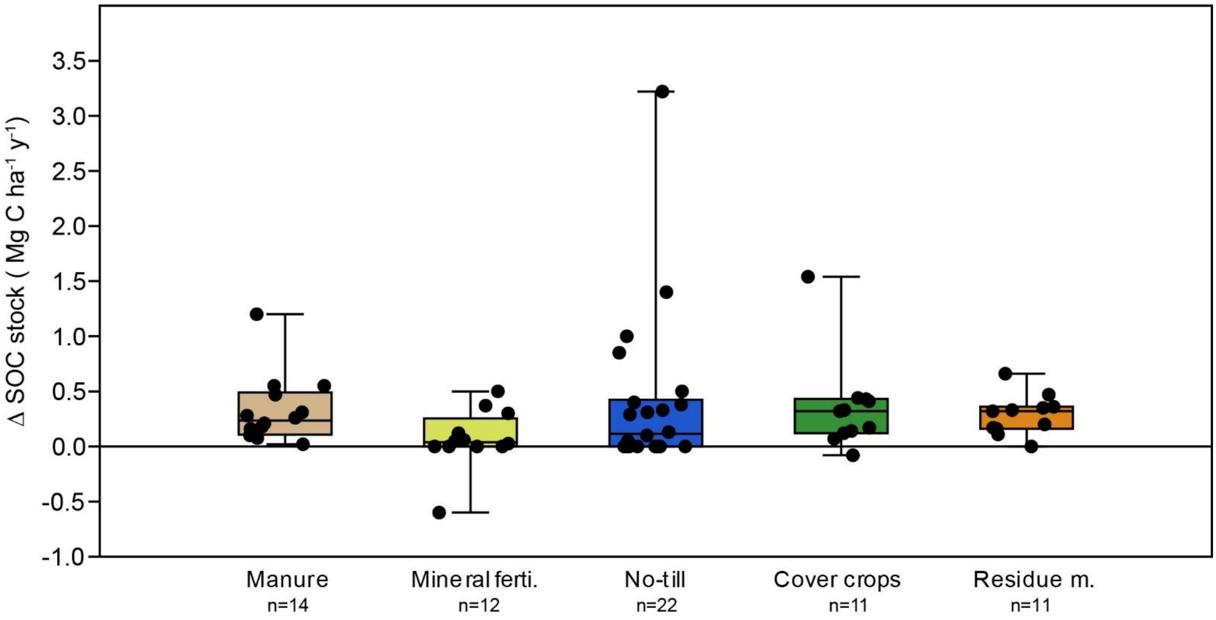

***Figure 7** Rates derived from provided studies: **Manure** (Baldi et al., 2018; Bleuler et al., 2017; Buysse et al., 2013; Fornara et al., 2016; Jokubauskaite et al., 2016; Kauer et al., 2019; Koopmans et al., 2019; Mondini et al., 2012; Singh and Lal, 2005; Taghizadeh-Toosi et al., 2014; Vanden Nest et al., 2015); **Mineral fertilizers** (Baldi et al., 2018; Borrelli et al., 2011; Dersch and Böhm, 2001; Fornara et al., 2016, 2013; Kauer et al., 2019; Keel et al., 2019; López-Bellido et al., 2020; Mazzoncini et al., 2016; Poeplau et al., 2018; Singh and Lal, 2005; Taghizadeh-Toosi et al., 2014); **No-till** (Anken et al., 2004; Barbera et al., 2012; Borges et al., 2018; Cillis et al., 2018; D'Hose et al., 2016; Dimassi et al., 2014; Freudenschuß, 2010; González-Sánchez et al., 2012; Hermle et al., 2008; Iocola et al., 2017; Keel et al., 2019; Leifeld et al., 2003; López-Bellido et al., 2020; Martínez et al., 2016; Mazzoncini et al., 2016; Meurer et al., 2018; Moreno-García et al., 2020; Powlson et al., 2012; Willekens et al., 2014); **Cover crops** (Autret et al., 2016; Bleuler et al., 2017; González-Sánchez et al., 2012; Mazzoncini et al., 2011; Poeplau and Don, 2015; Taghizadeh-Toosi et al., 2014; Wikström, 2019); **Residue managemen**t (Buysse et al., 2013; Dersch and Böhm, 2001; Lesschen et al., 2012; Lugato et al., 2006; Novara et al., 2016; Poeplau et al., 2015; Poulton et al., 2018a; Singh and Lal, 2005; Taghizadeh-Toosi et al., 2014; Triberti et al., 2008).*

The time periods mentioned for calculated carbon sequestration rates in the stocktake range from 2 to 100 years (mean 20 years). A total of 39 studies (40 %) considers time periods >= 20 years (IPCC default period) (Fig. 8).

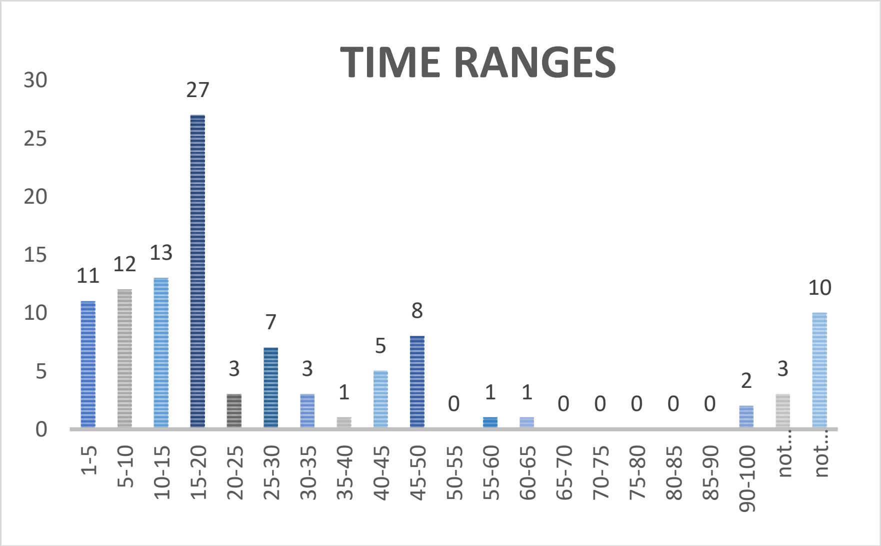

***Figure 8** Counts for time periods over which SCS was estiamed.*

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4.3 Organic soils

Organic soils are one of the most important terrestrial carbon sinks, storing as much carbon as all terrestrial biomass in the world. When drained for agriculture, they are a substantial source of greenhouse gases (GHG). In the last decade, peatlands have been suffering degradation mainly through drainage for agriculture, forestry and peat extraction (Joosten and Clarke, 2002). Organic soils account for 10 % of the total agricultural area for participating MS, with 70 % located in northern Europe (Denmark, Finland, Norway, Sweden) (Tanneberger et al., 2017). According to estimates by Joosten & Clarke (2002), in total 57 % of this area is used for agriculture (DK 70%, FI 2%, SE 5%, NO 8%). Further large peatland areas, of which more than 70 % are used for agriculture, can be found in Germany, Netherlands and Poland. From 14 MS where organic soils comprise an essential area (>1000 km2) only seven MS presented data for GHG studies of organic soils (DE, IR, NL, SV, SE, CH and UK) and two (IT, SV) for alluvial organic rich soils in floodplains. National reports (incl. NIR) as well as scientific studies do mostly report emissions from organic soils but only few measures for mitigation of GHG emissions are presented. In total 21 contributions were delivered of which 14 are published scientific literature and 7 are grey literature.

4.3.1 Question 3 (Q3): Are there any quantitative estimates for reducing GHG emissions (CO_2, CH_4, N_2O) from managed organic soils under different soil management in your country (finished or ongoing studies)?

Only few publications give quantitative estimations of the potential for reducing GHG emissions (CO_2, CH_4, and N_2O) from managed organic soils. This is mainly due to a lack of scientifically based mitigation options that still allow intensive agricultural production.

Four countries report possible national mitigation potentials, all by rewetting of drained organic soils:

- **Ireland** reports a mitigation potential of **3.2 Tg CO_{2e} yr^{-}** if 185,000 ha of drained histic soils were rewetted (50 % of the total drained histic soils in Ireland (Paul et al., 2018). This would compensate 16 % of the national GHG from the agricultural sector (EA) and 12 % also accounting for the EA inclusive LULUF sector. Emission savings were calculated by comparing emissions before and after rewetting. Generic (Tier 1) emission factors for organic soils (IPCC, 2014) were used to calculate emissions from drained and rewetted histic soils.

- Switzerland reports mitigation potentials of between **0.33 and 0.99 Tg CO_{2e} yr^{-}** for an area of 17,000 ha (Leifeld et al., 2003). This would lead to a compensation of between 5.6 %-17 % of the national EA. Estimates are based on literature values for rewetting of drained soils and assumptions on the area these can be applied.

- In the **UK** 95,000 ha of peatland have been subject to some form of active restoration, of which around 70,000 ha involve some form of re-wetting. In total, these activities are estimated to have generated an emissions reduction since 1990 of **0.43 Tg CO_{2e} yr^{-1}** (Evans et al. 2017). For UK this had led to compensation of 1 % of their EA's.

- Indirect potentials are indicated by **Germany**, showing that high GHG emissions result from draining peatland for cultivation. On average, **7.5 Mg CO_2-C ha^{-1} or 27.7 Mg CO_2 ha^{-1} yr^{-1}** were measured on German grasslands which were established on drained organic soils (Tiemeyer et al., 2016). Thus, rewetting drained peatland provides a large GHG mitigation potential and might even cause small net C sequestration in the future.

- **The Netherlands** reports an annual loss from cultivated organics soils of **1.158 Mt** of C, respectively of **4.3 Mt of CO_2** emissions, which could be hindered by restoration of the organic soils. Further they present mitigation potentials, which are based on specific water management measures: water level fixation (200 kha), submerged drainage (80 kha), and transition to paludiculture (20 kha), corresponding to **0,95 Mg CO_{2e} yr^{-1}, 0,6 Mg CO_{2e} yr^{-1}** and **0,4 Mg CO_{2e} yr^{-1},** respectively (Born et al., 2016). These results are based on the conversion of subsidence of the soil into CO_2 emissions. Direct GHG emissions are rarely measured. As a result, there are currently no experimental studies from the Netherlands that quantify the emission reduction potential on organic soils. Several national research programs and projects have however been initiated to study different effects of measures to prevent peat oxidation and improve predictions of GHG emissions (see list of projects in Annex C).

4.3.2. Question 4: Are there any estimated GHG mitigation potentials for managed organic soils derived from field studies in your country?

As already stated, there are still few studied mitigation options that still allow agricultural production. The **Netherlands** reports measures that include water level fixation by keeping the groundwater level constantly below 30-60 cm, drainage restrictions and alternate wetting and drying to be promising options to mitigate GHG. For instance keeping a constant groundwater level of 30-60 cm below ground can lead to a GHG reduction of 71.1 % r or 17.8 Mg CO_2-eq/ha/yr (van den Akker et al., 2018). By

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comparing two grasslands in **Ireland** with contrasting drainage, soil nutrient status and management practices, Renou-Wilson et al. (2014) assed the role of these parameters in respect to biomass productivity, GHG and waterborne C fluxes which lead to a net ecosystem C balance (NECB). The 2-year mean NECB of the deep- and shallow-drained nutrient-poor sites were considerably smaller than the nutrient-rich site (40 and 16 % respectively). Nutrient rich sites produce much higher GHG emissions and are hotspots of fluvial C losses. These results are relevant for the development of strategies to reduce GHG and the choice of grassland types in **Ireland**. Another study by Wilson et al. (2016) report that an estimated amount of **75 Mg CO_2-C a^{-1}** was mitigated by the restoration of the Bellacorick, bog complex (9519.75 ha) in east **Ireland**, this result in in an estimated value of €1506 ha^{-1} in avoided losses. Paul et al., 2018 reports that a considerable amount of **0,4 Tg CO_{2e} yr^{-1}** could be saved, if in nutrient rich grasslands drainage spacing was decreased to control the average water table at −25 cm or higher.

Ongoing **Swedish** field experiments are studying GHG mitigation measures such as sand addition, paddy and sphagnum farming. The first preliminary results for sand addition show that the CO_2 emissions is highest from the plots without sand addition (3.4 µmol*m-2s-1) and lowest from the plots where 5 cm sand was added (1.4 µmol*m-2s-1). The emission from the 2.5 cm treatment was 1.8 µmol*m-2s-1. The sand was applied in the autumn of 2015 and mixed in the top 10 cm of the soil. Penetration resistance, yield and CO_2 emissions will be compared during three years. Results will be available soon (see list of ongoing projects in Annex C).

In **Italy**, organic soils are relatively scarce (870 km^2), corresponding to 0.29 % of the total area. The area of organic soils cultivated annually (histosols) is estimated to be 232.47 km^2, corresponding to 0.18 % of the utilized agricultural area (ISPRA, 2020).The N_2O emissions from these cultivated soils are negligible and they are estimated to be 290 tons in 2018, representing 0.82 % of N_2O emissions for the agricultural sector. Nevertheless, Italy is the largest rice-producing region in Europe with 2170 km^2, corresponding to 1.68 % of the utilized agricultural area in Italy (ISPRA, 2020), where rice cultivation is most widespread in the Po Valley (Northern Italy). Methane (CH_4) emissions from rice cultivation have been identified as a key source in Italy. In 2018, CH_4 emissions from rice cultivation were 62,122 Mg, corresponding to 1.55 Tg CO_2eq, and representing 8.1% of CH_4 emissions from the agricultural sector (equal to 5.1 % of total CO_2eq). In Northern Italy, rice seeds are generally mechanically broadcasted in flooded fields. However, in the last 15 years, the submersion of the rice paddy field has been replaced by rice direct sowed into dry soil in rows, frequently irrigated. In 2018, direct sowing into dry soils covered 50 % of the total area cultivated with rice; its emission factor (EF) was about 25 % lower compared to the EF of the submersion sowing (24.74 *vs*. 32.69 g CH_4 m^{-2} yr^{-1}). In this context, some interesting studies involving GHG flux measurements comprising rice cultivation in organic-rich, but mineral alluvial floodplain soils have been carried out (Bertora et al., 2018; Lagomarsino et al., 2016; Meijide et al., 2017). Bertora et al. (2018) compare water management techniques such as seeding during flooding- or dry periods combined with tillage and crop residue management and show that the adoption of dry seeding resulted in the lowest cumulative CH_4 emissions with a reduction of 69 % compared to the water-seeding analogue. Meijide et al. (2017) investigate the effectiveness of managing the water table level of rice paddy fields and observe that an adequate management of the water table level has the potential to decrease the Global Warming Potential and reduces CH_4 fluxes. Similarly, Peyron et al. (2016) evaluate the effectiveness of alternative water management techniques (i.e., dry seeding with delayed flooding and intermittent irrigation) on the mitigation of CH_4 emissions from paddy soils and show that the adoption of alternative water management reduces annual CH_4 emissions by 60 % compared to the conventional water seeding and continuous flooding practices, while adoption of intermittent irrigation regimes can totally prevent CH_4 emissions. Lagomarsino et al. (2016) show how alternating wetting and drying reduces CH4 but can significantly increase N2O fluxes depending on the transition time from flooding to anaerobic conditions. These studies used chambers to measure GHG fluxes.

4.4 Knowledge gaps reported by MS

All member states (MS) received a targeted questionnaire aimed at compiling knowledge gaps regarding the achievable SCS in mineral soils and the potential for reducing greenhouse gas (GHG) emissions from managed organic soils. This report illustrates how the obtained information was processed in detail and presents the conclusions after synthesising all information received.

4.4.1 Knowledge gaps in C-Sequestration in mineral soils

In total, fifteen MS submitted 77 knowledge gaps regarding C sequestration in mineral soils in Europe. They were first structured by the formulated knowledge gap, whether it was published or not, and which MS stated the knowledge gap. Moreover, similarities between knowledge gaps were highlighted with the help of colour coding in order to identify connections throughout Europe. Based on this information, related knowledge gaps were grouped and formulated:

1. Measures for SCS
2. Assessment of SCS
3. Interaction of soil management approaches
4. Chemical, physical, biological and climatic factors
5. Economic, socio-economic and social factors

Briefly, most knowledge gaps stated by the MS concerned the impact of soil management on C sequestration potential of agricultural soils and the assessment of soil C pools. The number of knowledge gaps per group and the MS stating the gaps are presented in Table 3. The knowledge gaps for mineral soils are summarized for the European regions in Table 4. In the following, the findings, which were obtained by grouping the knowledge gaps, are presented in detail and when possible relations to the main EJP SOIL challenges (Fig. 9) are highlighted and sumarized in Figure 10. Published studies are indicated with the respective reference.

Table 3 *Counts of knowledge gap mentions per group and MS*

Knowledge gap	**Counts per group**	**Member states**
Measures for SCS	27	BE, FR, IT, NL, NO, ES, SE, TR
Assessment of SCS	22	AT, BE, CH, FR, IE, IT, LT, NO, PT, ES, SE, TR, UK
Interaction of soil management approaches	10	AT, BE, CH, FR, IE, IT, NL, SE, UK
Chemical, physical, biological and climate factors	12	IE, FI, FR, ES, SE, UK, CH
Economic, socio-economic and social factors	6	BE, FR, IT, CH
total	77	

Table 4 *Counts of knowledge gaps per European region*

European Region	**Member states per region**	**Counts per region**
Northern Europe	NO, SE, FI, DK	19
Western Europe	IE, UK, NL, BE, FR	23
Central Europe	EE, LV, LT, PL, DE, CZ, AT, CH, SK, HU, SI	12
Southern Europe	PT, ES, IT, TR	23

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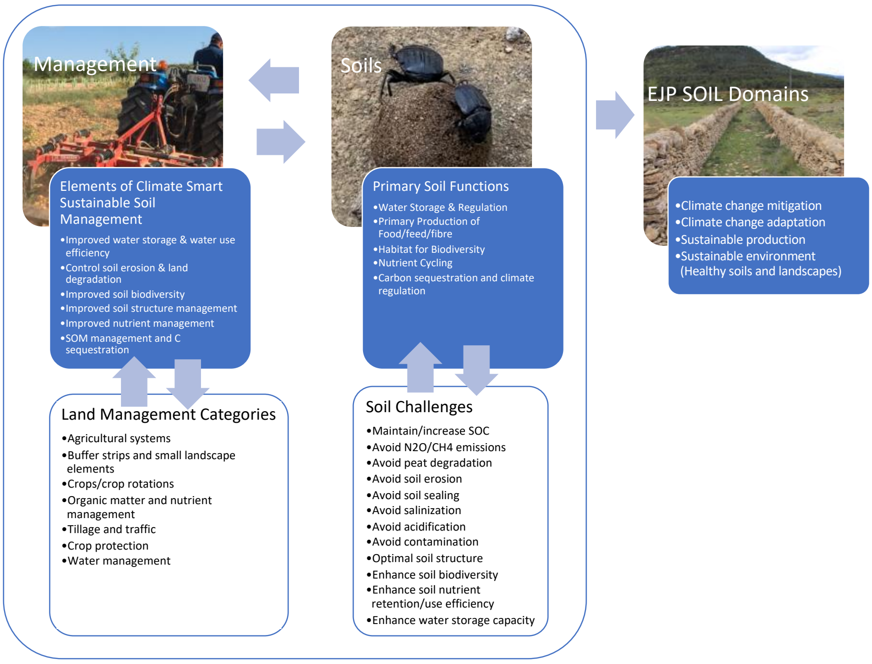

Figure 9 Link diagram illustrating i) how local land management choices can influence the elements defining climate-smart sustainable soil management; ii) the link between primary soil functions and soil challenges; and iii) how optimized interactions between soil functions and soil management will lead to achieving the EJP SOIL research domains.

Measures for SCS

The group “Measures for SCS” summarizes knowledge gaps about agricultural management options aiming at increasing soil carbon sequestration. This group of knowledge gaps is therefore closely connected with the EJP SOIL challenge **“Maintain/increase SOC”** (Fig. 9). Since participating MS defined different knowledge gaps related to this group, a detailed description for each country is presented.

Belgium (Flanders) and France report that the effect of grassland renewal/renovation on C stocks (reseeding) is understudied. Moreover, the effect of intensity of grassland management (number of cuts, grazing intensity) and species composition on C sequestration potential needs to be investigated. Detailed information on C input from above- and below-ground biomass residues and the contribution of roots of different crop plants and different cropping systems is largely missing as well. Limited understanding of carbon inputs by rhizodeposition was also noted as a knowledge gap by **Switzerland**. According to **Belgium (Wallonia) and France**, the potential of deep-rooting plants and agroforestry/agroecology practices in temperate context for SCS deserve closer attention. Subsoil carbon storage and persistence of sequestered SOC are other topics that are currently poorly addressed. Research on new processes to clean waste organic effluents (like sewage sludge or biosolids) and make them safe for recycling in agriculture is also critical to decrease the waste of exogenous organic matter.

Considering **Norway**, so far, no study on the use of different cover crops in relation to C sequestration has been published that is considered to cover this topic sufficiently. Especially data on the potential use of deep root cultivars is not available (and is generally limited internationally), even though they are considered to have a significant potential for C sequestration. Regarding conservation agriculture, there is a general knowledge gap on how much C sequestration potential can be obtained from this practice in Norwegian (C-rich) soils. **Norway** further highlights that the use of organic resources to increase SOC in agricultural soils is a major knowledge gap, especially regarding the net effect of using organic resources. The ability of biochar to influence the stabilization of plant-derived C and other C inputs needs to be looked into for Norwegian conditions (Rasse et al., 2019). Finally, optimized management of permanent grasslands is also an understudied topic in **Norway**.

Sweden also points out the lack of information on the net effect of biochar on GHG emissions and the net effect of irrigation on SOC stocks. The unknown fate of biochar in soil was also identified as a knowledge gap by **Switzerland and Belgium (Wallonia)**. Both recognise that biochar has a strong potential for SCS but also point out that the design of biochar application to soil has to primarily take into account its effect on soil fertility. As biochar lasts in soil for centuries to millennia, a precautionary approach is indispensable and in-depth study of the conditions of biochar application to soil for a successful use, as well as an evaluation of associated risks, is urgently needed. Moreover, the short-term effects of loosening and incorporation of straw slurry into the upper subsoil on soil physical properties and crop yield are understudied. Similar to Belgium and Norway, Spain considers the effects of management practices on C sequestration in grasslands as a knowledge gap.

In the **Italian** stocktake, the development of a landscape level assessment of the soil C sequestration rate in fruit orchards with poor SOC levels, starting with surveying the current management practices, is expressed as a knowledge gap. Italy also plans to extend its efforts towards understanding SCS potentials in different silvo-pastoral agroforestry systems and sheep-grazed pastures without the presence of trees. Further, few studies are examining the C stock in olive grove and vineyards in Italy. Assessing the dynamic changes of SOC stocks over time, using repeated sampling or chronosequence approaches, would allow to draw conclusions on the effect of soil management practices on SOC stocks in the long term. Optimization of cover crop management and the introduction of intercropping could contribute to enhance overall agroecosystem sustainability. Further studies including a larger number of sites and simulating SOC dynamics with modelling are necessary to achieve more general conclusions and to consider specific side-effects of contrasting tillage practices on SOC stock change.

In the **Netherlands**, measures whose effects are insufficiently substantiated to date are adjustments in crop rotations. Crop rotations including more cereal crops have been studied in 2018-2020, but including insufficient combinations so far. In addition, the application of green manure, grass-maize rotations, compost and organic manure in livestock farming and herb rich grasslands are understudied. The effect of additional measures introduced by the Common Agricultural Policy (CAP) also have not been quantified for their effect on SCS. This includes measures such as buffer strips, hedges and bird fields. **Spain** states that there is a need to asses SCS for managed grasslands (Aguilera et al., 2019). **Turkey** concludes that research efforts have to be increased on pastures, marquis shrublands, wetlands, poplar and orchards, urban areas and agricultural areas. More information should be gained on the use of organic materials such as animal manure, biochar and compost, organic crops, crop fertilizers and green fertilization, which will increase the C stock and soil quality. **Switzerland** noted that it is yet unclear whether conversion to organic fertilizers gives a net benefit for SCS. In this regrad, it must be considered that the re-allocation of organic residues across units of land does not represent a SCS measure (Powlson et al. 2011, Schlesinger 2000).

Assessment of SCS

This group summarizes knowledge gaps about methodological approaches to determine soil carbon sequestration (SCS) and can be connected to the EJP SOIL knowledge gap **"Maintain/increase SOC"** (Fig. 9).

Austria states the need to develop a quantitative/semi-quantitative method to determine SCS potentials. There are already initial approaches, but further development of these first methodological approaches is still necessary in order to draw a more differentiated picture of future possibilities and to be able to assess the contribution of different measures to achieve the climate goals more realistically. For example, many Austrian publications do not measure but calculate bulk density of soil, which can lead to inaccurate results regarding C stocks or sequestration. This issue will be looked into within the ongoing CASAS project (Carbon Sequestration in Austrian Soils). Similarly, **Spain** also notes that bulk density is often not measured and that more long-term studies in a broader range of representative systems and information n about fixed soil mass accounting of SOC stock changes are needed (Aguilera et al., 2019, 2013).

Belgium (Wallonia) underlines that, comparably to the "4per1000" scenario projected in France, the gains in terms of SCS that can be expected from innovative agricultural practices should be simulated to help decision-makers taking efficient measures for climate change mitigation. In that goal, the mapping of the soil carbon saturation deficit is indispensable to identify agricultural areas with the highest SCS potentials and design regional or national management strategies accordingly. Such a map exists for Wallonia but several elements might contribute to decrease the uncertainty of the prediction and therefore increase the accuracy and reliability of the map.

In **Italy**, reliable reference values in terms of SOC stock for any land use, management, soil type and climate are stated as knowledge gaps. Moreover, SOC sequestration rates achievable under different pedoclimatic conditions by applying specific strategies of land management are understudied. SOC variation in the sub-soil (below 30 cm soil depth) and soil inorganic C pool size and variation in the top and in the sub-soil is insufficiently addressed. **Italy** expresses that more comparisons between soil respiration results on similar experiments as well as data on GHG emissions and mitigation strategies for a wide range of land use and cropping is needed. Moreover, Italy stated that it would be necessary to develop a landscape level assessment of the GHG mitigation potentials of climate smart practices in fruit orchards with poor SOC levels. To better identify the drivers of GHG mitigation potentials, it will be important to pay attention to site-specific farming options, considering soil physicochemical properties and local water quality.

Ireland, **Sweden** and **France** (Pellerin et al., 2019) reported knowledge gaps on potential of subsoil for SCS as well. **Ireland** adds that the quantification of mechanisms for movement of OC into subsoils have to be better understood (Simo et al., 2019; Torres-Sallan et al., 2017). **Lithuania** expresses an insufficient integrated evaluation of SCS at the national scale and a general lack of research data on SOC stocks.

Norway has very limited information on SOC storage on a large part of the grasslands and rangelands, which make up a very large share of Norway's terrestrial ecosystems (Rasse et al., 2019)

The **Portuguese** national GHG inventory, which is the base for the estimation of the SCS potential, is not up to date. There is an urgent need for the extensive collection of data on soil C. This is clearly stated in the national inventory report where there is a recommendation for a detailed evaluation of SOC stocks to be carried out, together with the national inventory.

In **Switzerland,** there is a need to evaluate management practices that enhance SCS carried out at the regional or farm level, where site and management specific constraints can be considered (Leifeld et al., 2003).

In **Turkey**, there is a need for long-term measurements on SCS. They refer to the findings from multiple experiments at Rothamsted (Hertfordshire, UK) that show how rates of SCS can vary significantly through time during the entire duration of long-term experiments (Poulton et al. 2018).

Interaction of soil management approaches

This group focuses on knowledge gaps related to a combination of agricultural management options and their interactions. This section is in line with the EJP SOIL challenges **"Avoid N2O/CH4 emissions"** and **"Maintain/increase SOC"** (Fig. 9).

In **Austria**, GHG emissions from soils and SCS are rarely measured simultaneously, even though both are strongly affected by different management practices. Comparably, **Belgium (Wallonia)** considers that the complete life cycle analysis of agricultural systems representative of the regional context is needed to assess as well as possible their performance in terms of overall C balance and not only SOC storage or sequestration. A combined approach, estimating overall effects of farming practices on C dynamics is still missing. **Belgium (Flanders)** expresses that the relationship between permanent grassland age, ground water table level and C stocks is insufficiently investigated. Still, this knowledge could serve as a basis to pay farmers for keeping grasslands longer at the same place and for assessing C sequestration potentials.

Belgium (Flanders) states that an improved accuracy of regional N_2O simulations (using the DNDC model) is needed. Specifically, inclusion of more precise crop area surfaces, crop rotations, crop residues as well as improved simulations for temporary grassland, taking into account permanent grassland and spatial and temporal variations of N applications, are needed. There is a general need for high-quality N_2O emission datasets originating from field experiments including frequent N_2O measurements. New long-term N_2O emission datasets should account for differences in crop and grassland types, effects of land management, finer resolution for climate, geographical spread and temporal distributions. Further research focusing on soil-borne GHG mitigation strategies should include long-term field experiments and ensure a very frequent monitoring of N_2O in particular. The monitoring should take into account weather events and agricultural practices since these can strongly influence N_2O emissions. Finally, these datasets can facilitate the development of accurate models, which may allow better prediction of (regional) N_2O emissions. Therefore, in **Flanders**, GHG emission data on several crops and land management strategies are required.

More information on the (long-term) impact on N_2O emissions is required for:

- Slurry, farmyard manure, digestate and compost. To be precise, the application method, feedstock composition, timing of application, amount and frequency of application need to be studied more intensively.
- The effect of (reduced) tillage on GHG emissions, environmental circumstances during agricultural practices, the effect of specific crop rotations and catch crops and crop residue management.
- Nitrogen immobilization via addition of organic biological waste and crop residues: type of organic biological waste, application method and dose, and environmental circumstances.
- Emissions from temporary and permanent grassland and grazing vs mowing.
- Impact of land use change (including conversion of grassland to arable).

- Impact of temperature and moisture conditions in order to simulate seasonal and environmental conditions (including winter period) and effects of climate change.
- Life cycle-like assessments of soil management strategies fostering soil C sequestration, including a potential increase in mineral N fertilization and GHG losses during treatment and storage of organic materials prior to soil application.

France states that there is a general need to assess the effects of combinations of agricultural management options and their interactions is necessary to improve knowledge on SOC sequestration. The **Italian** stock-take states that assessing the effects of combining diversified and sustainable management practices on soil properties, such as the integration of no-till, cover crops, organic fertilization, return of crop residues and crop rotation is necessary to improve knowledge on SOC sequestration. Moreover, the spatial variability of SOC stocks needs to be assessed considering soil management, cropping systems and environmental zones.

In the **Netherlands**, there is still a lack of knowledge about realistic estimates of the area where different measures can be applied and regarding the effects of multiple measures applied at the same time (i.e. whether measures add on or exclude one another if applied at the same time). Further, the trade-off between soil C sequestration and nitrous oxide emissions is seen as insufficiently investigated in **Sweden**. In the **United Kingdom**, no published studies have specifically addressed the interaction of multiple management practices (e.g. tillage, nutrient applications, and liming applications) on the soil C sequestration potential.

Switzerland states that there is an urgent need to combine several SOC enhancing practices to sequester a significant amount of C in Swiss agricultural soils. In addition, application of novel measures as biochar, deep soiling and agroforestry should be tested (Keel et al., 2019).

Chemical, physical, biological and climate factors

This group summarizes knowledge gaps about chemical, physical and biological factors that influence the kinetics of SOC mineralization and therefore may affect the residence time of SOC. It can be connected to EJP SOIL challenges **“Optimal soil structure”, “Enhance soil biodiversity”** and **“Enhance soil nutrient retention/use efficiency”** (Fig. 9).

Finland identified that the effect of increased SOC content on the leaching of phosphorus and dissolved organic C (DOC) and further impacts on surface water quality is unknown. **Spain** underlines that organic debris > 2 mm are not taken into account in the measurement of SOC as only soil < 2 mm is analysed. Accordingly, SOC stocks can be over- or underestimated depending on whether the coarse fraction > 2 mm is mainly composed of stones or made of organic residues, respectively. **Sweden** states the effect of Al and Fe on the stabilization of SOC as a knowledge gap as well as the effect of microbial communities on C use efficiency (CUE) and SOC stabilization (Meurer et al., 2020). Moreover, the effect of pH on SOC stabilization is insufficiently studied under Swedish conditions. Switzerland also highlighted that management effects on microbial CUE are largely unknown. The **United Kingdom** expresses the need for knowledge on how (through which biogeochemical mechanisms) the interaction of different management practices (e.g. tillage, nutrient applications, liming applications) ultimately affect SOC dynamics.

Ireland, France (Pellerin et al., 2019) and **Sweden** expressed the need for studies about the effect of climate change on achievable soil C sequestration and the SOC net balance. Sweden further states a knowledge gap about the major controls on priming and its net effect on the SOC balance.

Economic, socio-economic and social factors

Within this group, knowledge gaps related to economic and social factors were complied. No direct connection to one of the EJP SOIL challenges could be drawn.

Developing an accurate and cost-effective system for C accounting at the farm level (including remote sensing, modelling and regional calibration) is considered as a knowledge gap in **Belgium (Flanders)**. Efficient decision-support tools and extra knowledge are needed to choose the optimal strategies for organic materials that can be returned to the soil based on a complete life cycle analysis, avoiding negative trade-off. The **French** stocktake raises the question, whether the development of bioeconomy is likely to reduce the achievable SCS because of competing use for available biomass. Further, it states that the effect of storing practices on global GHG emissions are uncertain. In **Italy,** there is no public perception of the importance of SCS. **Switzerland** reports that the implementation of SCS activities would have severe consequences for the agricultural sector and characteristic appearance of the landscape. The socio-economic feasibility of possible measures is therefore still an open question (Leifeld et al., 2003).

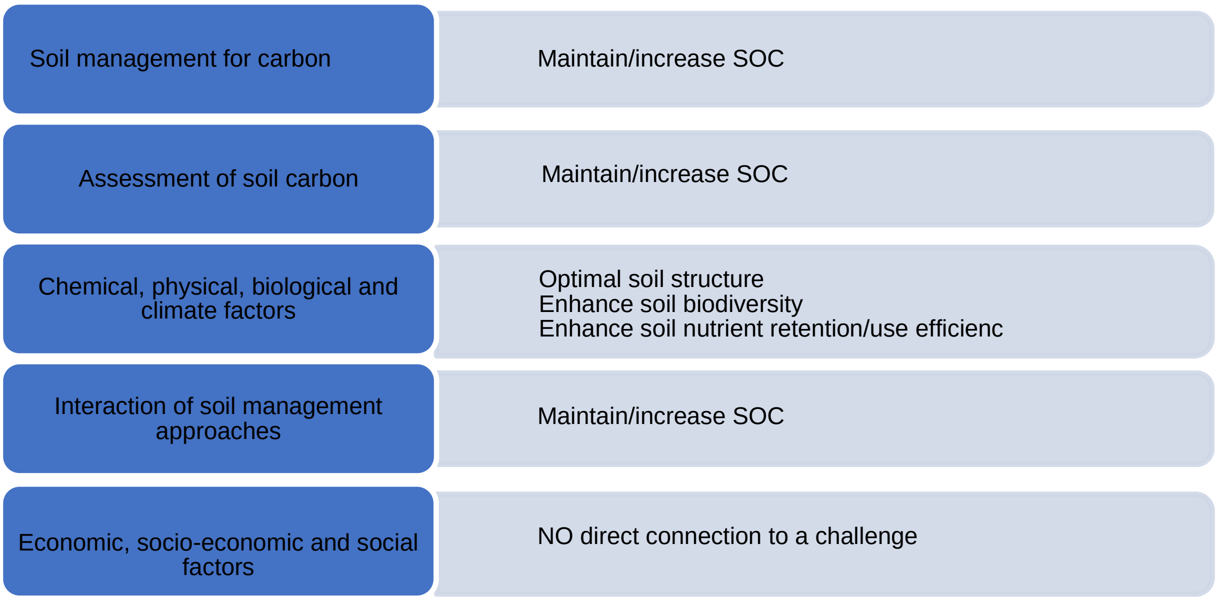

Figure 10 Knowledge gap groups for mineral soils and the corresponding EJP SOIL challenges (compare with Figure 9).

4.4.2 Knowledge gaps in organic soils

Twelve out of 24 MS submitted in total 33 knowledge gaps regarding organic soils in Europe (Table 5), which were separated into four groups:

1. Management options for organic soils
2. GHG emissions from organic soils
3. Assessment of organic soils and SOC
4. Other specify problems of organic soils

Table 5 *Number of knowledge gaps for organic soils and member states per group*

Group	**Nr. of knowledge gaps per group**	**Member states within this group**
Management options for organic soils	12	IE, NL, SE, DE, TR
GHG emissions from organic soils	9	BE, LT, LV, SE, CH, IT
Assessment of organic soils and SOC	7	AT, IE, IT, SE
Other specific problems of organic soils	3	AT, ES
Total	31	

Moreover, knowledge gaps were clustered by European regions (Table 6).

Table 6 *Knowledge gaps for organic soils per main European region*

European Region	**Member states per region**	**Nr. Of knowledge gaps per region**
Northern Europe	NO SE, FI, DK	6
Western Europe	IE, UK, NL, BE, FR	7
Central Europe	EE, LV, LT, PL, DE, CZ, AT, CHE, SVK, HU, SL,	11
Southern Europe	ES, TR	7

Management options for organic soils

This group comprises knowledge gaps about agricultural measures on peat soils and can be connected to the EJP SOIL challenge “Maintain/increase SOC” (Fig. 10).

The stock-take of the **Netherlands** showed that there is a lack of studies focusing on the assessment of GHG reduction potentials according to existing mitigation measures. For example, the influence of groundwater levelling needs to be quantified. Similar is stated by **Ireland** reporting that the impact of water table manipulation on emissions should be assed. Another potential measure that has not been evaluated so far is the effect of paludiculture compared to intensively managed grasslands. **Sweden** stated that there is an urgent need for new management options to mitigate GHG emissions and erosion on agricultural organic soils since only a small fraction of the area can be rewetted. In addition, it would be important to study the effect on GHG emission in simple ways to regulate the ground water table by plugging open ditches in paludiculture and to follow the long-term effects of rewetting projects on GHG emissions. Lastly, Sweden expresses that, as a climate change adaptation measure, conversion of organic soils to biomass production sites must be investigated as a feasible alternative in dry years.

Several MS also formulated knowledge gaps regarding the effects of agricultural management measures on GHG emissions. **Germany** established that a coordinated re-wetting project database is necessary to evaluate management options on rewetted soils (e.g. paludiculture) and their effect on GHG emissions. The effects of rewetting on the large diversity of organic soils should be studied, in particular fens (nutrient rich) and degraded organic soils. Swedish experts found that there is a need to measure the long-term effects of sand addition (or incorporation of underlying mineral material) and liming on GHG emission rates and C capture efficiency. As proposed by **Turkey**, long-term organic and inorganic fertilizer effects on CO_2 fluxes should be investigated.

GHG emissions from organic soils

This group summarizes knowledge gaps about GHG emissions from peat soils. It is related to the EJP SOIL challenge “Avoid N_2O/CH_4 emissions” (Fig. 10).

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N° 862695

Belgium (Flanders) states that there is a general need for high-quality N_2O emission datasets originating from field experiment including frequent N_2O measurements (Roelandt et al., 2007). New long-term N_2O emission datasets should account for difference in a.) Crop and grassland types, b.) Effects of land management and c.) Finer climate, spatial and temporal resolution (Roelandt et al., 2005). Finally, high quality GHG emission (especially for N_2O) data sets for several crops and land management strategies are required for Flanders. **Italy** suggests the creation of a free available library for GHG emission factors. **Lithuania** and **Latvia** sees, despite qualified calculations in its National Inventory Report (NIR), knowledge gaps on experimental GHG emission data on organic and mineral soils and an absence of emission factors at national scale. In **Sweden**, there is a great need for continuous measurements of N2O emissions in field trials with different mitigation options to capture spring and autumn peaks and to increase the knowledge on a process level. They suggest that such measurements could be combined with microbial studies. More emission data for organic soils at different spatial and temporal scales to assess the huge variation in emission rates within fields, between fields, between soil types, and between years is needed. Remote sensing techniques might be a suitable option for increasing our knowledge in this regard. In **Switzerland**, emission factors of organic soils are seen as knowledge gaps as well.

Assessment of organic soils and SOC

This section gathers knowledge gaps on mapping peat soils and measuring GHG emissions from peat soils, which is in line with EJP SOIL challenges “Maintain/increase SOC” and “Avoid peat degradation” (Fig. 10).

Austria identified that the mapping and reporting of peatlands was lacking in their national inventory, with no data on depth and bulk density of peat soils. **Switzerland** expressed similar knowledge gaps, also with respect to the amount of C stored in these soils (Wüst-Galley et al., 2020). **Italy** reported a lack in the availability of updated land use maps and georeferenced data about land management practices as well as analysing, accounting, and mapping GHG fluxes at a landscape scale. **Ireland** stated there is a need for assessment of the drainage status of organic soils.

Other specific problems of organic soils

Knowledge gaps that could not be assigned to one of the groups mentioned above were collected within the group “Other specific problems of organic soils” (Fig. 10).

Austria mentioned that the definition of peatlands is an issue. Peatlands are generally seen as natural biotopes whereas managed peat soils without vegetation are often overseen, which is why publications and their results divert substantially. Moreover, estimates of GHG emissions from peatlands in the Alpine foothills are generally extrapolated thanks to data from other countries (e.g. Germany). The suitability of calibration data must be verified for this context. **Spain** recognizes a huge gap between research on mineral soils and organic soils, mineral soils being much more studied. Additionally, cropping systems have been studied for GHG mitigation/quantification purposes much more frequently than livestock systems. Organic soils in the north of the country (e.g. grasslands) belong to the latter. More efforts are necessary in this field and type of systems/soils.

Generally, it can be concluded that very few studies deal with GHG emission factors of specific agricultural management methods on organic soils in Europe. Knowledge gaps on this topic are diverse, ranging from methodological problems such as mapping peatland and correctly estimating their SOC contents, to the GHG mitigation potentials of specific management measures. The general lack of research on organic soils is also reflected by the number of MS who did not submit studies and reports regarding reduction of GHG emission from organic soils despite the significant occurrence of peatlands on their territory.

Management options for organic soils	Maintain/increase SOC
GHG emissions from organic soils	Avoid N_2O/CH_4 emissions
Assessment of organic soils and SOC	Maintain/increase SOC Avoid peat degradation
Other specific problems of organic soils	No connection to a challenge

Figure 11 Knowledge gap groups for organic soils and the corresponding EJP SOIL challenges (compare with Figure 9).

5. General knowledge gaps and future research directions

This part of the report provides thorough information about the knowledge gaps and hot topics, which were identified throughout the synthesizing process of the national data submitted by the MSs. These are summarized into different main topics.

5.5.1 General methodological challenges:

The stocktake has shown that the comparability of results and especially country to country comparison is challenging due to different methodological approaches implemented. One possible explanation is that most studies and experiments were initially designed for other purposes (soil fertility, yields etc.) than measuring SCS. There is a large variation in sampling depth and periods over which SCS is estimated. Soil bulk density is often missing and therefore estimated, which however can lead to wrong numbers. To harmonize methodologies and improve the comparability of studies, the IPCC makes useful recommendations for the assessment of SCS. Nevertheless, a standard protocol is still missing. An international shared platform where countries can present and exchange approaches and data, as suggested by Smith et al. (2020), could be a first step and improve the reporting and verification of credible and reliable measurement/monitoring of soil carbon sequestration.

5.5.2 Socio-economic factors:

Socio-economic factors are key for a successful implementation of long-term measures (Amundson and Biardeau, 2018; MacLeod et al., 2010). There is an essential need of information about feasibility of implementation of agricultural measures with a high SCS potential, including the economic efficiency and social acceptability on a country scale. The stocktake shows that socio-economic factors are rarely included in the studies. For instance, consideration of a realistic area where measures can be implemented, practical applicability and costs are generally not taken into account.

5.5.3 SCS under climate change

There is an urgent need to consider the impact of climate change on agriculture to correctly design achievable SCS scenarios. At present, there are very few simulations of SCS conducted under different climate scenarios. Achievable carbon sequestration, as well as greenhouse gas emissions from the agricultural sector, must be considered in the context of climate change, which are expected to significantly affect soil carbon dynamics, land use, production systems and farming practices in a near future. The study of Mondini et al., (2012) clearly shows the importance of including climate change scenarios, which showed that sequestration rates could be three times lower than expected because of climate change. At present, almost no studies do include climate change scenarios for their estimates. Climate change will unevenly affect European regions and hence soil carbon dynamics (Kovats et al., 2014; Meersmans et al., 2016). Spatial predictions of future soil organic carbon stocks under different climate scenarios could be an important starting point for further investigation in key regions with highest SOC losses.

5.5.4 Trade off C-Sequestration vs other GHG:

A widely discussed knowledge gap is the trade-offs between SCS and other GHG emissions (Lugato et al., 2018; Paustian et al., 2016; Reay et al., 2012). There is a general agreement that long-term experiments should include a constant monitoring of GHG emissions, in particular of N_2O since it represents the largest source and is very dynamic in space and time (Lugato et al. 2018, Reay et al., 2012). Lugato et al. (2018) and Guenet et al., (2021), for instance, show that mitigation potential of soil carbon management can be significantly overestimated by neglecting N_2O emissions. The stocktake confirms that for all MS GHG emissions from soils and soil C sequestration are rarely measured simultaneously, even though they are both strongly affected by different management practices. There is one recent study by Launay et al. (2021) which take into account several factors including GHG balance, biomass production and nitrogen- and water-related impacts in addition to soil carbon stock changes. They use a high-resolution modelling approach and show that current systems in France, even though they are storing some C in soils, on average are strong sources of GHG. Finally, it highlights some key management issues to improve GHG balances.

5.5.5 Effects of measures and alternatives:

Many studies include reduced tillage and no-tillage to assess a possible effect on soil carbon sequestration. The stocktake clearly shows that in some cases there is no or little effect on C stock changes when considering the whole soil profile (Anken et al., 2004; D’Hose et al., 2016; Dimassi et al., 2013; Feiziene et al., 2018; Hermle et al., 2008; Martínez et al., 2016; Meurer et al., 2018; Willekens et al., 2014). The success of no tillage and reduced tillage on SCS depends on pedo-climatic conditions (Chenu et al., 2019), therefore their implementation in a SCS goal may be best suited for warm and dry conditions where positive effects on soil carbon stocks have been shown (Farina et al., 2018, 2018; López-Bellido et al., 2020; Moreno-García et al., 2020, Novara et al., 2019). Furthermore, another concern to accurately assess the effect of no tillage/reduced tillage on SCS arises from the sampling depth taken into account for the quantification of carbon stocks. The stocktake shows that 22 % of all studies consider a soil depth < 30 cm, 19 % sample precisely to 30 cm, 28 % sample deeper than 30 cm and 20 % do not mention the soil depth studied. With regard to the tillage studies, there are still more than 20%, which only consider top soils or do not mention soil depth studied. In order to guarantee net C sequestration future studies should therefore include the whole soil profile. The increase in soil bulk density that generally goes with no-till practices compared to annual ploughing is another source of bias in the quantification of carbon stocks between cropping systems with contrasting tillage practices. Accordingly, the quantification of soil carbon stocks corresponding to a given soil depth may be biased between systems, as a same sampling depth corresponds to contrasting soil masses. In that case, an equivalent soil mass approach is preferable and should be the norm (Wendt & Hauser, 2013).

Many studies do include crops residues, organic compost or manure, but the alternative fate of the amendments are rarely discussed. Even though such amendments can lead to an increase in soil carbon, it does not automatically imply an additional net transfer of C from the atmosphere into the soil (see definition of SCS section 1)(Chenu et al., 2019; Powlson et al., 2011; Schlesinger, 2000). The application of manure for example, which is currently adopted by some countries for their SCS estimates, is still highly debated. The application of manure is not always accepted as a soil carbon sequestration measure as it reallocates organic matter from one pool to another and is therefore not a net sink for CO_2 (Chenu et al., 2019; Schlesinger, 2000). Smith et al. (1997, 2000) however state that using agricultural by-products such as animal manure is crucial to recycling organic matter and sequester carbon in soils. Clear assessments of the way of production of manure and alternative fate should therefore be assessed to estimate net carbon sequestration. Another important example are resource limitations and trade-offs for alternative uses of straw for feed, bedding or fuel production (Taghizadeh-Toosi and Olesen, 2016). Finally, also negative impacts on carbon stocks due to straw removals must be taken into account to calculate net carbon sequestration. The study of Novara et al., 2018 for example shows, that soil carbon stocks in wheat systems need to reach saturation by applying sufficient residues before additional straw yield can be harvested for alternative use, otherwise SOC stocks would decline. The duration needed to reach SOC saturation is however depending on pedological and climatic conditions, which need to be considered at regional scale.

In recent years, **biochar** has been promoted as C negative emission technology including positive effects on soil fertility and crop production (Smith, 2016; Lehmann, 2006). Soil amendment with biochar is mentioned by several MS as a farming practice that could have large potential for SCS. Biochar also has positive interactions with the soil N cycle, as it does not require large amount of fertilizer N to sequester C in soils and contributes directly to reducing N_2O emissions (Guenet et al., 2021b). However, biochar is a technology under development, and questions of productions costs and competition for feedstock with other use such as bioenergy need to be addressed. There is also a need to optimize the technology for simultaneous C sequestration gains and increases in crop productivity, which requires further research and development. Studies indicate that biochar produced under the right conditions for agricultural purposes is safe, and the existing strict certification processes need to be applied to guarantee that these conditions are met. In this context, an in-depth risk evaluation of existing studies is urgently needed to precisely define which feed stocks and production methods are appropriate.

Agroforestry is a promising measure to sequester atmospheric carbon in soils, but still lacks consideration as management option in national soil carbon sequestration potential estimates. Only two countries (DE, FR) consider it as an option in their regional and national SCS estimate, respectively. Compared to crop- and grasslands, it can retain much higher quantities of carbon above and belowground biomass. Further, it comes with other crucial co-benefits such as simultaneous production of food and fibre, an increase in species diversity, water and soil conservation, and improved resilience against climate change (Abbas et al., 2017). The study of France, however, has shown that agroforestry comes with relatively high costs (Pellerin et al., 2019). This is especially true at the beginning because trees become profitable only after some years and in some cases also crop yields might be reduced, presenting rather unfavourable policy incentives (Beuttler et al., 2019; Pellerin et al., 2019). However, efforts are needed to estimate the change in costs taking into account the monetary value of co-benefits (see also section 5.5.6 Costs of measures).

Deep ploughing, a method used to improve soil structure or overcome hardpans of podzols, has been shown to increase SOC stocks by very significant amounts (Alcántara et al., 2016; Schneider and Don, 2019). Preliminary estimates made for Switzerland show that by applying deep ploughing on an area of 5000 ha per year, could offset the emissions of 15.4 million t CO_2 over 20 years. This would compensate 12 % of the annual emission from the agricultural sector. Nevertheless, it is important to note that deep ploughing is a major irreversible soil intervention influencing several soil ecosystem services (either positively or negatively), which has to be taken into account when optimising soil fertility for crop production (Schiedung et al.2019).

Deep soil carbon: Concerning deep soil horizons, it has been shown that the residence time of subsoil C can be several times higher than that of the topsoil. However, the potential for additional C sequestration in deep soil layers remains to be assessed (Rumpel and Kögel-Kanbner, 2010; Chenu et al., 2019) as well as the mechanisms controlling movement of OC into subsoils and its stabilization (Balesdent et al., 2018; Kögel-Knabner and Amelung, 2021; Simo et al., 2019; Torres-Sallan et al., 2017).

5.5.6 Costs of measures

Only two countries include costs of measures into their evaluation of the soil carbon sequestration potential. The study of Pellerin et al. (2019) for France for instance, shows that the implementation of most practices that sequester C will result in a cost to the farmer. As stated in the results, when acceptable costs are considered (e.g., 55 € t^{-1} CO_2-eq) the technical SCS potential of France is reduced by 50% (Pellerin et al., 2019). On the other hand, other measures are associated with essential co-benefits (e.g. biodiversity or regulation of the water cycle, erosion reduction, and other societal benefits), which are not yet monetised. Agroforestry, a relatively expensive measure for instance, comes with the simultaneous production of food and fibre, an increase of biodiversity, water and soil conservation, and improved resilience against climate change. Lanigan et al. (2018) further shows that costs for extra lime, clover seed, fuel and labour for improved grassland management in Ireland is overcompensated by the gain from higher grass yields leading to net-savings. The assessment of costs is essential to realistically estimate the potential of SCS. Studies should however also account for the savings through higher yield or other co-benefits, which could be key to meet social and economic acceptance and should therefore urgently be assessed in future studies (Amelung et al., 2020).

5.5.7 Soil (bio-) chemical properties

Most studies focussing on soil processes and farming practices that increase soil C storage report measurements of SOC content together with other soil fertility parameters such as total N content, cation exchange capacity physical soil properties (e.g. grain size, stone content). The mineralogy and elemental composition of soils, as well as soil (micro-) biology are rarely considered. Therefore, the way these variables affect SOC stabilization is not clear yet (Lal, 2018). It has however been shown that carbon stocks are soil type specific (Kögel-Knabner and Amelung, 2021) and that interactions of geochemical factors and climate do influence soil organic carbon storage and turnover which should be considered for further soil carbon stock predictions (Doetterl et al., 2015).

5.5.8 Carbon use efficiency in differently managed systems

Carbon use efficiency (CUE), i.e., the ratio of carbon transformed to microbial biomass to carbon uptake by the decomposer organisms, is key to understanding soil carbon sequestration. Only subtle differences in CUE have large effects on soil carbon storage. CUE is related to many environmental and microbial parameters (e.g. temperature, pH, nutrient availability, decomposer community etc.) (Sinsabaugh et al., 2013) and might thus be manageable, thereby providing ways to more sustainable agriculture. However, how management actually influences CUE still needs to be explored.

5.5.9 GHG mitigation measure of organic soils:

Although farmed organic soils in most European countries represent a small part of the total agricultural area, these soils contribute significantly to national greenhouse gas budgets. However, very few mitigation options exist to mitigate GHG emissions from organic soils without compromising agricultural production. Most GHG mitigation practices reported by the MS involve the restoration of organic soils, which means abandonment of land from food production or even any agricultural use. Only one contribution (NL) reports possible mitigation potentials, which are based on specific water management measures (water level fixation). Nevertheless, there is an increasing awareness of the need of mitigation measures reflected by the several ongoing research projects on peatland management (see list of research projects).

6. Conclusions

All participating countries (n= 25) returned their country specific information. The stocktake shows that there has been a clear increase in interest for topics covering soil carbon sequestration for climate change mitigation in the last two decades. A total of 111 ongoing projects have been reported dealing with SCS and GHG mitigation measures. However, at present country-based knowledge and engagement is still poor. Only half of the countries can provide information on achievable carbon sequestration at national and regional scales. Information provided is mostly based on rough estimates without consideration of technical and socio-economic feasibilities. Climate change is usually not included, although it is known that it will have an important impact on carbon stocks. The presented national SCS potentials do however point towards important contributions to mitigate climate change by covering considerable shares of national greenhouse gas emissions from the agricultural sector in the range of 1-27.2 %, underpinning the need for further and detailed investigations. The stocktake also shows that the availability of datasets concerning SCS is variable among Europe. While environmental zones in northern Europe and central Europe are relatively well studied, there is a lack of studies comprising parts of Southern, Southeastern and Western Europe. In contrast to mineral soils, effective mitigation measures for organic soils while maintaining agricultural production are much less studied. Very few mitigation options exist to mitigate GHG emissions without compromising agricultural production. Most GHG mitigation practices reported by the MS involve the restoration of organic soils, which means abandonment of land from agricultural use. Finally, the comparability of results is challenging due to different methodological approaches implemented.

7. Limitations of the synthesis

The aim of this stocktake is to get an overview on the available knowledge of achievable carbon sequestration potentials in mineral soils in agricultural land, including pasture/grassland across Europe, under different farming systems, soil types and pedo-climatic conditions as well as on GHGs mitigation measures for managed organic soils. The results in this report have however to be taken with caution, as quality of the individual contributions was highly variable.

Specific limitation of the analysis arise from the following points:

- The level of detail of the information provided by the participating countries was not uniform. Some participants were quite extensive answering all the questions while other provided incomplete or no answers to some questions.
- The participating teams were likely to adopt different definitions to soil carbon sequestration. This is mainly because many studies providing information on soil carbon sequestration were not specifically designed to report carbon sequestration but soil fertility, including data on soil carbon changes.
- The questionnaire could have been improved by a higher level of detail and restrictions for possible answers, which would lead to more homogenous answers more adequate for this analyse.

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Annex

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Lithuania

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No studies available

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C List of finished and ongoing projects

Austria:

1. CASAS: CArbon Sequestration in Austrian Soils ONGOING (1.9.2019-31.8.2022). Document: Austrian Agency for Health and Food Safety (2019): Form Part A 3 - Proposal. 11th ACRP Call.
2. ACRP (Autrian Climate Research Programme) project PeatGov-Austria "Governance options for climate smart agriculture on Austrian peatlands - Specific support for Austria's policymakers" (no publication/report available yet).
3. CRP project "PeatGov-Austria" Austrian peat soils under agriculture are going to be mapped. A best estimate (no measurements) is the goal. In the APCC report quantitative estimates for reducing GHG emissions will be published.

Belgium

4. Investigation on two nature-based negative emission technologies: enchance weathering and biochar. Prof. E. Verbruggen; University of Antwerp.
5. BASTA-project; dr. Bart Vandecasteele; ILVO (Flanders, Belgium): Research on the greenhouse gas (GHG) emission mitigation potential of biochar during compost production and the GHG mitigation potential of this mixture after incorporation in soil.

Czech Republic

6. Research project NAZV QJ1320122 Optimization of the afforestation management of the agricultural lands in relation to enhancement of the landscape retention potential. (2013 - 2017).
7. Research project TACR TD03000087 Interactive evaluation of carbon sequestration in agricultural landscape (2016 - 2017), Evaluation of environmentally friendly practices within the RDP (rural development program) - impacts of interventions on the state of organic matter, biological activity in the soil and soil erodibility (2019).
8. Research project NAZV QK1910232 - The optimization of subsidy title for agricultural land afforestation (2019 - 2023),
9. Research project QK1910299 - Sustainable management of natural resources with emphasis on non-production and production ability of soil (2019 - 2023). General information about projects and its results are available on https://starfos.tacr.cz/

Estonia

Running project of Estonian Agricultural Research Centre:

10. The impact of no-till on soil properties
11. Peat and eroded soil in the soil protection measure (comparing arable fields and grasslands and changes in them during 6 years)
12. Fertility research to study SOC changes in the arable field depending on different types of subsidies (organic, environmentally friendly, single area payment)

Finland

13. Multi-benefit solutions to climate-smart agriculture, MULTA: https://carbonaction.org/en-stn-multa/

France

14. Stocker du carbone dans les sols français: https://inra-dam-front-resources-cdn.wedia-group.com/ressources/afile/487878-58615-resource-etude-4-pour-1000-synthese-en-francais-pdf.pdf
15. DEDYCAS: Soil carbon, a depth-dependent dynamic system: new concepts, measurements and

modelling

16. StoreSoilC: Potential and sustainability of carbon storage in agricultural soils (2017-2021)
17. NanoSoilC: Organo-mineral interactions: nanoscale mechanisms for carbon storage in soils (2017 - 2021)
18. DSCATT: Agricultural Intensification and Dynamics of Soil Carbon Sequestration in Tropical and Temperate Farming Systems (2019-2023)
19. CarSolEl: Construction of a methodology and a frame of reference on carbon fluxes in agricultural soils in cattle breeding territories (2018 – 2021)
20. BRAWO: enhance fundamental knowledge of mechanisms involved in the degradation of woody litter. It will also contribute to the global effort for enhancing carbon sequestration in soil by assessing the potential of altered lignin for carbon sequestration and by developing an innovative microbial model of soil carbon dynamics.
21. CLAND: Convergence Institute to perform in the next decade the research urgently needed on land-management solutions for managing the ecological and energy transitions of the 21st century (2017 – 2027)
22. SUPRA: Develop new knowledge on carbon storage in urban soils in relation to climate change (2017 – 2020)
23. PROTERR: Insertion of Organic Residual Products in culture systems (2018 – 2021)

Germany

24. Application-oriented carbon budget modelling of organic soils
25. BESTLAND-GHG reduction and soil Biodiversity in poorly drained soils under perennial crop
26. Soil hydraulic properties and release of CO2 from peat soils
27. CarboCheck - A software tool to accumulate soil organic matter in agricultural soils
28. CarboHedge: Hedgerows and field copses in the emission inventories – Potential for carbon sequestration
29. Mitigating Agricultural Greenhouse Gas Emissions by improved pH management of soils (MAGGE-pH
30. Eternal-C – Long term turnover and stabilisation of organic matter in topsoils and subsoils
31. VESBO - Impact assessment of vascular plant encroachment on water and carbon cycling in a Sphagnum dominated bog
32. National Contribution to the Integrated Carbon Observation System (ICOS)
33. Climate change mitigation through catch crops
34. Measuring and Modelling Greenhouse- Gas Emissions and nitrate leaching of raw material crop rotations (MASTER)
35. Effects of data requirements and uncertainty on prediction accuracy for model based evaluation and mitigation of nitrous oxide emissions from raw material cropping systems (THG-EMOBA).
36. Peatland monitoring program for climate protection
37. Reduction of NH3 losses and improvement of nitrogen use efficiency after application of synthetic nitrogen fertilizersSOC-Sand - Stability of organic matter in sand mixing cultures
38. SUBSOM - The Forgotten Part of Carbon Cycling: Organic Matter Storage and Turnover in Subsoils
39. Submerged drains in the model project "Gnarrenburger Moor"
40. Temporal trends of carbon stocks in agricultural soils
41. Water management for the reduction of GHG emissions from grasslands on peat soils (SWAMPS)https://www.thuenen.de/en/ak/projects/)
42. DESIRE project starting -Paludiculture in the Neman River
https://www.moorwissen.de/en/index.php

Hungary

Interdisciplinary Research Group for Promoting Climate-Smart and Sustainable Agriculture

43. Evaluation of different management systems based on CO2 and N2O emissions
44. Short-term and long-term responses of growth, carbon allocation and water balance of canopy tree species to fluctuation and extremes of climate conditions in mixed deciduous forest stands
45. Effect of climate change on Hungarian humid, mesoic and dry oak forests and their soils organic carbon storage capacity
46. Improving the greenhouse gas budget estimation for Hungary using tall tower observations
47. Measuring and modelling water and carbon balance of managed agricultural lands
48. Impact of spatial allocation of soil water and soil organic carbon on greenhouse gas emission in a small catchment (NKFIH - OTKA pályázat, témavezető: Horel Ágota)
49. Evaluation of different management systems based on CO2 and N2O emissions (NKFIH-OTKA pályázat, témavezető: Tóth Eszter)
50. Effect of soil management on soil carbon-dioxide emission at different Croatian and Hungarian agricultural sites" - (TÉT pályázat, témavezető: Tóth Eszter).
51. Compilation of indicator SO1 ‘Proportion of land that is degraded over total land area’ from three sub-indicators for UNCCD reporting of Hungary
52. Methodology to establish an indicator of ’Trends in land productivity or functioning of the land’ (SO1-2)
53. Elaboration of methods for calculation of indicator SO1-3 ’Trends in carbon stocks above and below ground’ for UNCCD reporting of Hungary
54. Quantification, evaluation and communication of uncertainty of predictive soil maps using advanced statistical approaches: On the example of soil organic carbon stock and its change.
55. Elaborating a methodology for estimating and mapping the potential organic carbon storage capacity of Hungarian soils

Ireland

56. Soil Quality Assessment & Research (SQUARE). https://www.teagasc.ie/environment/soil/research/square/The focus of the SQUARE project is to; further develop understanding of the soil functional capacity (incl. C sequestration) and quality concepts; assess the impact of soil structural degradation on the functional capacity of the soil.
57. The Agricultural Greenhouse Gas Research Initiative for Ireland (AGRI-I) is a consortium of researchers, students and professionals working collaboratively on multiple projects to develop verified strategies to decrease greenhouse gas emissions from Irish agriculture. https://agri-i.ie/projects/
58. AGRI-SOC: Evaluating Land-Use and Land Management Impacts on Soil organic Carbon in Irish Agricultural Systems.

Italy

59. LIFE15 CCM/IT/000141 - OLIVE4CLIMATE - LIFE - OLIVE4CLIMATE - LIFE. CLIMATE CHANGE MITIGATION THROUGH A SUSTAINABLE SUPPLY CHAIN FOR THE OLIVE OIL SECTOR. Duration, 01/07/2016 – 30/12/2019: https://olive4climate.eu/it/
60. LIFE18 CCM/IT/001093 - LIFE agriCOlture - Livestock farming against climate change problems posed by soil degradation in the Emilian Apennines. Duration, 02/09/2019 – 31/08/2023: https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=7140
61. LIFE14 CCM/CY/000990 - LIFE+ ORGANIKO - Revamping organic farming and its products in the context of climate change mitigation strategies. Duration, 01/09/2015 – 31/08/2019:

https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=5354

62. LIFE15 PRE/IT/000001 - LIFE MEDINET - Mediterranean Network for Reporting Emissions and Removals in Cropland and Grassland. Duration, 01/04/2016 – 31/01/2018: https://www.lifemedinet.com/
63. LIFE17 CCM/GR/000087 - LIFE ClimaMed - Innovative technologies for climate change mitigation by Mediterranean agricultural sector. Duration, 01/07/2018 – 31/12/2022: https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=6814
64. LIFE14 CCM/GR/000635 - CLIMATREE - A novel approach for accounting & monitoring carbon sequestration of tree crops and their potential as carbon sink areas. Duration: 16/07/2015 - 28/06/2020: http://adapt2clima.eu/it/il-progetto
65. Horizon2020-DIVERFARMING. Duration, 01/05/2017 – 31/10/2022: http://www.diverfarming.eu/index.php/en/
66. Horizon2020-SoilCare - Soil Care for profitable and sustainable crop production in Europe. Duration, 01/03/2016 – 28/02/2021: https://www.soilcare-project.eu/en/
67. Terras project Soil in sustainable agriculture - national project financed by Sardinia Region. Started in 2017: http://www.sardegnaagricoltura.it/innovazionericerca/agris/
68. LIFE15 CCM/IT/000039 - LIFE+FORAGE4CLIMATE - FORAGE SYSTEMS FOR LESS GHG EMISSION AND MORE SOIL CARBON SINK IN CONTINENTAL AND MEDITERRANEAN AGRICULTURAL AREAS. Duration, 01/09/2016 – 31/08/2020: http://forage4climate.crpa.it/nqcontent.cfm?a_id=14261
69. LIFE17 CCM/IT/000062 - LIFE AGRESTIC - Reduction of Agricultural GReenhouse gases EmiSsions Through Innovative Cropping systems. Duration, 01/01/2019 – 30/06/2023: https://www.agrestic.eu/
70. LIFE + 12 ENV/IT/000578 HelpSoil. Duration, 01/07/2013 – 30/06/2017: http://www.lifehelpsoil.eu/
71. LIFE12 ENV/IT/000404 - LIFE+ Climate changE-R - Reduction of greenhouse gases from agricultural systems of Emilia-Romagna. Duration, 01/02/2010 – 31/12/2013: https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4564 https://progeu.regione.emilia-romagna.it/it/climatechanger
72. LIFE11 ENV/IT/000302 - IPNOA - Improved flux Prototypes for N2O emission reduction from Agriculture. Duration, 01/06/2012 – 30/11/2016: http://www.ipnoa.eu/it/
73. 2014–2020 Rural Development Programme for Basilicata Region (Misura 16.1, PROSIT CUP H86G18000080002). Duration, 2017 – 2020: https://www.alsia.it/opencms/opencms/Temi/attivita/PRO.S.IT.-Vitivinicoltura/ (in Italian).

Latvia

74. Climate change mitigation possibilities in organic soils https://www.orgbalt.eu/?page_id=1719&lang=lv
75. Peat restoration project https://life-peat-restore.eu/lv/projekts/latvija/

Lithuania

76. Investigation on development tendencies of soils with different genesis and geoecological potential under contrasting land management.

Netherlands

In the program Smart Soil Use projects have been started in 2018 to quantify the effect of C-sequestration in Dutch agricultural mineral soils:

77. Test field underwater drainage Friesland (Praktijkproeven onderwaterdrainage Friesland)
78. Pilot cattail in Marickenland (Pilot lisdodde in Marickenland)
79. Calculating greenhousegas emissions for a waterarea plan Groot Wilnis-Vinkeveen (Berekening broeikasgasemissies voor watergebiedsplan Groot Wilnis-Vinkeveen)
80. National measurementcampaign greenhousegas emissions from peat (Landelijk meetprogramma broeikasgassen uit veen)
81. Fieldstudy effects of soil measures on peat oxidation (Veldonderzoek effecten bodemmaatregelen op veenoxidatie)

Norway

82. National project on the effects of reduced grassland management on SOC (ongoing, results by this/next year). Funded by the Norwegian Research Council: https://www.nibio.no/en/projects/carbon-storage-in-long-and-short-term-grasslands?locationfilter=true
83. The PLATON project comprises a large platform in which agriculture and land uses are key elements. NIBIO participates in this project and will provide expertise with the aim to establish a plan for SOC monitoring in Norway as well as working towards the implementation of biochar as part of the GHG Inventory Report of Norway submitted to UNFCC every year.: https://www.platonklima.no/landbruk

Poland

No information

Portugal

No information

Slovakia

84. Agricultural soil management with regard to its sustainability 2019-2021. Research project of the Ministry of Agriculture of Slovakia/2019-2021/Slovak: One of the important task of this project is modelling of SOC stock on another two agricultural farms. Project descriptions is not publically available
85. Scientific support of climate change adaptation in agriculture and mitigation of soil degradation (URANOS), Task A 3.2. Prediction of soil organic carbon stock in conditions of climate change. 1.4.2020 – 30.6.2023
86. Sustainable smart farming systems taking into account the future challenges (SMARTFARM), Activity 1: The optimalization of cultivation systems from the viewpoint of production and non-production functions of the soil.1.10.2020 – 31.3.2023

Slovenia

No information

Spain

No information

Sweden

87. Many ongoing projects granted by FORMAS (a Swedish Research council focusing on management of natural resources) are addressing questions that are relevant in this context: http://proj.formas.se/default.asp?funk=as
88. Several more applied projects are granted by SLF (database only in Swedish): http://www.lantbruksforskning.se/projektbanken/
89. Several project granted by VR (Swedish research council for all more basic sciences) is also granting project related to the subject: https://www.vr.se/english.html
90. Carbon sequestration potential in top- and subsoil – analyzing soil databases and long-term trials.: http://www.lantbruksforskning.se/projektbanken/kolfastlaggningspotential-i-matjorden-och-alven-an/?app_year=&pub_year=&page=1&category=&search=k%C3%A4tterer
91. Turnover of organic matter in agricultural soil throughout the year: http://proj.formas.se/detail.asp?arendeid=9272&x=250&y=20&sprak=1&redovisning=0
92. Effects of soil organic carbon fractions on soil structure and preferential solute transport: http://proj.formas.se/detail.asp?arendeid=9267&x=250&y=20&sprak=1&redovisning=0
93. Mistra Food Futures: https://www.mistra.org/nyhet/64-msek-till-forskning-om-hallbart-och-resilient-livsmedelssystem/
94. Project PEATWISE: https://www.eragas.eu/en/eragas/Research-projects/PEATWISE.htm
95. KLIMASMART: www.slu.se/torv
96. MAGGEpH: https://www.eragas.eu/en/eragas/Research-projects/MAGGE-pH.htm
97. Fullständiga växthusgasbudgetar för odlade mulljordar skapar underlag för klimatsmarta åtgärder: http://www.lantbruksforskning.se/projektbanken/fullstandiga-vaxthusgasbudgetar-for-odlade-mulljor/?search=torv&app_year=&category=&page=1&pub_year=

Switzerland

98. Ongoing project on biochar addition to soil and its effect on SOC. This is not a classical research project, but rather a monitoring of farmer's practices on five fields.
99. Ongoing modelling study on C-sequestration potentials in Swiss agricultural soils considering crop rotation, biochar, agroforestry. The whole country will be covered, level of spatial disintegration is not yet decided on. Results are expected not before 2021.
100. Experiment on soil coverage: An ongoing project studies the GHG balance of an intensively managed organic soil under grassland with and without coverage with mineral soil. Results are expected in 2022.
101. Planned experiment on paddy rice on organic soil: A controlled experiment with organic soil in a mesocosm unit is planned to test these practices on their effect of GHG budgets: soil coverage, biochar addition, paddy rice with different water management.

Turkey

102. Soil Organic Carbon Project., TÜBİTAK BİLGEM, 2017-2018. (With the production of TOC stock map, gap analysis, areas without soil organic carbon data were identified and these areas were prioritized. In addition, Carbon Focused Biogeographical Regions were created within the scope of the Project).
103. Effects of Soil Tillage Techniques on Carbon Involvement and Sustainability of Soils. 2010-2017. Ministry of Agriculture and Forestry, DG of Agricultural Research and Polices(TAGEM), Soil, Fertilizer And Water Resources Central Research Institute (In this project; As a alternative to traditional tillage applications in fallow-wheat and leguminous-wheat crop rotation, the effects of reduced and zero tillage applications on increasing and maintaining soil efficiency and organic matter potential, have been tried to be put forward).

104. Determination of Seasonal and Annual Carbon Dioxide Output Amounts of Şanlıurfa Harran Plain Soils. 2017-2019. Ministry of Agriculture (TAGEM, GAP Agricultural Research Institute). (In this project; Amount of soil respiration was determined on different irrigated corn and cotton fields with tillaged and non-tillaged applications).
105. Turkey: Mapping Soil Carbon Stocks. 2016. Encyclopaedia of Soil Science, Third Edition DOI: 10.1081/E-ESS3-120052900
106. National Geospatial Soil Fertility and Soil Organic Carbon Information System Project (UTF/TUR/057/TUR) 2012-2015. Ministry of Agriculture and Forestry, DG of Agricultural Research and Polices(TAGEM), Soil, Fertilizer And Water Resources Central Research Institute-FAOSEC.

UK

107. UK Greenhouse Gas Inventory, 1990 to 2018: Annual Report for submission under the Framework Convention on Climate Change. https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2004231028_ukghgi-90-18_Main_v02-00.pdf
108. NERC Project (NE/P019455/1): Soils Research to deliver Greenhouse Gas REmovals and Abatement Technologies (Soils-R-GGREAT) http://gotw.nerc.ac.uk/list_full.asp?pcode=NE%2FP019455%2F1
109. NERC Soil Security Programme (2015-2020) - a multi-million research investment to understand how soils resist, recover and ultimately adapt to land use and climate change. https://soilsecurity.org/
110. NERC Project (NE/S005137/1): 'LOCKED UP': The role of biotic and abiotic interactions in the stabilisation and persistence of soil organic carbon. http://gotw.nerc.ac.uk/list_full.asp?pcode=NE%2FS005137%2F1
111. The Soil Carbon project is an innovative project that aims to help farmers manage soils in a more sustainable and profitable way. https://farmcarbontoolkit.org.uk/soil-carbon-project

D List of experts and contacts Task T 2.4.3

No.	Participating **organisation**	Abbreviation	Country	Contact for T2 4.3
1	Institut National de la recherche Agronomique	INRAE	France	**Sophie Cornu** sophie.cornu@inrae.fr **Sylvain Pellerin** sylvain.pellerin@inrae.fr **Eloïse Mason** eloise.mason@inrae.fr
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3	BIOS Science Austria	BIOS	Austria	**Sophie Zechmeister** Sophie.zechmeister@boku.ac.at
4	Flanders Research Institute for Agriculture, Fisheries and Food	EV-ILVO	Belgium	**Maarten De Boever** maarten.deboever@ilvo.vlaanderen.be
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6	Czech University of Life Sciences	CULS	Czech Republic	**Lenka Pavlu** pavlu@af.czu.cz
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8	Estonian University of Life Sciences	EMU	Estonia	**Karin Kauer** karin.kauer@emu.ee
9	Natural Resources Institute Finland	LUKE	Finland	**Nils Kauer** nils.borchard@luke.fi **Markus Lier** markus.lier@luke.fi
10	Johann Heinrich von Thünen-Institut	Theunen	Germany	**Axel Don** axel.don@thuenen.de **Daria Seitz** : daria.seitz@thuenen.de
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14	Council for Agricultural Research and Economics	CREA	Italy	**Claudia Di Bene** claudia.dibene@crea.gov.it
15	University of Latvia	UL	Latvia	**Andis Lazdiņš** andis.lazdins@silava.lv. **Raimonds Kasparinskis** raimonds.kasparinskis@lu.lv

16	Lithuanian Research Centre for Agriculture and Forestry	LAMMC	Lithuania	**Dalia Feiziene** dalia.feiziene@lammc.lt **Kestutis Armolaitis** kestutis.armolaitis@lammc.lt
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18	Institute of Soil Science and Plant Cultivation – State Research Institute	IUNG	Poland	**Jacek Niedźwiecki:** jacnk@iung.pulawy.pl **Grzegorz Siebielec** gs@iung.pulawy.pl
19	National Institute for Agrarian and Veterinarian Research I. P.	INIAV	Portugal	**Corina Carranca** corina.carranca@iniav.pt **Raquel Mano** raquel.mano@iniav.pt
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25	Ministry of Agriculture and Forestry, General Directorate of Agricultural Research and Policies	TAGEM	Turkey	**Sevnic Madenoglu:** sevinc.madenoglu@tarimorman.gov.tr
26	Agri-Food and Biosciences Institute	AFBI	United	**Dario Fornara** dario.fornara@afbini.gov.uk

E Questionnaire for MS

Questionnaire Task 2.4.3

The **goal of T2.4.3.** is stocktaking and synthesis on available knowledge of **achievable carbon sequestration** in mineral soils, including pasture/grassland across Europe, under different farming systems, soil types and pedo-climatic conditions as well as on GHGs mitigation measures for managed organic soils under cropland or pasture/grassland.
The questionnaire below should give a framework for the kind of data and literature needed to response to the main objectives of the task. The information should include all kind of information, data, reports and literature on those subjects which are available **for each country** in any language. We kindly ask you to collect all the literature and data available and send it together with the completed questionnaire to Leonormaria.gondimrodrigues@agroscope.admin.ch and jens.leifeld@agroscope.admin.ch if possible before June.
Together with the data and questionnaire , please also deliver a summary in word format with a maximum of 3 pages excluding references, which include information on state-of-the-art knowledge on the achievable carbon sequestration in mineral soils in agricultural land, including pasture/grassland in your country, under different farming systems, soil types and pedo-climatic conditions as well as on GHGs mitigation measures for managed organic soils.

Also please indicate once again who is/are the appropriate contact persons and experts in your country (name, institution and contact details) for mineral soils and organic soils.

Achievable C-sequestration in MINERAL SOILS Here we are asking for the **achievable carbon sequestration under a specific land management,** and not for carbon stocks and soil carbon contents. C-sequestration as defined by Olson et al. (2014), “the process of transferring CO2 from the atmosphere into the soil of a land unit, through plants, plant residues and other organic solids which are stored or retained in the unit as part of the soil organic matter (humus) for a given time period.”	
MS country:	
EJP SOIL Partner:	
Experts and contact persons achievable C sequestration mineral soils:	
E-mail:	
Are there any quantitative estimations of the achievable carbon sequestration under different soil management in your country (finished or ongoing studies)?	
Yes	**No**
What is the form and accessibility of this information? (Published scientific or commercial literature, grey literature etc.)	Are there any studies planned for the future? Are there other studies comprising **carbon storage** potentials?
On which spatial scale did the studies operate? (Local, regional, national, environnemental zones)	

Is this information available for the whole country or which regions have been studied?	
Please describe briefly, which methods were used to estimate or calculate the achievable carbon sequestration?	
If possible, please indicate which soil types have been considered for each study.	
For which period and duration has the C-sequestration been quantified?	
Are there any estimated C sequestration rates for different management practices derived from field studies in your country (finished or ongoing studies)?	
Yes	**No**
What is the form and accessibility of this information? (Published scientific or commercial literature, grey literature etc.)	Are there any other experiments or scenarios to estimate the achievable C-sequestration under different soil management using other C sequestration rates (e.g. global meta- analysis) relevant for your country?
What measures are involved?	
What are the potentials of these measures (e.g. rate/increase per year)?	
Potential for reducing GHG emissions from managed ORGANIC SOILS	
MS country:	
EJP SOIL Partner:	
Expert and contact person reducing GHG emissions from managed organic soils:	
E-mail:	
Are there any quantitative estimates for reducing GHG emissions (CO2, CH4, N2O) from managed organic soils under different soil management in your country (finished or ongoing studies)?	
Yes	**No**
On which spatial scale did the studies operate? (Local, regional, national, environnemental zones) Is this information available for the whole country or which regions have been studied?	Are there other country-specific studies on mitigation of GHG emissions from managed organic soils in your country?
Please describe briefly, which methods were used to estimate or calculate the GHG mitigation potential for managed organic soils.	
For which period and duration has the mitigation potential being quantified?	
Are there any estimated GHG mitigation potentials for managed organic soils derived from field studies in your country?	

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Yes	**No**
What is the form and accessibility of this information? (Published scientific or commercial literature, grey literature etc.)	Are there any other experiments or scenarios to estimate the GHG mitigation potential for managed organic soils (e.g. global meta-analysis) relevant for your country?
What measures are involved?	
What are the potentials of these measures (e.g. rates per year)?	
Additional information	
What are the latest insights from your country over the last 5 years and which experiments and observations are running and results underway?	
Yes	**No**
Link to programmes and projects ongoing Do you have any project descriptions publically available?	
What are the most urgent knowledge gaps that you may have identified?	
Yes	**No**
Have these knowledge gaps been published and available to all?	