FACCE-MACSUR

The Availability of Carbon Sequestration Data in Europe

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Abstract/Executive summary

With growing interest in the carbon sequestration potential of soils, experimental research and mapping projects have produced a wealth of datasets in this subject area. However, the coverage, quality and scope of available data vary widely across Europe, and the extent to which these data are accessible to experimental researchers and modellers is also highly variable. This report describes the availability of soil carbon data at the global and European levels, and reviews the on-line resources for accessing these data and meta-data. The extent to which researchers in the field share findings, based on institutional links in projects and on-line resources, is investigated. Future priorities for research and data accessibility relating to carbon sequestration are discussed.

Many soil data resources are available online. Global and European soil data portals draw together much information from across Europe, and include the outcomes of major soil carbon mapping exercises. However, much project and national research is not accessible through these portals, and information on datasets derived from many research initiatives is difficult or impossible to locate online. Data on carbon sequestration (carbon fluxes in soils) specifically is more limited, although some such datasets are available through the general soil data resources described. Improved clarity in the presentation of research, and work to link more national and sub-national data to European and global online resources is required, with initiatives such as GSIF (Global Soil Information Facility) active in encouraging direct reporting of soil-related data at the global level. Priorities for research on SOC stocks include measuring carbon storage below the topsoil (>30cm), improving records of SOC in peatlands, improving the number and distribution of samples available for Europe-wide soil carbon mapping, and developing recognised methodological standards to allow easier comparisons of datasets. In the field of carbon sequestration research specifically, priorities include linking long-term SOC data to historical land use, developing understanding of the movement of SOC between top-soil and sub-soil and increasing dialogue between modellers and empirical researchers to improve dynamic modelling of SOC.

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1. Introduction

Globally, it has been estimated that 2344 Gt of carbon are stored in the soil (Stockmann et al. 2013), with around 5% of this total being found in the EU (Panagos et al. 2013a). With an estimated 8.7 Gt of carbon emitted by human activities each year (Denman et al. 2007; Lal 2008) a change of 10% in SOC would be equivalent to around 30 years of carbon emissions (Kirschbaum, 2000) making the storage of carbon in the soil, and fluxes in the amounts of carbon stored, important topics in relation to the mitigation of climate change and the prevention of emissions resulting from particular soil management choices. Because of the prevalence of peatlands in the north of Europe (UK, Sweden, Norway and Finland) estimates suggest that 50% of the SOC in the EU is stored in soils in these countries (Montanarella et al. 2006).

With growing interest in SOC, experimental research and mapping projects have produced a wealth of datasets in this subject area. It is important to distinguish two types of data related to SOC: 1) Data on carbon stocks (how much carbon is stored in the soil at a given time) and 2) Data on carbon fluxes (processes of carbon sequestration and carbon emissions from the soil). The difference is captured by a useful definition of carbon sequestration given by Stockmann et al. (2013):

> 'an increase in soil carbon for a defined period against a baseline condition where the increased carbon is sourced from atmospheric CO_2'

Data on carbon stocks can help us to understand the importance of SOC in relation to climate change, but data describing how (and why) these stocks vary is essential to understanding how we can conserve (and add to) the stock of sequestered carbon. Better data on carbon sequestration can drive the development of more accurate modelling of carbon cycles, and allow a better evaluation of different soil management practices in terms of carbon sequestration and emission. In wider terms, this will add to our understanding of the GHG footprint of different farming systems, and of how this footprint can be reduced. In particular, current research suggests that grasslands are important stores of SOC. This GHG emissions mitigation potential represents an important benefit of extensive livestock production systems, which might otherwise be considered relatively inefficient in terms of productivity (in terms of GHG emissions per unit of meat/milk) (Soussana et al. 2010). To aid the development of our understanding in this area, it is important that modelling teams have access to high quality datasets on both SOC stocks and carbon sequestration. Here, the availability of such data and strategies to improve data accessibility are discussed, gaps in our knowledge of carbon sequestration processes are identified and priorities for future research considered.

2. Methods

2.1. Review of on-line resources

Google searches were initiated using strings of keywords such as 'Carbon + sequestration', 'soil + carbon + European', 'EU + soil + database' etc. These searches identified both global and European soil data resources. In addition, searches were made of EU projects related to soil Carbon and Carbon sequestration in grasslands, using online project databases:

CORDIS database of FP projects: http://cordis.europa.eu/home_en.html
LIFE database: http://ec.europa.eu/environment/life/project/Projects/
COST Action database: http://www.cost.eu/domains_actions

For each project that has a website, the availability of online data resources was assessed. For relevant projects, project names were cross-checked in the global and European soil data portals, to ascertain if project-related research had been fed into accessible data resources. In addition, task partners at SRUC and TI (Johann Heinrich von Thünen Institute) were asked to provide information on further online resources that they were aware of. By exploring links from all relevant identified sites, a fairly comprehensive overview of European soil Carbon data resources could be assembled.

2.2. Network analysis of carbon sequestration projects

Network analysis was undertaken to gain a better picture of the extent to which project outputs were shared and accessible, and to understand the pattern of connections between institutes created through project partnerships. This information contributed to a discussion of potential improvements in the sharing of knowledge, and helped to identify potential institutional sources of data for researchers.

In order to visualise the links formed between institutes through partnerships in EU projects, a search of EU project databases (CORDIS (FP7), LIFE, COST – details as above) was undertaken, using the following keywords in turn to identify potentially relevant projects: 'carbon, 'sequestration', 'grassland'. Database returns were filtered manually to exclude projects unrelated to grassland carbon sequestration, specifically projects focussing on: industrial remediation, biofuels, soil additives (manure etc.) and crops. Projects with a wide focus that included grassland carbon sequestration as an element were included. The search revealed 30 relevant projects. It is recognised that the filters used could have excluded some projects of relevance to the subject of carbon sequestration in grasslands, but the method at least provided a focused, unbiased sample of projects.

The social network analysis programme UCINET (Borgatti et al. 2002) was used to convert a database of project details (title, funding programme, institutional partners, project lead institutes, countries involved, start and end dates of project) into maps indicating the connections between institutes (nodes) and projects (hubs). These maps showed the degree to which carbon sequestration projects connected different institutes through shared project partnerships. This level of connectivity was in turn considered likely to be indicative of information sharing between research groups in the involved institutes. Online data resources that brought together the outputs of different projects were over-laid onto the network map, to show how such resources created 'clusters' of projects for which data was shared at one location online. Finally, individual project websites were checked to identify links to downloadable data, lists of dataset metadata or other outputs (journal outputs etc.) to determine the extent to which project findings were accessible or visible to other researchers and modellers in the field.

2.3. Review of the state-of-the-art

Reports from SRUC, Scotland (Buckingham et al. 2013) and papers produced by partners at TI, Germany (Don et al. 2009; Poeplau et al. 2011; Poeplau and Don 2013) along with recent reviews in the literature and reports from EU projects were used to gain an overview of the state-of-the-art in carbon sequestration research, and this is reported here, along with a discussion of future research priorities.

3. Results

3.1. Review of on-line resources

On-line resources for soil data can be found at the global and regional (in this case European) scale, with these portals for data access linking down into national and project level datasets and mapping. The gathering of information at successive scales is incomplete, with the global ISRIC (International Soil Reference and Information Centre) portal (ISRIC 2014a) containing only a subset of the information available at European level, and European-wide resources only including a subset of national and project level data. Here, the resources available at the three levels (global, European level are described, while project-level resources are considered in Section 3.2 (Network Analysis of carbon sequestration projects). The initiatives identified in this review, which collate and disseminate data at different scales, are inter-related (Fig. 1) and are described in Table 1.

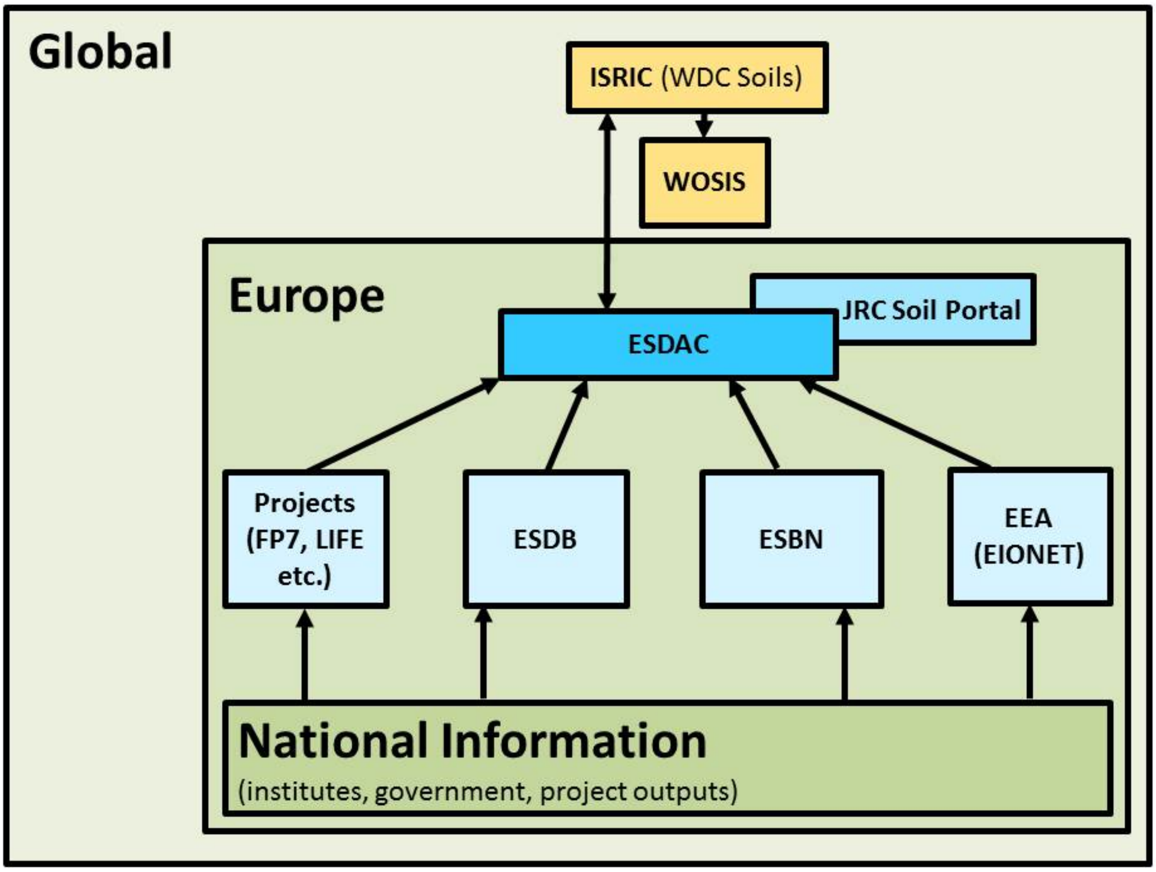

Fig. 1: Sources of information on SOC at different scales. See glossary (Appendix 1) for explanation of acronyms

3.1.1. Global Resources

ISRIC is the World Data Center (WDC) for soils and is based at Wageningen UR in The Netherlands. The ISRIC website (ISRIC 2014a) describes the role of ISRIC as the WDC for soils, including regular membership of the ICSU World Data System and involvement as a participating organisation in in the intergovernmental group on Earth Observations (GEO) which is producing a combined inventory of quality-assessed scientific datasets in a 'System of Systems' (GEOSS). The ISRIC website provides links to a number of meta-data and data sharing resources. These resources include WOSIS (ISRIC 2014b), the world soils database, the meta-data service 'Geonetwork' (ISRIC 2014c) which enables users to access WOSIS and other resources, and GSIF (ISRIC 2014d) which collects and collates data from researchers for inclusion in the global soils database. These resources are described in more detail below. Website links can be found in Table 1.

- WOSIS (ISRIC 2014b) is the world soils database and aims to make available valid, authorised databases, projects, papers and maps. This single central database (a virtual database made up of other component databases) will include all the information associated with ISRIC and, according to the ISRIC website, is presented so as to allow easy access and visualisation through a single set of tools
- The ISRIC meta-data service uses a Geonetwork catalogue application to enable users to search for and retrieve meta-data records from: i) any dataset published by ISRIC, ii) maps and reports published by ISRIC, iii) harvested external data providers including FAO and CGIAR. These datasets include meta-data relating to carbon sequestration, with an online search in June 2014 returning 41 hits for meta-data using the search term 'carbon sequestration'.
- GSIF (ISRIC 2014d) has the aim of collating and saving historical soil data including maps, using a crowd-sourcing 'Wikipedia' style approach in which researchers can contribute to the global soil database. GSIF also includes a number of services relating to mapping data and visualisation resources, applications to access GSIF data from mobile devices and a manual for those using GSIF resources, links to which can be found via the GSIF website

3.1.2. European resources

ESDAC (European Soil Data Centre) (the thematic centre for soil-related data hosted at the Joint Research Centre) and the closely related European Soil Portal gather and present meta-data from a range of sources within Europe (Fig. 1). Although the respective websites suggest that the ESDAC and European Soil Portal databases contain the same information, the current review found some meta-data and links in one resource and not the other. As a result, the two are treated separately in Table 1 and shown as overlapping but not identical in Fig. 1.
The information sources for ESDAC/European Soil Portal can be considered in turn:

- The ESBN (European Soil Bureau Network) represents strategic institutes for soil research across Europe, and is used to bring together national information at the European level, and as a resource for specific soil-related initiatives (some of these are described in in the review of the state-of-the-art in carbon sequestration research below).
- The EEA (European Environment Agency) uses the EIONET (European Environment Information and Observation Network), a network of institutes and experts from around Europe, to collect and organise environmental data, and to disseminate information. The EIONET is made up of national environmental agencies and other active organisations in the field and has also been used for the collection of soil data in some recent Europe-wide mapping initiatives (see the review of the state-of-the-art in carbon sequestration data below)
- ESDAC and the JRC soil portal include data and meta-data from national and international (EU funded) projects, however this coverage is by no means comprehensive, and many projects do not have clear links to the two European level resources (ESDAC and European portal websites were searched using project names to identify related datasets – this method does not preclude the possibility that some data from these projects are included but not identified explicitly with them). Of the 17 relevant FP7 projects identified during network analysis (see below), information from only two (SoilTrEC and eSOTER) could be found from searches of the ESDAC/European Soil Portal websites. The Max Planck Institute for Biogeochemistry hosts an online resource giving access to data from two more FP7 projects (CARBO-Extreme and GEOCARBON) and includes access to its own soil data resources (Table 1). The Carbon Portal (Table 1) provides access to data from the ICOS (Integrated Carbon Observation System) project, which collects information on Carbon at a global level and beyond the scope of this investigation. Finally, the

eSOTER project contributes to ISRIC (World Soil Information) but no links were found to the European level resources of ESDAC/European Soil Portal.

- ESDB contains data on soil related parameters from across Europe based on vector data. Data can be accessed free (with registration for the 1km x 1km data). ESDB data underlies most other Europe-wide information and services (EC, 2013).

Table 1: Sources of soil data and meta-data, including weblinks and short descriptions. Acronym meanings can be found in the glossary or with first mention of the resource in the text. ID numbers (column 1) are used to identify linked resources in column 3. Levels refer to the scope of the resource, from global to inter-project (resources pooling meta-data from two or more research projects). Individual project resources are not listed here.

ID	Acronym	Nested within	URL	Level	Short description
1	ISRIC		http://www.isric.org/content/data ISRIC	Global	International Council for Science (ICSU) accredited World Data Centre for Soils (WDC-Soils), maintains World Soil Museum
2	WOSIS	1	http://www.isric.org/data/wosis	Global	World soils database, providing access to all ISRIC and ISRIC-related soil databases
3	GeoNetwork	1	http://meta2.isric.org/geonetwork/srv/en/main.home	Global	Meta-data service providing access to WOSIS resources
4	GSIF	1	http://www.isric.org/projects/global-soil-information-facilities-gsif	Global	framework for production of open soil data, aimed at collating historical and new soil data, including through 5 & 6 below. Uses crowd-sourcing of information from researchers
5	World Soil Profiles	1,4	http://worldsoilprofiles.org/en-us/	Global	Project to create a single, comprehensive, accessible compilation of global soil info, in a web-based soil profile database
6	SoilGrids	1,4	http://soilgrids1km.isric.org	Global	Updatable soil property and class maps of the world
7*	ESDAC	1	http://esdac.jrc.ec.europa.eu/esdac_about.jsp	European	European Soil Data Centre, providing searchable access to a range of soil-related data and meta-data from Europe
8*	JRC Soil Portal	1	http://eusoils.jrc.ec.europa.eu/	European (& Global SOC data)	Part of ESDAC and also providing access to a range of soil-related data and meta-data from Europe. Overlaps with ESDAC resource, but not completely at time of writing
9	ESDB	7,8	http://eusoils.jrc.ec.europa.eu/esdb_archive/ESDB/Index.htm	European	data on soil-related parameters from across Europe based on grids of 1km x 1km and 10km x 10km, free access
10	Max Planck		http://www.bgc-jena.mpg.de/geodb/projects/Home.php	Inter-project	Common data portal for data from the FP7 projects CARBO-Extreme, GEOCARBON and from the Max Planck Institute for Biogeochemistry (hosted by the Max Planck Institute)
11	Carbon Portal		http://www.icos-infrastructure.eu/node/16	Global	Provides access to data gathered from the ICOS (Integrated Carbon Observation System) station network, and 'value added' data derived from these data. This initiative is concerned with carbon fluxes in general, not just SOC and soil C sequestration

*Sources 7 and 8 are not nested, but overlapping resources

3.2. Network analysis of carbon sequestration projects

Network analysis of projects and an examination of individual project websites demonstrated visually how shared project membership in carbon sequestration-related projects links different institutes (Fig. 2). The single COST Action in the sample (Carbon Storage in European Grasslands) connected a large number of partners, and these partners in turn were well connected to other identified projects. However, despite the high relevance of the action to the current investigation (indicated by the project name) no website was found online, no datasets or reports were discovered and there were no links to project outputs through ESDAC or other online data resources.

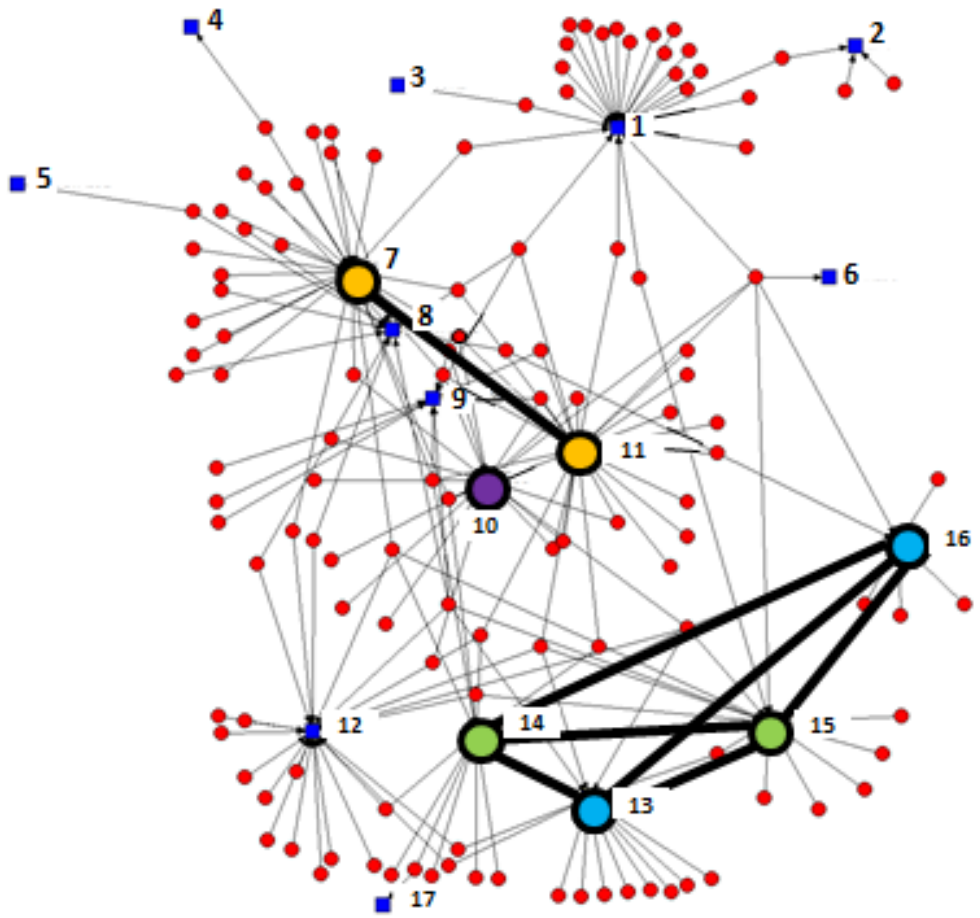

Fig. 2: Network of European carbon sequestration-related projects (blue squares) showing links between institutes (red dots) formed by shared project membership (narrow lines) and overlaid by connections made by shared web resources (broad lines with coloured circles: Green = ESDAC, Blue = Soil Tech, Orange = Max Planck, purple = Carbon portal). Projects with no institutional links to the main network are not included in the figure. Numbers represent project names: (1 = COST Carbon storage in European Grasslands, 2 = LIFE RegaDIOX, 3 = CSECURE, 7 = GEOCARBON, 8 = SMART SOIL, 9 = CARBONES, 10 = ICOS, 11 = CARBO EXTREME, 12 = RECARE, 13 = ISOIL, 14 = SoilTrEC, 15 = E-SOTER (this project also contributes to ISRIC and the Global Soil Observing System), 16 = DIGISOIL, 17 = SLAVONIC).

The sample included 12 'LIFE' projects, which were classed as discrete (having varying numbers of partners with no / few links to other projects). This pattern is explained by the regional focus of this funding stream, which links geographically close partners in order to address local challenges or issues. Because only two of the projects (SOILCONS-WEB and Carbon Dairy) were linked via shared institutional partners, with two more linked to one other project from a different funding stream (LIFE Regadiox and LIFE NaturEtrade) there may be a potential for a duplication of work between LIFE projects, and for variation in methodological approaches which could reduce the comparability of data outputs.

The Soil Technology Research Centre (http://www.ufz.de/soiltechnologyresearch/) connects a further two projects (ISOIL and DIGISOIL) to a wider cluster of institutes and projects beyond the scope of the current investigation (relating to soil rehabilitation and the characterisation of contaminated soils), although the site does not include links to meta-data.

Of the 17 FP7 projects identified, only 12 have reports online (via website or EU website links) and only ten were found to have project websites. Only five of the projects had websites including access to dataset meta-data or links to downloadable data, and seven had links to data resources at the supra-project level (GeoNetwork etc.). Four projects had links to the ESDAC.

3.3. Review of state-of-the-art

3.3.1. Initiatives for mapping SOC at the European scale

Recent research has provided a number of estimates of soil carbon content for Europe, using sample data and modelling to produce maps of carbon levels across the continent. Data and information on those covered below is available through ESDAC (see Table 1). This section provides a brief summary of three major European initiatives to estimate soil carbon, and uses information from key reports and papers stemming from these initiatives to draw conclusions about future research priorities in this field.

Jones et al. (2005) report on the OCTOP modelling exercise, which estimated the carbon contents of top-soils in Europe based on pedo-transfer rules for converting information from the ESDB, taking into account expected impacts of vegetation type and land use as well as temperature on organic carbon levels. The method was believed to provide a more accurate estimate of organic carbon than previous surveys which used point data on the carbon content of different soil types to produce estimates of regional carbon content based on the coverage of those soil types on soil maps. The survey only considered soil to 30cm depth. Uncertainty was identified stemming from a number of sources, including geographic variation in organic carbon content resulting from previous land use, differences in the timing of sampling and in soil drainage, differences between actual land use and land use defined by the land cover dataset used, limitations related to the pedo-transfer rule utilised, and accuracy of the underlying data, specifically in the representation of highly organic soils. The authors recommended that findings should be validated using actual data on organic carbon content from across land use types.

Subsequent to OCTOP modelling, an EIONET survey (Tóth et al. 2013) was carried out by ESDAC in 2009 with the aim of estimating carbon stocks in the EU, as well as to collect information on soil erosion. The survey requested data from all EU countries, however there was no fixed methodology – data provided were the official national estimates of SOC from each country, some of which were based on modelling. In the end only six countries provided data that were useable and only in Italy did the EIONET survey estimates match those from OCTOP (OCTOP was validated for Italy and the UK). In some cases recorded carbon stocks were up to 50 % less than those predicted by OCTOP. This may be a result of the fact that some ESDB data (on which OCTOP modelling was based) are old and do not capture subsequent declines in carbon stocks resulting from agricultural changes. Again, the EIONET survey related only to soil depths of up to 30cm.

The Land Use/Land Cover Area Frame Survey (LUCAS) was also undertaken in 2009 (Panagos et al. 2013a) and Tóth et al. (2013) reported on the findings. The survey was based on almost 20.000 topsoil samples which were collected according to a standard method, with samples taken from the topsoil to 20 cm. Subsoil (depth > 20cm) organic carbon was not taken into account, there were limitations in the design of sampling (similar sampling density in different countries despite differences in soil heterogeneity), and a relatively small number of sample points were used considering the geographic area covered. The latter points relate to the fact that LUCAS was designed as a soil monitoring rather than a soil mapping exercise. Some bias resulting from oversampling of some land use types (e.g. arable) was also recognised. However, Tóth et al. (2013) emphasize the potential of LUCAS sampling to validate modelling and to form a methodological template for future surveying, utilising a larger number of samples and an improved sampling design.

Europe-wide mapping and modelling of soil carbon through OCTOP, EIONET and LUCAS demonstrate that techniques for estimating soil carbon content are developing, with LUCAS representing the first study to use harmonised sampling standards across the EU for all land cover types. OCTOP estimates were based on datasets from as far back as the 1960s, while the EIONET study suffered from a lack of consistency in data provision from different countries. In order to build on LUCAS, the need for more and better designed sampling (especially for under-represented land use and soil types), using methodologies standardised across Europe, has been recognised. This will be required to update and fill gaps in the ESDB. The next section will consider gaps in knowledge relating to carbon sequestration research, including issues relating to soil depth (also mentioned above) and land management.

3.3.2. Review of the state-of-the-art in carbon sequestration research

Although the sections above show that much data and modelling has been focused on carbon stocks in soil, gaps in knowledge remain in terms of fluxes in soil carbon levels and how these are affected by environmental conditions including management (Köchy et al. 2014). Research has shown that land use change can result in the rapid depletion of SOC, while in contrast subsequent recoveries in SOC levels may be slow, with timescales of more than a century required to regain an equilibrium level (Poeplau et al. 2011).

When studying fluxes in SOC it is important to consider not only the topsoil, but also the subsoil (depths of > 30cm) if an accurate description of SOC is to be obtained (Don et al. 2009). While carbon in the topsoil may accumulate relatively quickly after changes in management from crop to grassland (due to increased biomass), subsoil changes seem to be much slower (Don et al. 2009). However, the more slowly changing subsoil may act as a sustainable carbon sink under favourable management conditions (Poeplau and Don 2013).

In 2013 a team of UK researchers reviewed the literature relating to the impacts of land management on soil carbon in crop and grasslands in the UK (Buckingham et al. 2013). The conclusions were that options for increasing SOC in the UK were limited, with the wider application of manure to low SOC arable land the most promising option, despite logistical barriers. In grasslands increased species diversity (including deep rooting species) appears to increase SOC in low productivity grasslands, and manure application can also be effective for increased carbon sequestration in these environments. In contrast, where nutrient resources are not limiting to plant growth, extensive management (without liming) may prevent loss of SOC from organic soils, while high grazing intensities can reduce carbon sequestration by reducing plant productivity and through the introduction of urine (which mobilises soil organic matter). These findings indicate that the impacts of management on SOC are likely to vary according to pre-existing soil type and nutrient conditions. Not enough evidence was available to indicate that zero tillage cropping systems were effective in increasing SOC, as positive impacts on carbon accumulation through improved soil structure and increased mycorrhizal activity could be offset by decreases in productivity (and therefore a decrease in carbon accumulation) caused by compaction and weed proliferation, and by the switch from permanent to temporary vegetation cover. The report emphasized that its findings were limited by the small number of studies addressing land management and its impact on SOC levels and fluxes, especially over the long term, and that this represented an important priority for further research (Buckingham et al. 2013).

Based on the Soil Carbon Summit held in Australia in 2011, Stockmann et al. (2013) reviewed the most important issues that require tackling if more carbon is to be sequestered in the soil. Consistent with the work considered above, the issues identified by the authors were: improved soil carbon measurement techniques, work to better understand how the soil system functions, the optimization of soil sampling strategies, investigation of the role of soil erosion in either increasing or burying SOC, research into both long- and short-term carbon sequestration and the practical implications of these processes for management. They also emphasized the importance of improved dialogue between experimental researchers and modellers, in order to better characterise soil carbon-related processes in the soil, to model SOC at the landscape scale (taking into account redistribution of SOC within landscapes) and to model changes in SOC across the whole soil profile. A more recent meeting on Soil Carbon Sequestration held Reykjavik in 2013 provided further insights, with presentations and proceedings published online (http://scs2013.land.is/?page_id=1341).

4. Discussion

This report has attempted to give an overview of the online availability of soil carbon data, and more specifically, of data on carbon sequestration. A network analysis of project and institutional interconnectedness, a survey of project websites and a review of online resources related to soil were used to achieve this aim, and in addition a brief literature review was conducted to highlight gaps in knowledge and priorities for future research. These approaches have produced insights in two related areas: 1) The limits to and gaps in online data resources relating to soil and carbon sequestration, 2) Gaps and limitations in the research underlying available resources in this field.

At the global level, an impressive array of online resources are being developed by ISRIC to collect, collate and present as open access a wide range of soil-related data and meta-data, including reports, papers and mapping. Innovative resources for users (such as applications for mobile devices) are being provided, and researchers are appealed to directly for data and meta-data, alongside the collation of project and institutional data and information.

In practical terms, the ISRIC websites can be confusing to navigate, with a plethora of acronyms and nested initiatives making it difficult to understand the relationships between and the nature of different resources. A simple overview, in the form of a visual schematic, including the relationship of ISRIC to other global groupings such as ICSU (perhaps similar in style to Fig. 1 in this report) would greatly facilitate user understanding of ISRIC resources, and may increase awareness and use of these valuable services. The same criticism about presentation can be made in relation to the European-level ESDAC online resources, especially in the apparently incomplete overlap between ESDAC and the JRC Soil Portal resources. Again, these issues of presentation may hamper or prevent users identifying relevant information, despite the availability of a wide range of valuable information.

Beyond the issues of presentation discussed above, both European and global soil resources face a challenge in incorporating and making available data and meta-data from national and sub-national projects and research. Often projects were found to have no, or limited online resources, and few project-related data or information could be found via ESDAC or the JRC Soil portal when searching by project name. This finding does not mean that project information is not shared or used, but if this occurs, it is apparently in an *ad hoc* fashion, without a clear online footprint for interested researchers to identify. The sharing and collation of meta-data, data and other project outputs is a major challenge when a myriad of funding streams, projects and initiatives at national, regional and global levels constantly produce outputs presented in different forms and through different outlets. In this respect, efficiently linking experimental researchers producing data to those who can utilise these data (including modellers) should be a priority. These issues are beginning to be addressed, for example in the inclusion of provision of open access to project outputs as a condition of Horizon 2020 funding (EU 2014). Networks of researchers such as MACSUR, in bringing together a range of experimental researchers and modellers in one consortium, may offer opportunities to discuss and explore methods for achieving more effective sharing of experimental research outputs, increasing the effectiveness with which advances in knowledge can be converted to beneficial on-the-ground changes (for example in land management for improved carbon sequestration).

The advantages of improved information sharing include:

- increasing the awareness of researchers about other groups working in their field
- a reduction in the duplication of research efforts and increased opportunities for identifying potential collaborations as a result of this better awareness
- an opportunity for modellers to identify datasets of relevance to their work (and to accurately assess gaps in data provision)
- increased opportunities for meta-analysis and comprehensive reviews of the state-of-the-art

Havemann et al. (2009) also point out that

> 'Improved coordination and sharing of methods would support developing countries in particular to adopt better management of terrestrial carbon at the national level'

The existence of diverse forms of funded project within the EU and within individual nations, facilitates and maintains creative and novel research approaches, and allows specific project structures to be matched to specific local and sectorial research problems. However, such diversity can lead to a duplication of efforts, continued re-invention of the wheel in terms of methods and findings, and a lack of comparability between studies. This can stymy attempts to scale up results to the regional and global scales required to inform effective policy decisions. By sharing information on outputs through common data portals (in addition to their presentation, description and discussion in journal papers) many of these drawbacks can be overcome, reducing problems such as the under-reporting of negative results (Dwan et al. 2008) that accompany a reliance on peer-reviewed journals to share findings.

The review of literature on soil carbon sequestration highlighted the importance of further research into the impacts of land management practices and changes on soil carbon sequestration, particularly in the long term and considering soil depths of >30cm in addition to topsoil changes. In terms of soil carbon stocks, harmonising and mapping at the European scale requires more and standardised sampling across Europe, including in relation to peatland soils which are known to store large amounts of carbon. Again, the importance of collecting data for the subsoil as well as the topsoil is emphasized. This work can allow an updated ESDB to provide a valuable resource for improved modelling of European soil carbon stocks.

5. Conclusion

This report has highlighted a number of sources of soil-related information, and provided an overview of the state-of-the-art in soil carbon sequestration research and the mapping of soil carbon content. At the global level, ISRIC provides a range of valuable resources relating to soil, including meta-data relating to carbon sequestration, while ESDAC/JRC Soil Portal provide similar resources at the European level.

ISRIC and ESDAC resources can be complicated to identify and access due to the number of acronyms and initiatives presented, and improving clarity is an important challenge that needs to be met if the full value of scientific data is to be realised and communicated.

The outcomes of national and sub-national research related to both soil carbon stocks and carbon sequestration are not consistently shared online, and the quality and level of access to findings varies from comprehensive to completely absent. Informal communication and data-sharing not picked up by the methods employed by this report will of course occur, but the findings presented show the need for more comprehensive systems for the sharing of meta-data.

A number of priorities for research in carbon sequestration and soil carbon storage have been identified in the literature. Specifically, more studies looking below the topsoil at carbon stores and changes in carbon levels are needed, and research to better understand the links between fluxes in carbon and changes in land management (especially in the long term) should also be a priority.

By bringing together experimental researchers and modellers from across Europe, the MACSUR knowledge hub offers the opportunity to explore ways to share research outputs more effectively between scientists, in order to develop new collaborations and raise the awareness and impact of scientific research. Carbon sequestration in grasslands represents an important component of the net global warming impact of livestock agriculture, and understanding how management changes can affect soil carbon levels and accumulation is essential to making the most effective use of this characteristic of grassland-based production systems. Interactions with other modelling groups and with experimental researchers are vital in helping modellers to improve the way that their models characterise these processes, and the MACSUR knowledge hub can provide an arena in which such interactions can be encouraged and developed.

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Appendix 1: Glossary of acronyms

CGIAR	a global partnership that unites organizations engaged in research for a food secure future (term CGIAR is now a name and does not 'stand for' anything)
COST	European Cooperation in Science and Technology
EEA	European Environment Agency
EIONET	European Environment and Observation Network for Soil
ESBN	European Soil Bureau Network
ESDAC	European Soil Data Centre
ESDB	European Soil Database
FAO	Food and Agriculture Organisation of the United Nations
FP7	EC Seventh Funding Programme
GEO	Earth Observations
GEOSS	GEO System of Systems
GSIF	Global Soil Information Facility
ICSU	International Council for Science
ISRIC	International Soil Reference and Information Centre
JRC	Joint Research Council
LIFE	EU funding instrument for the environment and climate action
LUCAS	Land Use/Cover Statistical Area Frame Survey
MACSUR	Modelling European Agriculture with Climate Change for Food Security
NUTS2	Nomenclature of Units for Territorial Statistics (levels are determined by population; level 2 are areas with populations between 800000—3000000)
OCTOP	European Topsoil Organic Carbon content
SOC	Soil Organic Carbon
WDC Soils	World Data Centre for Soils
WOSIS	World Soil Information Service