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# FOREWORD

The EC funded project CIRCASA[1] (Horizon 2020) has 22 partners from 15 countries in the five continents. It started in 2017 for a duration of three years with the aim of developing international synergies concerning research and knowledge transfer on agricultural soil C sequestration at European Union (EU) and global levels with active engagement of all relevant stakeholders.

The CIRCASA Strategic Research Agenda (SRA) on soil carbon sequestration in agricultural soils is **grounded both on scientific evidence showing research and innovation needs and on the demands expressed by stakeholders** in 10 world regions. The ultimate goal of the SRA is to inform widely relevant priority goals and measures that align with broader European and international research in the area of SOC and to allow partners to jointly promote the generation of new relevant knowledge.

By engaging with multiple stakeholders at a strategic level[2], the CIRCASA SRA offers a unified field for research on soil carbon sequestration in agriculture showing the knowledge gaps that need to be filled given top priorities for end user's needs, aligning research on SOC sequestration in agriculture inside and outside of the EU research landscape.

The SRA underlines the need to develop an international research consortium (IRC) on soil organic carbon in agriculture and the **large benefits of international research cooperation in this field for stakeholders both in the EU and in other world regions.** Research and Innovation activities in this field need to be highly interdisciplinary and to be guided by stakeholder's demands. This **requires a dedicated tool to carry ambitious international R&I programs.**

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[1] www.circasa-project.eu

[2] This Strategic Research Agenda has received feedbacks from CIRCASA partners, members of the 4p1000 Initiative Scientific and Technical Committee, the Intergovernmental Technical Panel of Soils (ITPS) of the Global Soil Partnership (GSP) and its RECSOIL project, and the Integrative Research group of the Global Research Alliance on Agricultural Greenhouse Gases (GRA) as well as from relevant European Commission Services.

# INTRODUCTION

Healthy soils store large quantities of carbon (C) in the form of soil organic carbon (SOC). Through stabilization mechanisms in soil organic matter (SOM), the SOC contained therein can remain stored in the soil for thousands of years. Soils constitute the largest terrestrial carbon pool: an estimated total of 2,344 Gt C, more than the sum of carbon contained in the atmosphere and vegetation[3]. Soils perform crucial functions in the global carbon balance and recognition of the importance of soils and their sustainable management for addressing climate change adaptation and mitigation is increasing. A recent assessment by IPCC and discussions in the climate negotiations[4] particularly highlighted the positive role of soils for climate change adaptation and mitigation, agriculture and food security. There exists substantial scientific and practical evidence of how sustainable soil management (SSM) can provide multiple benefits for the environment, people and livelihoods. SSM preserves and increases SOM, a key element of soil health, which regulates many soil functions, including carbon storage in the form of SOC. In this way, SSM supports the retention and enhancement of carbon stocks in soils and thus climate change mitigation, while generating benefits for agriculture, food security and nutrition, provision of ecosystem services, climate change adaptation, and advancing multiple Sustainable Development Goals (SDGs). Investing in SSM constitutes a cost-effective and feasible climate change mitigation option, which, at the same time, enhances soil health and climate resilience. 128 countries include the Agriculture, Forestry and Land Use sector in their pledges for the Paris Agreement. Limiting warming to 1.5°C will require the use of 'negative emissions technologies' – methods that remove $CO_2$ from the atmosphere such as soil organic carbon sequestration[5].

There is vast scientific evidence that affirm that maintaining current SOC stocks where they are high and fostering SOC sequestration, where potential exists, could greatly contribute to mitigating the impacts of climate change. Up to 1.4 Gt C could be stored annually in agricultural soils (after IPCC, 2007, 2014). About 20% of the mitigation from SOC sequestration is achieved at negative cost and 80% below US$100/t$CO_2$eq making SOC sequestration a low-cost mitigation option. It requires conserving carbon stocks, storing carbon in agricultural landscapes also in biomass through agroforestry, reducing SOC loss through e.g. drainage of peatlands and wetlands and better recycling organic carbon through improved circularity and lifecycle of urban and agri-food industries organic wastes, thereby contributing to the bioeconomy.

SOC conservation and sequestration also have multiple co-benefits for food security, climate change adaptation, land degradation neutrality (an objective agreed by the UNCCD), desertification, biodiversity and water resources as shown by the IPCC Special Report on Climate Change and Land[6], highlighting that increased SOC content is one of the most cost effective options for climate change adaptation and mitigation, and to combat desertification, land degradation and food insecurity. Further, SOC content is a target (15.3) of the life on land Sustainable Development Goal 15. Both for UNCCD and for UNFCCC, countries are requested to report on SOC status. However, only a few countries have the capabilities and methods to monitor agricultural soil carbon with country specific methods; so, more capacity building activities in developing and least developed countries are required. Moreover, less attention has been paid on soil inorganic carbon the dominant form of carbon in drylands.

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[3] U. Stockmann, et al. 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ., 164, pp. 80-99.

[4] IPCC (2019). Special report on Climate Change and Land; Koronivia Joint Work on Agriculture (KJWA)

[5] Soussana, J. F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Torquebiau, E., Ciais, P., ... & Lal, R. (2019). Matching policy and science: Rationale for the '4 per 1000-soils for food security and climate' initiative. Soil & Tillage Research, 188, 3-15.

[6] IPCC, 2019

# INTEREST ON AGRICULTURAL SOIL CARBON BOTH AT GLOBAL AND EU SCALES

Momentum for action on soil organic carbon is growing in political, financial and technical circles to address multiple sustainability goals. Political headway at the global level is growing through avenues such as the 4 per 1000 Initiative, the UNFCCC Koronivia joint work on agriculture that explicitly provides for the inclusion of soil carbon, and the central role of soils in the UN Sustainable Development Goals target 15.3 on land degradation neutrality, which links to the UNCCD. Technical momentum includes substantial work on mapping soil organic carbon, sharing information and developing cost-effective measurement systems[7].

Achieving sustainable soil management in the EU will be crucial for several of the planned actions within the European Green Deal (EGD). The mission “Caring for Soil is Caring for Life” proposed by the Soil Health and Food Mission Board[8] has the goal to ensure that 75% of soils are healthy by 2030 and are able to provide essential ecosystem services. Target 2.1 of this Mission states that “current carbon concentration losses on cultivated land (0.5% per year) are reversed to an increase by 0.1-0.4% per year” and plans commitments to achieve land degradation neutrality in the EU by 2030. In terms of policies, the mission will be a tool for achieving the objectives of the UN Sustainable Development Goals (SDGs) and the EU Green Deal. Soils are therefore expected to play an important role in the future agricultural policy (CAP, Farm to Fork strategy), environmental protection (Biodiversity strategy) and climate change (Climate Law). These EU policies will need an efficient monitoring, reporting and verification framework (MRV) allowing for the quantitative assessment of soil properties relevant to agriculture, biodiversity and climate change. Especially relevant will be the establishment of an efficient MRV system of SOC stocks in agricultural soils.

# STRATEGIC RESEARCH AGENDA ON SOIL ORGANIC CARBON

## Stakeholder approach

While there is considerable private and public interest in soil carbon and health, adoption of soil enhancing agricultural practices appears to be slow. Farmers[9] from several world regions see the main barriers to adoption as socio-economics (e.g. additional costs are too high; lack of funds to access technology or machinery; farm extension services do not have knowledge and capacity). Overcoming these barriers requires a strengthened knowledge base and advisory services, improved awareness in the public, increased availability of indicators and tools, as well as financial support for agricultural transition and payments for soil carbon and other ecosystem services. Although barriers may vary with national circumstances, stakeholders and farmers from different world regions have similar views on the major barriers preventing an increased adoption of soil carbon sequestration and soil health enhancing practices

This Strategic Research Agenda (SRA) is derived from a multi-stakeholder, multinational, interdisciplinary approach that covers a range of interested parties and the variety of relevant institutions funding research. It has been co-designed through interactions with project partners, a

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[7] Vermeulen, S., Bossio, D., Lehmann, J. *et al.* A global agenda for collective action on soil carbon. *Nat Sustain* **2,** 2–4 (2019). https://doi.org/10.1038/s41893-018-0212-z

[8] Mission Board’s proposal to the European Commission for a mission in the area of Soil health and food
Report number: KI-02-20-673-EN-N

[9] International online survey in 7 languages organized by CIRCASA, with views from more than 1,500 farmers from 10 world regions.

Stakeholder Advisory Board and a Research Policy Committee. There are two CIRCASA deliverables supporting the creation of this international Strategic Research Agenda for SOC, a central envisioned outcome of the CIRCASA project:

### 1. Synthesis report on knowledge demands and needs of stakeholders[10]:

To date, a systematic review of constraints and barriers to adoption of SOC management options is lacking. To tackle this gap, the CIRCASA project carried out a stakeholder dialogue on challenges, opportunities, and knowledge needs related to SOC management. This dialogue involved 11 workshops worldwide (235 participants), exchanges with a stakeholder advisory board, a global survey targeting farmers and other stakeholders including researchers, government authorities, farm advisors, policy makers and members of NGOs, associations and industry (1369 usable answers) and a survey with Danish farmers (1807 usable responses, representative of Danish farming structure). Analysis carried out in the CIRCASA project showed that stakeholders perceive a lack of knowledge around SOC management as a key barrier to scaling up beneficial practices and that improved knowledge creation and exchange is seen as a central solution to further the uptake of SOC management. In this report, knowledge gaps identified by stakeholders are examined. In this way, the findings support the creation of an international strategic research agenda for SOC. The most frequently mentioned knowledge gaps relate to farm-level management practices, their effects, economic costs and benefits, as well as questions on policy mechanisms, the enabling environment, and monitoring, reporting and verification for SOC.

### 2. The science base of a strategic research agenda[11]:

In this report CIRCASA identified knowledge gaps, trans-disciplinary frontiers, novel technologies and knowledge synthesis needs to draft the science base of the SRA on agricultural SOC sequestration by showing priorities for research alignment and for enhanced international research cooperation, by building upon priorities expressed by the scientific community. The main challenges to maintaining and enhancing agricultural soil carbon stocks were identified from a literature review and evaluated through a questionnaire to researchers around 14 challenge topics with the aim to prioritise these for a future research agenda. To address those intellectual, logistical, and technical challenges to implementing the best land management practices for soil carbon sequestration in agriculture, testable hypotheses are presented. These hypotheses and innovative solutions span both the physical scales and disciplines of the challenges considered in the questionnaire.

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[10] CIRCASA, 2020. DeliverableD2.3: “Synthesis report on knowledge demands and needs of stakeholders”" https://doi.org/10.15454/Q0XVVD

[11] CIRCASA, 2019. Deliverable D1.3: “The science base of a strategic research agenda - Executive Summary”. https://doi.org/10.15454/YUFPFD

## Research Challenges

The number of scientific publications on soil organic matter and soil carbon is growing exponentially with increasing emphasis placed on climate change issues[12]. Researchers[13] based around the world see three main themes in this field:

- understanding soil processes,
- managing and monitoring soil,
- farm management and socio-economic dimensions.

Based on a literature review, 14 research challenges were identified (Figure 1), each covering several spatial scales (from soil aggregate to global) and contributing to at least one testable research hypothesis. These hypotheses are shown below

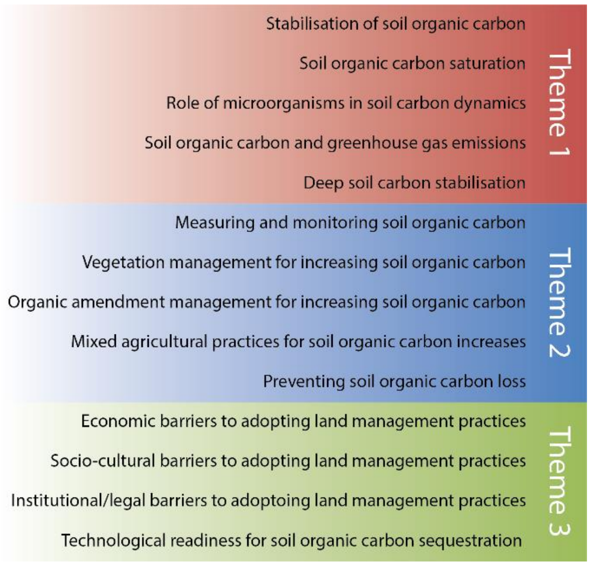

Figure 1. Research challenges identified from literature and through a survey completed by more than 200 scientists internationally. Each challenge contributes to at least one testable research hypothesis.

All challenges are relevant for science and for societal impacts. Challenges under Theme 2 (managing and monitoring soil) correspond best to knowledge asked by farmers and other land managers, while challenges under Theme 3 (socio-economics and adoption) correspond more to demands in the domains of policy-makers, farmers and industries.

## Research Priorities

### Pillar 1 – Frontiers research: unlocking the potential of soil carbon

System's biology, ecology and physico-chemistry need to be combined to create the next generation of data and models that will help to unlock the potential of agricultural soils by improving our understanding of the role of agricultural management for soil health. International cooperation through generation and analysis of big data, combined with artificial intelligence and ecological theories, has the

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[12] Smith, P., Lutfalla, S., Riley, W. J., Torn, M. S., Schmidt, M. W. I., & Soussana, J. F. (2018). The changing faces of soil organic matter research. European journal of soil science, 69(1), 23-30.

[13] International online survey organized by CIRCASA of research needs concerning soil carbon sequestration answered by 211 research scientists from 15 countries

potential to deliver a renewed understanding of soil functions, dynamics and biodiversity, which together govern soil carbon, soil health, and ecosystem services. Especially, in croplands and grasslands, interactions between soil carbon turnover and buildup and roots (including root litter, mycorhizae, exoenzymes and exsudates) as affected by crop type, climate change, breeding (during the last decades) and agricultural management need to be further understood.

*Testable hypotheses*

1. *Organic carbon preservation is the result of the interplay between mineralogical and microbiological processes*
2. *For a given soil type, there exists a finite amount of carbon that can be stabilized through organo-mineral interactions*
3. *Living soils have a net positive impact on soil organic carbon persistence*
4. *Calculating the ratio of soil carbon sequestration to nitrogen release will enable the realization of net agricultural greenhouse gas budgets*
5. *The persistence of deep soil organic carbon is governed by OC movement to depth, substrates for soil microbial activity and type of organo-mineral associations.*

## Pillar 2 – Soil carbon monitoring, reporting and verification (MRV) system

Technological, institutional and regulatory advances related to MRV can be promoted through international cooperation, to develop and scale up rapid cost-effective assessment methods for SOC monitoring, reporting and verification. This may involve remote and proximal sensing technologies, but equally important in this context are farm-level monitoring tools and mechanisms, and the potential of crowd-sourcing farm level data. Soil analysis either by classical or proximal sensing (e.g. NIRS) methods are also needed to complete or update existing data.

International cooperation on a soil carbon monitoring system will require a strong collaboration with partners and initiatives such as EC JRC, Copernicus, GEOSS (Group on Earth Observations), ICOS (Integrated Carbon Observation System), GSP (Global Soil Partnership), long-term soil studies and the integration of agricultural activities data into a global framework (Figure 2).

Although tools are now developed and tested on regional pilots, there is still technological progress to make to achieve a scaling up. This concerns both the technologies mobilized in the sensors, but also the development of solutions capable of handling large volumes of data at high spatial resolution, using cloud technologies. There is considerable interest in the development of MRV methodologies for soil carbon from a large range of agri-food sector industries, of remote sensing companies and of certification agencies.

(See Appendix: Design of a global high-resolution dynamic soil organic carbon monitoring system for agricultural land)

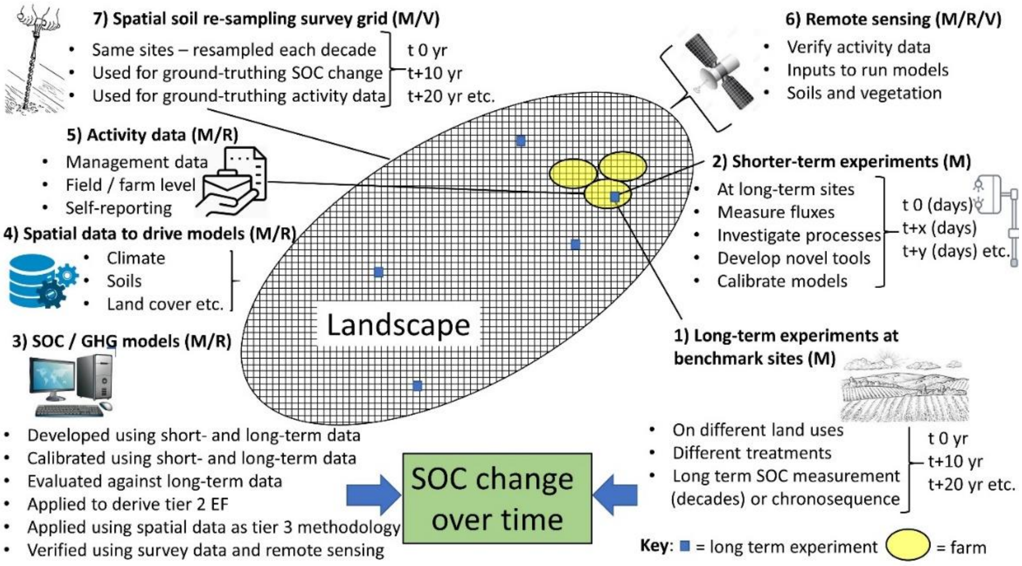


Figure 2. New vision for a global framework for Monitoring, Reporting and Verification of SOC change (Smith, Soussana et al. 2019, Global Change Biology)

*Testable hypothesis*

6. *Changes in soil organic carbon stocks can be measured at low cost and with sufficient accuracy with design-based sampling and a standardized methodology calculating soil carbon balance.*

## Pillar 3 – Agro-ecological and technological innovations

This pillar will support transformation of agricultural systems for improved soil health and increased soil carbon. This requires increasing the duration of the vegetation cover in cropping systems, avoiding over-grazing in pastoral systems, developing landscape mosaics that can reduce soil erosion, increasing the conservation of soil organic carbon stocks and developing agro-forestry systems. To support such changes in agricultural systems, technological innovation through public-private cooperation is moreover needed. Some examples include:

**Plant breeding.** The phenotyping of root systems is still largely to be achieved. The technological challenge is to develop this phenotyping and thus to promote the adaptation of plant material, in order to select species and varieties grown on the basis of optimization of their root development and their ability to exude more C in soils, thus meeting two simultaneous objectives: more long-term carbon storage and increased tolerance to drought. The challenge is therefore to phenotype both the root architecture, if possible *in natura*, and the quality of the interaction between the root system and the soil, via microbial activities capable of transforming labile C (root exudates) into stable C (microbial exopolymers) that can be stored sustainably in soils. The plant-breeding sector is already expressing interest in this innovation perspective. Moreover, agro-forestry has a strong potential to contribute to above and below-ground carbon storage, but this also requires targeted plant breeding to develop crops better adapted to altered radiation levels.

**Biochar and organic amendments.** From a circular economy perspective, various technologies exist today to use the potential of wastes (agricultural, industrial or urban) and functionalize them to enrich the soil and promote the storage of carbon. Further innovation is required for composting, anaerobic digestion, pyrolysis (biochar), hydrothermal carbonization, etc. Most of these processes generate bioenergy (bio-methane, hydrogen, heat) and their optimization must be designed for both the energy transition and the agricultural transition. If each process is today essentially viewed independently of the others, innovations could emerge by working on the coupling and the optimal arrangement of these processes, to reinforce the benefits associated with their mobilization, but also to minimize possible risks for food safety. The challenge is also to come up with flexible solutions, since they will have to adapt to the needs of the soil, the energy needs and the available waste deposits. There is large interest from the biogas sector and from organic amendments and biochar industries for this innovation theme.

**Precision agriculture and machinery.** Digital agriculture, sensors (e.g. spectrometry for soil organic matter), novel machinery for green tilling, cover crops, crop mixtures and long crop rotations, pasture renovation etc.. need to be developed and could provide data that could also contribute to the traceability of soil carbon storing practices and to carbon certification by low carbon labels. Moreover, the use of block chain technologies could be combined with precision agriculture to support this certification process. Agri-food industries invest in the traceability of their supply chains and farmers adopt digital agriculture and precision agriculture technologies that can support the development of soil carbon farming.

These innovation domains can support

*Testable hypotheses*

7. *Sustainable intensification (e.g. through plant breeding, organic amendments, digital agriculture) and agro-ecological approaches can reduce soil organic carbon (SOC) loss and restore SOC in depleted soils*
8. *Combining crop, livestock, and tree production in mixed agroforestry systems stabilizes more soil organic carbon than when separate in production.*
9. *Agricultural soil carbon losses e.g. through erosion can be minimized, while maintaining connected environments*
10. *Soil organic carbon has inherent value through regulation of ecosystem services*

## Pillar 4 – Enabling environment and knowledge co-creation

Scaling up soil carbon sequestration activities is a challenge that would need to address a variety of socio-economic barriers and incentives (cultural, social, economic and political especially for farmers. International cooperation can lead to better understanding those barriers and incentives for soil carbon sequestration in different contexts. Starting from understanding farmers' motivation, engagement, ability and willingness to adopt measures, awareness among stakeholders may result in more consistent advice and policies aiming for change. Mechanisms for scaling out soil carbon farming projects need to be further developed and a community of practices across these projects could be supported through online collaborative platforms, while connecting farmers and industries with green finance initiatives.

While the stakeholder consultation in CIRCASA project clearly shows that these barriers are significant to implementation, there is an absence of research and insights on cultural and policy dimensions of soil carbon sequestration. What are the most effective ways to overcome barriers and what types of enabling environment needs to be put in place? What is the most appropriate way of framing SOC sequestration in communicating with farmers? Do carbon credits and carbon certification result in permanent and effective carbon sequestration, or are other economic and capacity building tools and instruments more effective? Are there any negative side-effects of these certification schemes? These and similar questions need to be addressed if policy is to facilitate scaling up of SOC sequestration that results also in efficient and socially equitable interventions, without producing negative trade-offs for society. Understanding financial, policy, and capacity building mechanisms that are effective and equitable is a key open research gap from various levels, bottom-up to national to international

International cooperation can benefit from advances in methodologies related to these barriers such as costs and benefits analysis , from farm level to societal scale (e.g. assessment of ecosystem services with focus on soil carbon and co-benefits), as well as critical research on social and cultural dimensions of upscaling soil carbon sequestration.

The stakeholder consultation also identified a range of farm specific knowledge needs. For farmers, guidance is especially needed for crop choice (including rotation, crop combination, interactions and impacts on subsequent crops), which was the most frequently mentioned item in farm-level management. Other needs include questions about inputs of organic material, reduced tillage, machinery or testing of new measures (including biochar, or 'exotic' measures such as compost teas), and information on the effects of individual practices, interactions between practices, and management regimes (combinations of practices). The role of microorganisms, earthworms and more broadly interactions between soil microorganisms (fungi, bacteria), nutrients, and water could also be part of the advisory system.

Science can provide solutions which are grounded in and make use of regional research and advisory infrastructures. An international research agenda can stimulate the setting up of these infrastructures, provide an impulse for different ways of working through co-creation methods or more transdisciplinary approaches that involve not just soil scientists, agronomists but also economists, legal expertise, and socio-economic, institutional scientists. Methodological approaches such as living labs, lighthouse farms or advances around communication and innovative incentive mechanisms can be essential to support enabling environments that are required for scaling up SOC management.

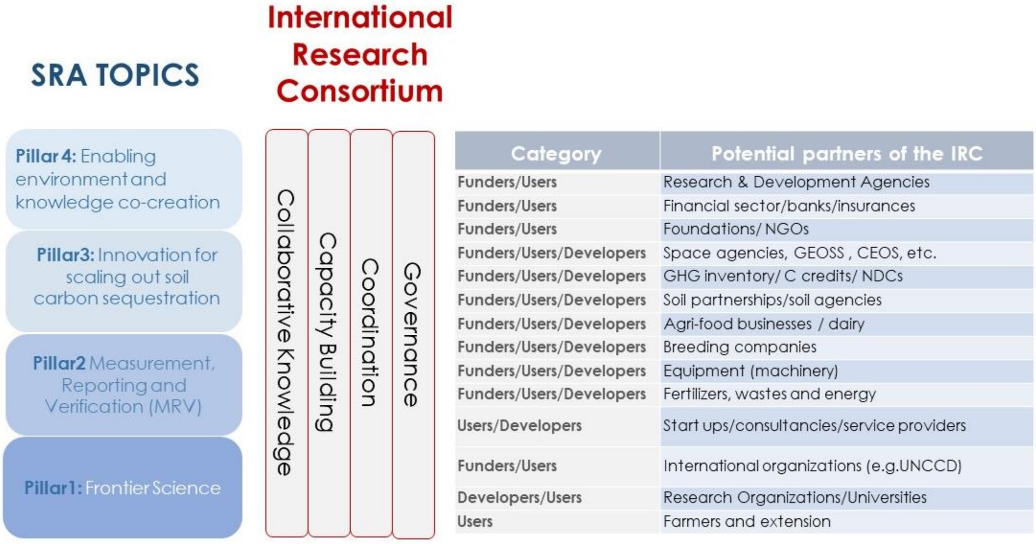
### Testable hypotheses

11. *The scaling up of soil carbon sequestration is dependent on an integrated enabling environment that addresses socio-economic and technological barriers to implementation*
12. *Stakeholder engagement, knowledge exchange and learning can help to overcome socio-cultural barriers to increase soil organic carbon*
13. *The lack of soil governance limits agricultural soil carbon sequestration*
14. *Valuing the natural capital inherent in soil organic matter appropriately will incentivize investment in its enhancement.*
15. *Long term carbon sequestration requires long term commitment and continued action to protect organic carbon stocks requiring commitments by farmers and land owners and long term incentives and agreements that are new to the agriculture sector.*

## Designing an International Research Consortium (IRC) on agricultural soil carbon sequestration

Better structuring international research cooperation, not only requires agreed priorities (see above pillars) but also developing an implementation plan for these priorities through institutional and investment arrangements. An International Research Consortium (IRC) includes research funders and programme owners from several countries, as well as international organisations and the representation of foundations and companies. The IRC should deliver measurable advancements through the alignment of both public and privately funded research programmes around the world. In that sense, CIRCASA is organizing a formal dialog with each partner in order to identify the key people to contact in each country. Also the interest of foundations which have strategy towards sustainability and interest in soils health and soil carbon will be seeked.

CIRCASA preliminary vision for this IRC (Figure 3) shows how the four pillars of the SRA could be pursued in interaction with different categories of IRC members, including scientists, public agencies, and private sector with farmers associations and industries. While an overarching governance of the IRC will be needed with specific funding arrangements, each topic may require specific consortia and institutional arrangements.



| Category | Potential partners of the IRC |
|---|---|
| Funders/Users | Research & Development Agencies |
| Funders/Users | Financial sector/banks/insurances |
| Funders/Users | Foundations/ NGOs |
| Funders/Users/Developers | Space agencies, GEOSS , CEOS, etc. |
| Funders/Users/Developers | GHG inventory/ C credits/ NDCs |
| Funders/Users/Developers | Soil partnerships/soil agencies |
| Funders/Users/Developers | Agri-food businesses / dairy |
| Funders/Users/Developers | Breeding companies |
| Funders/Users/Developers | Equipment (machinery) |
| Funders/Users/Developers | Fertilizers, wastes and energy |
| Users/Developers | Start ups/consultancies/service providers |
| Funders/Users | International organizations (e.g.UNCCD) |
| Developers/Users | Research Organizations/Universities |
| Users | Farmers and extension |

Figure 3. Preliminary vision of an International Research Consortium on agricultural soil carbon, showing the four pillars of the Strategic Research Agenda, the activities of the IRC, the potential partners and their roles as funders, users and developers of IRC activities.

For the needs of this SRA to be met, funders have to be able to see why they should invest in research and innovation activities within the IRC, end users need to see how specific activities will create desirable outcomes and researchers need to find funding and an attractive environment. International cooperation for research and innovation can generate a large range of outputs for national and local stakeholders, including access to knowledge and innovation, demonstration of new technologies and of new assessment methods, training and capacity building.

The IRC will program the development of these research priorities in close collaboration with the EC[14], with research organizations, public agencies and private sector. To this end, CIRCASA has started to take stock of the interest of organizations considering the categories of potential partners of the IRC shown in Figure 3. For each category, a task force led by CIRCASA partners has been organized to broker interest, develop use cases, customer stories and seek expressions of interest for this Strategic Research Agenda.

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[14] Orientations towards the first Strategic Plan for Horizon Europe (https://ec.europa.eu/info/sites/info/files/research_and_innovation/strategy_on_research_and_innovation/documents/ec_rtd_orientations-he-strategic-plan_122019.pdf)

# CONCLUSION

By engaging with multiple stakeholders at a strategic level, this Strategic Research Agenda offers a unified field for international research cooperation on soil carbon sequestration in agriculture that strategically shows the knowledge gaps that need to be filled based on views both by international research scientists and end users from several world regions. This SRA is also aligned with international assessments and with the Soil Health and Food Mission board report. An IRC on soil carbon can have a large role in supporting the EU Green Deal, especially regarding the Farm to Fork Strategy, the Biodiversity Strategy and the commitment that Europe becomes the first carbon neutral continent by 2050. Strengthening international research cooperation in this field is also essential to support national commitments for Land Degradation Neutrality (UNCCD) and to improve transparency of commitments concerning soil carbon under the Paris agreement on climate change (UNFCCC).

# Appendix: Design of a global high-resolution dynamic soil organic carbon monitoring system for agricultural land

For applications ranging from carbon offsetting, to low carbon sourcing of agricultural commodities and low carbon policies in agriculture, soil carbon monitoring is required as well as the associated estimation of the GHG balance at field and farm scales. We focus here on soil carbon balance monitoring.

The goal is to monitor in Europe and globally soil organic carbon (SOC) balance at high spatial resolution e.g. 10 m) in agricultural lands with a target accuracy of less than 0.1 tC per ha and per yr (i.e. less than 0.2% of an average arable SOC stock of 50 tC/ha in the top 0-30 cm).

This is not possible at scale by directly measuring SOC stocks and their changes over time, since for a single field detecting within 5 yrs a 1% change in top soil SOC stock requires intensive soil coring and laboratory or spectrometry analysis and this comes with high costs. An alternative approach is to calculate the SOC balance as the difference between organic C inputs and C outputs from a field. A generic mass balance approach (Soussana et al., 2010, 2019) can be used:

$$\Delta SOC=(NPP - Rh-\Delta AGC)+(Fmanure- Fharvest - Fanimal\text{-}products-FCH4\text{-}C)-(Ferosion+Ffire+Fleach+FVOC) \quad \text{(Eq. 1)}$$

Where NPP is the net primary productivity, $Rh$ is the heterotroph respiration from soils and from grazing livestock and $\Delta AGC$ is the change in above-ground vegetation C stock. All above fluxes are in g C $m^{-2}$ $yr^{-1}$.

Eq. (1) shows the three categories of fluxes that govern $\Delta SOC$ at the ecosystem scale: the flux of organic carbon partitioned below-ground ($NPP- Rh-\Delta AGC$), the human appropriation of above-ground carbon ($Fmanure - Fharvest - Fanimal\text{-}products-FCH4\text{-}C$) and the carbon losses at ecosystem scale ($Ferosion+ Ffire+ Fleach +FVOC$).

This equation can be simplified (assuming that changes in above-ground C (AGC) and C emissions caused by fires, VOC compounds, macro-fauna and erosion can usually be neglected) as:

$$\Delta SOC = (NPP - R_{h\text{-}soil} - R_{h\text{-}livestock} - F_{CH4\text{-}C}) + (F_{manure} - F_{harvest} - F_{animal\text{-}products}) - F_{leach} \qquad \text{(Eq. 2)}$$

Without grazing (arable crops and mown grasslands) a further simplification applies (e.g. Béziat et al., 2009):

$$\Delta\ SOC= NPP - R_{h\text{-}soil} + F_{manure} - F_{harvest} - F_{leach} \qquad \text{(Eq. 3)}$$

$\Delta\ SOC$ in the above mass balance equations concern the full soil depth. In contrast, for practical reasons SOC stock direct measurements are often limited to the top soil (e.g. 0-30 cm).

## 1. Basic monitoring, reporting and verification (M, R, V) concepts

Main data sources are shown in Figure 2, with their M, R and V roles. An open-access database, where short- or long-term soil C measurements can be uploaded and shared (e.g. https://dataverse.org/ and the online collaborative platform as used in the CIRCASA project: https://www.circasa-project.eu/), would also be of great benefit for progressing a global MRV system.

Below is a list, to be completed especially for regions outside the EU, of data sources in these categories:

(1) **Long-term field experiments at benchmark sites** where ΔSOC can be monitored with intensive soil coring campaigns **(M).**

- CIRCASA and GRA/IRG work on a data repository part of the OCP (Open Collaborative Platform (www.ocp.circasa-project.eu )

- Global Inventory of Long-Term Soil-Ecosystem Experiments including nearly 250 LTSEs with metadata found on all continents, including Antarctica (Richter, Hofmockel, Callaham, Powlson, & Smith, 2007) (Figure 4). The metadata currently hosted by the International Soil Carbon Network (iscn.fluxdata.org/partner-networks/long-term-soil-experiments/)

- In Europe these sites will be based on the existing long-term experiments (http://iscn.fluxdata.org/partner-networks/long-term-soil-experiments/) and additional existing sites to be identified by the MS, but should also include the existing level 2 monitoring sites within ICP forest (http://icp-forests.net/page/level-ii).

**Figure 4.** Global Inventory of Long-Term Soil-Ecosystem Experiments - LTSEs

(2) **Shorter-term field experiments** where eddy flux covariance monitors NEE (Net Ecosystem Exchange), which is the balance between NPP and ($R_{h\text{-soi}}$+$R_{h\text{-livestock}}$) **(M)**

- EU data are organized by ICOS and international data by FluxNet (and other regional flux networks) (www.icos-cp.eu https://fluxnet.fluxdata.org)

**(3) SOC/GHG models (M/R)** to derive IPCC Tier 2 emission or SOC stock change factors, which are specific to the region and conditions represented within the region (e.g. Begum et al., 2018) or spatially over the whole landscape (or the entire land area of a country) using spatial databases of soil characteristics, and land cover, management and climate data, to directly simulate SOC change and GHG emissions, thereby delivering a Tier 3 methodology to report emissions (Table 1)

- An EU wide consistent modelling approach needs to be adopted avoiding duplication of efforts and competing/contradictory results. The EU Competence Centre on Modelling (CC-MOD) promotes a responsible, coherent and transparent use of modelling to support the evidence base for EU policies. (https://ec.europa.eu/knowledge4policy/modelling_en)

Table 1. Examples of models used in National GHG Inventories to estimate Carbon dioxide emissions and removals from the cropland remaining cropland soils component (Tier 3 method)

| Country | Model | | Reference |
|---|---|---|---|
| Australia | The Full Carbon Accounting Model (FullCAM) | Estimates emissions from soil through a process involving all on-site carbon pools (living biomass, dead organic matter and soil) on a pixel by pixel (25m x 25m) level. | (Richards, 2001) |
| Canada | CENTURY | process model used for estimating CO2 emissions and removals as influenced by management activities, based on the National Soil Database of the Canadian Soil Information System | (Parton, Schimel, Cole, & Ojima, 1987; Parton, Stewart, & Cole, 1988) |
| Denmark | C-TOOL | 3-pooled dynamic soil model parameterised and validated against long-term field experiments (100-150 years) conducted in Denmark, UK (Rothamsted) and Sweden and is “State-of-the-art”. | (Taghizadeh-Toosi et al., 2014) |
| Finland | Yasso07 soil carbon model | The parameterisation of Yasso07 used in cropland was the one reported in (Tuomi, Rasinmäki, Repo, Vanhala, & Liski, 2011) | (Palosuo, Heikkinen, & Regina, 2015) |
| Japan | Soil Carbon RothC model | In order to apply the model to Japanese agricultural conditions, the model was tested against long-term experimental data sets in Japanese agricultural lands (Shirato & Taniyama, 2003) | (Coleman & Jenkinson, 1987) |
| Sweden | Soil Carbon model ICBM-region | Calculate annual C balance of the soil based on national agricultural crop yield and manure statistics, and uses allometric functions to estimate the annual C inputs to soil from crop residues | (Andrén & Kätterer, 2001) |
| Switzerland | Soil Carbon RothC model | The implementation of RothC in the Swiss GHG inventory is described in detail in (Wüst-Galley, Keel, & Leifeld, 2019) | (Coleman et al., 1997) |
| United Kingdom | CARBINE Soil Carbon Accounting model (CARBINE-SCA) | Simplified version of the ECOSSE model (Smith et al., 2010), coupled with a litter decomposition model derived from the ForClim-D model (Liski, Perruchoud, & Karjalainen, 2002; Perruchoud, Joos, Fischlin, Hajdas, & Bonani, 1999). | (Matthews et al., 2014) |
| United States | DAYCENT biogeochemical model | Utilizes the soil C modelling framework developed in the Century model (Metherell, Harding, Cole, & Parton, 1993; Parton, Ojima, Schimel, & Cole, 1994; Parton et al., 1987, 1988), but has been refined to simulate dynamics at a daily time-step. | (Del Grosso & Parton, 2011; Del Grosso et al., 2001; Parton, Hartman, Ojima, & Schimel, 1998) |

(4) **Spatial data** to drive models (climate, land cover, soil properties including top SOC content) **(M/R)**

- Climate data for agriculture are available from AgMIP (https://data.giss.nasa.gov/impacts/agmipcf/agmerra/) and other sources

- Soil interpolated maps are developed by ISRIC with support of the Global Soil Partnership and FAO (https://www.isric.org/explore/soilgrids ) including the SOC content and its uncertainty for a 250 m resolution available on CIRCASA OCP.

- Other prominent data sources include for the EU LUCAS (https://esdac.jrc.ec.europa.eu/projects/lucas ) also included in CIRCASA OCP concerning soil C (www.ocp.circasa-project.eu)

(5) **Activity data** (field and farm, management, self-reporting by farmers) **(M/R)**

- Remote sensing of land use (Corine LandCover, https://land.copernicus.eu/pan-european/corine-land-cover)

- Remote sensing of crop and grassland types by field (see Cropland products from COPERNICUS, to be released in 2021 for the EU)

- Remote sensing of phenology, NDVI, faPAR, fcover (see Phenology products from COPERNICUS, to be released in 2020 for the EU)

- Farmers activities are reported through the Land Parcel Identification System (LPIS) showing fields and their margins as part of the IACS of the Common Agricultural Policy (https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/financing-cap/controls-and-transparency/managing-payments_en). Data about management practices adopted at farm scale in the EU are collected through the Farm Structure Survey https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Farm_structure_survey_-_methodological_articles

- However, for carbon monitoring purposes there are gaps in CAP declarations, including presence or not of cover crops and management of crop residues and of organic fertilizers)

(6) **Remote sensing** (verify activity data, soils and vegetation inputs to run models) **(M/R/V)**
Remote sensing tools as available within the COPERNICUS program can provide very valuable data for detecting SOC changes and for monitoring agricultural practices/land management practices. Extensive work done by ESA as well as the recently launched GEO initiative for monitoring land degradation in support to UNCCD and the related Land Degradation Neutrality target within SDG 15 can provide a lot of synergies in achieving an operational remote sensing component for MRV of SOC http://worldsoils2019.esa.int/

- Proxies of Net Primary Productivity (NPP) derived from (5)

- Proxies of Surface Soil Moisture (SSM) to constrain SOC modeling forthcoming at 1 km resolution (https://land.copernicus.eu/global/products/ssm )

- Surface SOC content (https://sentinels.copernicus.eu/web/sentinel/news/-/article/copernicus-sentinel-2-data-to-estimate-soil-organic-carbon-in-croplands)

**(7) Spatial soil re-sampling survey grids (M/V)**

The on-going LUCAS soil monitoring system based on a regular 2kmx2km grid is a solid base for the operational in-situ measurement of SOC across the EU. After 3 sampling campaigns (2009, 2015 and 2018) it is by now a consolidated system providing regular monitoring data on soil properties in the EU https://esdac.jrc.ec.europa.eu/content/chemical-properties-european-scale-based-lucas-topsoil-data

Further development of LUCAS needs to be fully adopted as the monitoring system at National scale on the basis of the same common grid.

- EU member state data to be harmonized by EJP soil (https://cordis.europa.eu/project/id/862695/fr)

- National gridded soil surveys in several EU countries (e.g. France: www.gissol.fr/le-gis/programmes/rmqs-34 )

## 2. Dynamic soil carbon and GHG balance modeling

As shown in Figure 2, models (3) informed, constrained, calibrated and verified by the various data streams in Figure 2 are required to calculate *ΔSOC* and the GHG balance. Several approaches were used, noting however that soil carbon modelling is still evolving rapidly (e.g.(Woolf & Lehmann, 2019):

### A. Land surface models including soil carbon and GHG emissions

Global land surface models (e.g. https://orchidee.ipsl.fr/) integrate biosphere, land use and land management and provide simulations of coupled carbon and water fluxes, including SOC balance (Camino-Serrano et al., 2017) and were also used to calculate SOC balance e.g. in global grasslands (Chang et al., 2015).

- Main application domains for soil carbon: climate change and land use projections and historical assessments at regional to global scales.

### B. Crop and pasture models including soil carbon and GHG emissions

A recent intercomparison (Ehrhardt et al., 2018) , developed by Global Research Alliance, Integrative Research Group, GRA IRG) shows the potential of ensembles of crops and pasture models to simulate N2O fluxes and yields at a range of long-term field sites. Simulations for soil carbon have been assessed by (Sándor et al., 2020) developed as well by GRA IRG.

Modeling platforms based on a single model are proposed, such as COMET farm a whole farm carbon and GHG accounting system (http://comet-farm.com/ ) which is based on the DayCent simulation model. Other examples in France include the STICS model, which has been used for nationwide tests of SOC sequestration potential for a range of changes in agricultural practices (https://www.inrae.fr/en/news/storing-4-1000-carbon-soils-potential-france)

- Main application domains for soil carbon: site based and farm based estimates of SOC change and GHG emissions. Note that these models are usually not coupled to data from remote sensing and that their calibration may be limited to certain crops only and to specific soil and climate conditions.

### C. SOC models

SOC models and their ensembles can be used for predictions of organic carbon, despite uncertainties concerning the first order kinetics used for decomposition and the roles of microbial and stabilization processes (Menichetti, Ågren, Barré, Moyano, & Kätterer, 2019; Woolf & Lehmann, 2019) and interactions with energy sources for microbes and soil nutrients. Some SOC models require prior information on SOM structure (e.g. aggregate structure, thermal stability as estimated by RockEval, (Poeplau, Barré, Cécillon, Baudin, & Sigurdsson, 2019)) which prevents their use on a large scale. However, spin-up runs based on steady state or on past land use have often been used to run these models (such as Century,(Dimassi et al., 2018), without further knowledge of SOM structure. Robust predictions from ensembles of SOC models are obtained in long-term bare fallow soils (Farina et al., in revision, developed by GRA IRG).

However, to predict Δ SOC in vegetated systems, carbon inputs to soils are required (see Eqs. 2-3). For instance in France (Simeos-AMG, www.simeos-amg.org ), which is a commercial tool calibrated for main field crops and estimating crop residues based on allometry with yields. Well established SOC models such as RothC can be used in an inverse mode (e.g.(Meersmans et al., 2013), which allows to estimate e.g. the OC inputs required to maintain SOC in a steady-state (or to increase SOC by 0.4% per year, which is the aspirational target of the 4 per 1000 initiative (Soussana et al., 2019)). This inverse RothC approach has been used at global scale in the CIRCASA project (www.circasa-project.eu) by comparing OC input needs for SOC steady-state and for 4 per 1000 target with croplands OC inputs (Global EPIC simulations of crop residues https://iiasa.ac.at/web/home/research/researchPrograms/EcosystemsServicesandManagement/EPIC.en.html) and grasslands OC inputs (from GLEAM model, FAO, http://www.fao.org/gleam/en/). Results are available on the CIRCASA OCP (Section 2. Global maps of agricultural SOC stocks baselines and of technical sequestration potential)

- Main application domains for soil carbon: site to global scale, in direct mode forcing SOC models by OC inputs to soils and in inverse mode estimating OC inputs to soils required for an assumed baseline of SOC change. Note that these models are usually not coupled to data from remote sensing and from vegetation and that their calibration may be limited to certain soil and climate conditions. Note also that GHG emissions (e.g. $N_2O$) are not simulated.

## 3. Regional, national and project scale SOC monitoring systems

We distinguish three nested scales for SOC monitoring: international/regional, national and project.

Internationally, the UNFCCC Annex-I Parties are subject to the GHG accounting rules of that Convention and the IPCC Guidelines (see https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ ). The IPCC Guidelines are designed to help estimate and report national inventories of anthropogenic GHG emission reductions including SOC. A tiered approach is proposed:

- Tier 1 or default method: simplest order of methods with the higher uncertainties. Reference carbon stocks are multiplied by Land use change factors.
- Tier 2: on the same principle as Tier 1 but with better accuracy taking into account country-specific data for land use change factors.

- Tier 3: lowest uncertainties order of method with the use of models, considering fluxes. For instance, Tier 3 methods are the only option to take into account the impact of soil erosion on C flows. Examples of model use (e.g. DayCent are provided in the 2019 refinement).

At national scale, diverse assessment methods, consistent with the international framework exist and are based on scientific advances and availability of input data from each country. For example, in the USA, COMET- Farm is the official GHG quantification tool of the USDA and developed in partnership with Colorado State University. The Methodology is a combination of process simulation models, empirical models and IPCC methodologies and peer-reviewed research results.

At project scale, MRV methods implemented for local emission reduction projects are aligned with specific frameworks respecting themselves national and international guidelines. For instance, the Australian Government's compliance offset program, the Emissions Reduction Fund (ERF), has currently two methodologies dedicated specifically to soil carbon sequestration: *Estimating Sequestration of Carbon in Soil Using Default Values* and *Measurement of Soil Carbon Sequestration in Agricultural Systems.*

The latest is the only one, which registered projects so far (44 of which one has issued Australian Carbon Credit Units in May 2019). *Measurement of Soil Carbon Sequestration in Agricultural Systems* methodology includes direct measurements, detailed sampling protocols and lab techniques as well as thermal analysis. Another example is Alberta Offset program in Canada, which is, based on the conservation Cropping Protocol, using Canada's National Emissions Tier 2 methodology based on country-specific sequestration coefficients (Paustian et al., 2019).

At national and project levels, a standardized, cost effective methodology is available to assess C benefits. The Carbon Benefits Project (CBP) provides tools for anyone wanting to estimate the impact of their activities on climate change mitigation (carbon stock changes and greenhouse gas (GHG) emissions). This includes agriculture, forestry or land management projects in simple or complex landscapes. The tools are freely available web-accessible system (https://banr.nrel.colostate.edu/CBP/) developed by Colorado State University and partners under a Global Environment Facility co-financed project implemented by the United Nations Environment Program. It offers tools for:

- Simple assessment for a quick estimate at any stage (including proposals) of C and GHG impacts;
- Detailed assessment for detailed analysis
- A Cost Benefit Analysis and a DPSIR (causal framework to describe interactions between society and the environment)

The H2020 NIVA project (https://cordis.europa.eu/project/id/842009/fr) aims to modernize the Integrated Administration and Control System (IACS) of the European CAP by making efficient use of digital solutions and e-tools. It will test a large scale implementation of environmental indicators calculated at plot scale by combining LPIS with Sentinel remote sensing data (Tier 1), eventually considering climate and/or soil and/or farmer's data (Tier 2) or relying on modeling approaches (Tier 3). Within this frame, in Tier 1 a proxy of the cropland carbon budget will be estimated based on a relationship between the net annual $CO_2$ fixation (NEE) and the duration of the periods with active vegetation (Ceschia et al., 2010), as estimated from remote sensing at plot scale. In Tier 2, a C budget will be calculated based on this approached combined with farmer's self-reporting on yield, straw management and organic fertilization and in Tier 3 C budget will be estimated based on the SAFY-CO2 crop model assimilating LAI derived from Sentinel 2 data (Pique et al. submitted).

# 4. Design principles for a high resolution EU and global dynamic SOC monitoring system

A global coverage at Tier 1, however with higher Tiers to be developed by members of the IRC (e.g. in some countries/regions, or by some corporates for their sourcing, carbon offsetting). For instance Tier 2, based on local to national data provided and verified by consortium members. A Tier 3, verifying systematically SOC change estimates from soil surveys and long-term fields sites, as well as eddy flux covariance.

A high spatial resolution (ca. 10 m to include small fields and small owners) based on remote sensing

A high accuracy target (detecting changes of less than 0.1% per year of top SOC stock) that will take several years to reach. A low initial accuracy is expected, but investment needs to attain high accuracy will be estimated each year.

An estimate of $N_2O$ emissions and of the balance of other soil derived GHGs in $CO_2$ equivalents, noting that emissions from enteric fermentation and manure management cannot not be calculated with this approach.

A three pillar structure:

i) SOC pillar (soil science community, GSP, soil maps, remote sensing of surface soil),
ii) Vegetation pillar (remote sensing of vegetation, phenology and cropland/grassland COPERNICUS products to calculate NPP by crop/grassland types),
iii) Activity pillar (agricultural activities based on statistics or on self-reporting).

Land use change emissions could also be estimated in this way, however with substantial extensions in the monitoring system to cover deforestation areas (Quin et al., 2019) and the corresponding carbon balance (e.g. through LVOD, SMOS, Quin et al., submitted).

A modular structure, each pillar derives products that are coupled with other pillars products to derive gridded *Δ SOC* estimates with their associated uncertainties. Ensembles of calibrated models rather than single models could be used when possible.

A strong data infrastructure providing seamless access by multiple users and using the FAIR principles (www.go-fair.org/fair-principles). Initially, this data infrastructure could be hosted by CIRCASA's OCP. It would include options for self-reporting especially for activities currently not reported (e.g. organic fertilizers, crop residues, etc.) A gradual implementation, combining proxies at global scale in the first year (e.g. changes in annual duration of vegetation cover in arable systems could be used as a proxy of OC input to soil) and advanced implementation in pilot areas.

Provision of resources for ground truthing and for calibration data (e.g. calibration of NPP at eddy flux covariance sites, direct measurements of crop residues etc.).

The development cycles are anticipated to last 2 years, with 3 cycles:

- **2021-2023**: Design stage (all components designed and tested, implementation in 3-5 countries, including e.g. 2 countries outside the EU)
- **2023-2025**: Implementation stage 1. Targeting Tier 1 implementation at global scale, Tier 2 and Tier 3 implementation started in the EU)
- **2025-2027**: Implementation stage 2. Improved Tier 1 accuracy, Tier and Tier 3 implementation in the EU and in at least two other world regions.

## 5. Reporting and verifying SOC change estimates

Reporting would primarily be through gridded data extraction for any spatially defined entity (e.g. a field, a farm, a small region, the sourcing area of an industry, or a given crop type, a country etc.) and any time period (several months to decades).

All $\Delta$ *SOC* estimates would be provided in gC $m^{-2}$ per time period selected. An uncertainty estimate would be provided (if possible as RMSE) systematically. Uncertainties would be calculated by reference with verification methods, noting however that reference methods are also uncertain.

Verification would be based on some of the data sources specified in Figure 2:

(1) Long-term experiments at benchmark sites

(7) Spatial soil re-sampling (surveys, grids, demonstration farms, etc.)

Verification would target a high accuracy estimate of $\Delta SOC$ over the full soil profile, with sampling and analytical methods limiting biases in final vs. initial SOC stock estimates. For instance, using the same sampling protocol and tools, using geo-referenced sampling points, using the same analytical procedure done in a single lab. The number of replicate soil samples in each site would be sufficiently high to provide a good accuracy (e.g. see CarboEurope soil sampling protocol at eddy flux sites). Therefore, part of the costs of the infrastructure would be caused by the increased measurement effort compared to classical soil surveys. Statistical studies will be required to optimize the design of the verification component.

Some countries will run a national soil C inventory based on stratified sampling of agricultural land with a design allowing to detect a change in national SOC stock above (in absolute value) a certain threshold. For instance, New Zealand is planning to detect an average change by 2 t C/ha/yr for the country with 500 sampling sites. This type of design would allow ground truthing of the carbon balance by the monitoring system.

Beyond traditional MRV, Artifical Intelligence approaches could be tested to optimize the predictive power of the monitoring based on calibration and verification data.

## 6. First assumptions for the three pillars in the EU

**Activity pillar**

- Corinne Land Cover for land use (available)
- Copernicus Cropland for crop types (2021)
- Sentinels for soil tillage and cover cropping
- For grasslands, permanent grasslands can be used

**Vegetation pillar**

- Climatic data (e.g. ERA5 for Europe on a 30 km grid, https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5 )

- Copernicus Phenology (2020) coupled with Croplands for NDVI integral by crop cycle (2021), estimates available in near real time (providing Activity-Vegetation coupling)
- Simulate NPP from NDVI/LAI, partition NPP to shoots and roots and estimate leaf area increase and hence change in NDVI/LAI
- Assimilate NDVI/LAI change in the vegetation model for calibrating NPP (procedures that could be based on e.g. SAFY, (Claverie et al., 2012; Duchemin, Maisongrande, Boulet, & Benhadj, 2008) or SAFYE CO2, Pique et al. submitted)
- Sentinels for soil moisture (see also Theia, https://www.theia-land.fr/product/humidite-du-sol-a-tres-haute-resolution-spatiale/ for soil moisture)
- Estimate crop yields, calibrate with statistical data, yield maps from combined harvester, with farmer's self-reporting etc.
- Estimate crop residues, calibrate with ground truthing, statistical data and farmer's self-reporting
- With grasslands, a similar approach can be used however with estimates of biomass exports by mowing and of herbage use by grazers.

SOC pillar

- LUCAS top soil survey coupled to ISRIC Soil Grids to provide first estimate of SOC stock
- Remote sensing of surface soil to derive SOC content, e.g. see (Castaldi et al., 2019; Vaudour, Gomez, Fouad, & Lagacherie, 2019) (and possibly soil nutrients and pH)
- Additional calibration data (from data sources (1) and (7) and from self-declaration by users)
- Modeling SOC balance through an ensemble of SOC models constrained by climatic data, soil type, initial SOC stock and OC inputs to soil (provided by Vegetation Pillar)

# REFERENCES

Andrén, O., & Kätterer, T. (2001). Basic principles for soil carbon sequestration and calculating dynamic country-level balances including future scenarios. *Assessment Methods for Soil Carbon*, 495–511.

Camino-Serrano, M., Guenet, B., Luyssaert, S., Ciais, P., Bastrikov, V., De Vos, B., … Janssens, I. A. (2017). ORCHIDEE-SOM: Modeling soil organic carbon (SOC) and dissolved organic carbon (DOC) dynamics along vertical soil profiles in Europe. *Geoscientific Model Development Discussions*, 1–38. https://doi.org/10.5194/gmd-2017-255

Castaldi, F., Hueni, A., Chabrillat, S., Ward, K., Buttafuoco, G., Bomans, B., … van Wesemael, B. (2019). Evaluating the capability of the Sentinel 2 data for soil organic carbon prediction in croplands. *ISPRS Journal of Photogrammetry and Remote Sensing*, *147*(August 2018), 267–282. https://doi.org/10.1016/j.isprsjprs.2018.11.026

Ceschia, E., Béziat, P., Dejoux, J. F., Aubinet, M., Bernhofer, C., Bodson, B., … Wattenbach, M. (2010). Management effects on net ecosystem carbon and GHG budgets at European crop sites. *Agriculture, Ecosystems and Environment*, *139*(3), 363–383. https://doi.org/10.1016/j.agee.2010.09.020

Chang, J., Ciais, P., Viovy, N., Vuichard, N., Sultan, B., & Soussana, J. F. (2015). The greenhouse gas balance of European grasslands. *Global Change Biology*, *21*(10), 3748–3761. https://doi.org/10.1111/gcb.12998

Claverie, M., Demarez, V., Duchemin, B., Hagolle, O., Ducrot, D., Marais-Sicre, C., … Dedieu, G. (2012). Maize and sunflower biomass estimation in southwest France using high spatial and temporal resolution remote sensing data. *Remote Sensing of Environment*, *124*, 844–857. https://doi.org/10.1016/j.rse.2012.04.005

Coleman, K., & Jenkinson, D. S. (1987). *RothC - A model for the turnover of carbon in soil. Model description and users guide*. *ROTHC manual*. Harpenden, Herts, UK.

Coleman, K., Jenkinson, D. S., Crocker, G. J., Grace, P. R., Klír, J., Körschens, M., … Richter, D. D. (1997). Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. *Geoderma*, *81*(1), 29–44. https://doi.org/https://doi.org/10.1016/S0016-7061(97)00079-7

Del Grosso, S., & Parton, W. J. (2011). Understanding Greenhouse Gas Emissions from Agricultural Management. In L. Guo, A. Gunasekara, & L. McConnell (Eds.), *Symposium A Quarterly Journal In Modern Foreign Literatures*. Washington, D.C.: American Chemical Society.

Del Grosso, S., Parton, W., Mosier, A., Hartman, M., Brenner, J., Ojima, D., & Schimel, D. (2001). "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In M. Schaffer, L. Ma, & S. Hansen (Eds.), *Modeling Carbon and Nitrogen Dynamics for Soil Management* (pp. 301–332). Boca Raton, Florida: CRC Press. https://doi.org/10.1201/9781420032635.ch8

Dimassi, B., Guenet, B., Saby, N. P. A., Munoz, F., Bardy, M., Millet, F., & Martin, M. P. (2018). The impacts of CENTURY model initialization scenarios on soil organic carbon dynamics simulation in French long-term experiments. *Geoderma*, *311*(March 2017), 25–36. https://doi.org/10.1016/j.geoderma.2017.09.038

Duchemin, B., Maisongrande, P., Boulet, G., & Benhadj, I. (2008). A simple algorithm for yield estimates: Evaluation for semi-arid irrigated winter wheat monitored with green leaf area index. *Environmental Modelling and Software*, *23*(7), 876–892. https://doi.org/10.1016/j.envsoft.2007.10.003

Ehrhardt, F., Soussana, J. F., Bellocchi, G., Grace, P., McAuliffe, R., Recous, S., … Zhang, Q. (2018). Assessing uncertainties in crop and pasture ensemble model simulations of productivity and N2O emissions. *Global Change Biology*, *24*(2), e603–e616. https://doi.org/10.1111/gcb.13965

Liski, J., Perruchoud, D., & Karjalainen, T. (2002). Increasing carbon stocks in the forest soils of western Europe. *Forest Ecology and Management*, *169*(1), 159–175. https://doi.org/https://doi.org/10.1016/S0378-1127(02)00306-7

Matthews, R., Malcolm, H., Buys, G., Henshall, P., Moxely, J., Morris, A., & Mackie, E. (2014). *Changes to the representation of forest land and associated land-use changes in the 1990-2012 UK Greenhouse Gas Inventory. Report to Department of Energy and Climate Change, Contract GA0510,*. Edinburgh.

Meersmans, J., Martin, M. P., Lacarce, E., Orton, T. G., De Baets, S., Gourrat, M., … Arrouays, D. (2013). Estimation of Soil Carbon Input in France: An Inverse Modelling Approach. *Pedosphere*, *23*(4), 422–436. https://doi.org/10.1016/S1002-0160(13)60035-1

Menichetti, L., Ågren, G. I., Barré, P., Moyano, F., & Kätterer, T. (2019). Generic parameters of first-order kinetics accurately describe soil organic matter decay in bare fallow soils over a wide edaphic and climatic range. *Scientific Reports*, *9*(1), 1–12. https://doi.org/10.1038/s41598-019-55058-1

Metherell, A. K., Harding, L. A., Cole, C. V., & Parton, W. J. (1993). *"CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS*. FT. Collins,CO. Retrieved from https://www2.nrel.colostate.edu/projects/century/MANUAL/html_manual/man96.html#CONTENTS

Palosuo, T., Heikkinen, J., & Regina, K. (2015). Method for estimating soil carbon stock changes in Finnish mineral cropland and grassland soils. *Carbon Management*, *6*(5–6), 207–220. https://doi.org/10.1080/17583004.2015.1131383

Parton, W. J., Hartman, M., Ojima, D., & Schimel, D. (1998). DAYCENT and its land surface submodel: description and testing. *Global and Planetary Change*, 35–48. https://doi.org/10.1016/S0921-8181(98)00040-X

Parton, W. J., Ojima, D., Schimel, D. S., & Cole, C. (1994). A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. Pages 147-167 in R.B. Bryant and R.W. Arnold, editors. Quantitative modeling of soil forming processes. In *Quantitative Modeling of Soil Forming Processes* (SSSA Spec., pp. 147–167). 677 S. Segoe Rd., Madison, WI 53711, USA: Soil Science Society of America.

Parton, W. J., Schimel, D. S., Cole, C. V, & Ojima, D. S. (1987). Analysis of Factors Controlling Soil Organic Matter Levels in Great Plains Grasslands 1. *Soil Science Society of America Journal*, (i), 1173–1179.

Parton, W. J., Stewart, J. W. B., & Cole, C. V. (1988). Dynamics of C , N , P and S in grassland soils : a model. *Biogeochemistry*, *131*, 109–131.

Paustian, K., Collier, S., Baldock, J., Burgess, R., Creque, J., DeLonge, M., … Jahn, M. (2019). Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. *Carbon Management*, *10*(6), 567–587. https://doi.org/10.1080/17583004.2019.1633231

Perruchoud, D., Joos, F., Fischlin, A., Hajdas, I., & Bonani, G. (1999). Evaluating timescales of carbon turnover in temperate forest soils with radiocarbon data. *Global Biogeochemical Cycles*, *13*(2), 555–573. https://doi.org/10.1029/1999GB900003

Poeplau, C., Barré, P., Cécillon, L., Baudin, F., & Sigurdsson, B. D. (2019). Changes in the Rock-Eval signature of soil organic carbon upon extreme soil warming and chemical oxidation - A comparison. *Geoderma*, *337*(September 2018), 181–190. https://doi.org/10.1016/j.geoderma.2018.09.025

Richards, G. P. (2001). *The FullCAM carbon accounting model: development, calibration and implementation for the National Carbon Accounting System* (National Carbon Accounting System Technical Report No. 28). Australian Greenhouse Office, Canberra.

Richter, D. deB., Hofmockel, M., Callaham, M. A., Powlson, D. S., & Smith, P. (2007). Long-Term Soil Experiments: Keys to Managing Earth's Rapidly Changing Ecosystems. *Soil Science Society of America Journal*, *71*(2), 266–279. https://doi.org/10.2136/sssaj2006.0181

Sándor, R., Ehrhardt, F., Grace, P., Recous, S., Smith, P., Snow, V., … Bellocchi, G. (2020). Field Crops Research Ensemble modelling of carbon fluxes in grasslands and croplands. *Field Crops Research*, *252*(September 2019), 107791. https://doi.org/10.1016/j.fcr.2020.107791

Shirato, Y., & Taniyama, I. (2003). Testing the suitability of the Rothamsted Carbon model for long-term experiments on Japanese non-volcanic upland soils. *Soil Science and Plant Nutrition*, *49*(6), 921–925. https://doi.org/10.1080/00380768.2003.10410357

Smith, J., Gottschalk, P., Bellarby, J., Richards, M., Nayak, D., Coleman, K., … Smith, J. (2010). *Model to Estimate Carbon in Organic Soils – Sequestration and Emissions ( ECOSSE ).* (Vol. 44).

Soussana, J., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., … Smith, P. (2019). Matching policy and science: Rationale for the '4 per 1000-soils for food security and climate'initiative. *Soil and Tillage Research*, *188*, 3–15.

Taghizadeh-Toosi, A., Christensen, B. T., Hutchings, N. J., Vejlin, J., Kätterer, T., Glendining, M., & Olesen, J. E. (2014). C-TOOL: A simple model for simulating whole-profile carbon storage in temperate agricultural soils. *Ecological Modelling*, *292*, 11–25. https://doi.org/10.1016/j.ecolmodel.2014.08.016

Tuomi, M., Rasinmäki, J., Repo, A., Vanhala, P., & Liski, J. (2011). Soil carbon model Yasso07 graphical user interface. *Environmental Modelling and Software*, *26*, 1358–1362.

Vaudour, E., Gomez, C., Fouad, Y., & Lagacherie, P. (2019). Sentinel-2 image capacities to predict common topsoil properties of temperate and Mediterranean agroecosystems. *Remote Sensing of Environment*, *223*(January), 21–33. https://doi.org/10.1016/j.rse.2019.01.006

Woolf, D., & Lehmann, J. (2019). Microbial models with minimal mineral protection can explain long-term soil organic carbon persistence. *Scientific Reports*, *9*(1), 1–8. https://doi.org/10.1038/s41598-019-43026-8

Wüst-Galley, C., Keel, S. G., & Leifeld, J. (2019). *A model-based carbon inventory for National greenhouse gas reporting of mineral agricultural soils (in prep)*.

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