

Extended Strategic Research and Innovation Agenda

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Abbreviations and acronyms

Acronym	Description
AI	Artificial Intelligence
API	Application Programming Interface
C	Carbon
GDPR	General Data Protection Regulation
GHG	Greenhouse Gas
ILP	Integrated Crop-Livestock System (Integração Lavoura-Pecuária)
ILPF	Integrated Crop-Livestock-Forestry System (Integração Lavoura-Pecuária-Floresta)
LTE	Long-term Experiment
LUC	Land-use change
MAOM	Mineral-Associated Organic Matter
MRV	Monitoring, Reporting, Verification
N	Nitrogen
NGO	Non-Governmental Organization
OM	Organic Matter
PU	Public
SIC	Soil Inorganic Carbon
SOC	Soil Organic Carbon
SRA	Strategic Research Agenda
SRIA	Strategic Research and Innovation Agenda
SUITMA	Soils of Urban, Industrial, Traffic, Mining and Military areas
LUC	Land-use change
SOCLUC	Soil Organic Carbon Land-use change

Executive Summary

Purpose

This deliverable presents the extended Strategic Research and Innovation Agenda (SRIA) on soil organic carbon (SOC) developed within the ORCaSa Horizon Europe project (GA 101059863). Its purpose is to identify, structure, and justify global and region-specific research and innovation priorities on SOC for the coming years. The SRIA expands and updates the previous CIRCASA agenda (CIRCASA, 2020) by considering all major land uses (cropland, grassland, forest, wetlands, Soils of Urban, Industrial, Traffic, Mining and Military areas (SUITMA)) and by integrating priorities emerging from diverse ecological, socio-economic, and governance contexts worldwide. The SRIA is intended to guide coordinated international action and to support the future Soil Carbon International Research Consortium, known as Soil Carbon Futures.

Intended audience

The SRIA is addressed to public and private research funders, international research organizations, scientists from soil science, experts in monitoring and modelling, economists, and social scientists. It is also of interest for stakeholders designing carbon certification and associated MRV systems or soil health strategies. It is particularly relevant for funding agencies participating in the Soil Carbon Futures consortium.

Description of main activities

The identification of research and innovation priorities relied on a multi-step process:

1. **Analysis of existing agendas and roadmaps**

   Nineteen SRIAs and roadmaps were reviewed, representing a wide diversity of regions and land uses. These documents helped identify common priorities and understudied areas, with special attention to non-Western regions and to socio-economic dimensions.

2. **Synthesis of scientific literature**

   Recent global evidence syntheses—including the large evidence map and second order meta-analysis by Beillouin et al. (2022–2023)—were analyzed to detect robust knowledge gaps concerning the effects of land-use change, management, and climate change on SOC.

3. **Workshops and surveys worldwide**

   Ten workshops were held across Africa, Asia, Latin America, Europe, North America, and Oceania, complemented by online surveys using Google Forms and EU Survey. Regional ambassadors supported the collection of locally contextualized priorities. In total, more than 750 priorities from 48 countries were collected and assessed.

4. **Categorization and consolidation of priorities**

   Priorities were evaluated, harmonized, and grouped by region, land use type, and topic (monitoring and MRV, impacts of practices, impacts of climate and land-use change, processes, ecosystem services, economics & social sciences, capacity building). Only true research needs—distinct from action items—were retained.

Key results

Result 1 — A consolidated global framework of universal SOC research priorities

Across all world regions, several common needs emerged, including:

- improving SOC monitoring, including subsoil horizons and under-represented soils;
- developing harmonized MRV methods and cost-effective measurement tools;
- improving models of SOC dynamics and proxies of SOC persistence/vulnerability;
- examining the impact of C-smart practices according to the soil and climate context, not to mention monitoring conventional practices;
- tackling the complexity of systems and studying the effects of several types of climate constraints that successively impact ecosystems, as well as the joint adoption of several practices
- assessing the impact of urban sprawl
- understanding biotic and abiotic controls of SOC dynamics;
- quantifying synergies and trade-offs between SOC and other soil functions and between SOC and GHG emissions;
- assessing socio-economic determinants of adoption and policy effectiveness.

These shared priorities establish a global baseline for coordinated research and for harmonizing methodologies across countries.

Result 2 — A detailed set of region-specific priorities reflecting diverse socio-environmental contexts

The SRIA provides specific priorities for **Africa & Near East, Asia, Europe, Latin America, North America, and Oceania**. These priorities vary depending on climate risks, land pressures, governance capacities, and data availability. Examples include:

- Africa: urgent need for basic SOC monitoring, evaluation of sustainable practices under nutrient-poor soils and integration of SOC with food security;
- Asia: priorities on paddy systems, biochar, erosion/flood impacts, and SOC-biodiversity interactions;
- Europe: SOC in the context of soil health policies, MRV harmonization, land use transitions, and systemic socio-economic analyses;
- Latin America: impacts of deforestation & restoration of degraded lands, impacts of integrated crop–livestock–forestry systems on SOC;
- North America: strong demand for MRV frameworks, permanence of practices, equity among landowners;
- Oceania: SOC measurement in tropical islands, water-limited systems, and integration of SOC into national accounting.

These region-specific results allow funders and governments to align research investment with local needs.

Result 3 — A structured decision-support architecture for future calls and collaborations

The SRIA provides a harmonized categorization, as a decision tree, that can help developing:

- international or regional calls for proposals;
- coordinated research programs;
- thematic networks and living labs;
- policy-relevant research strategies (e.g., carbon markets, soil health frameworks).

Using this decision tree enables international coordination, reduces duplication, and ensures that future initiatives respond to the most pressing knowledge gaps.

Research and technical implications

The SRIA provides a global roadmap for future research on SOC. It encourages the development of interoperable datasets, improved modelling approaches, harmonized measurement guidelines, and strengthened long-term experiments. It also highlights the need for interdisciplinary research combining soil science, agronomy, ecology, modelling, economics and social sciences. Technically, the SRIA will support more reliable MRV systems, better estimates of SOC vulnerability, and more precise quantification of SOC-related ecosystem services.

Policy implications

The SRIA identifies policy-relevant research needs concerning incentives, governance, equity, and long-term sustainability of SOC-friendly practices. It aligns with EU Mission Soil objectives by supporting the development of soil health indicators, harmonized monitoring systems, improved knowledge for carbon farming certification, and robust approaches to climate mitigation and adaptation.

Conclusion

This document provides the first global, region-specific Strategic Research and Innovation Agenda on soil organic carbon. It synthesizes inputs from existing agendas, scientific evidence, global workshops and surveys to deliver a robust, actionable, and internationally harmonized framework. The SRIA will guide future funding calls, foster international collaboration, support the Soil Carbon Futures consortium, and strengthen the global scientific capacity to address SOC-related challenges in climate mitigation, soil health, biodiversity, and food security.

1 Context and objectives

This region-specific Strategic Research and Innovation Agenda (SRIA) brings together the needs for new knowledge and tools, for a diversity of land uses (cultivated land, grasslands, forests, wetlands, urban areas…). The ambition is to identify context-specific priorities, in relation to local socio-economic constraints, local governance,

as well as climate, soil use and properties. This need emerged following the production of a strategic agenda for global research on carbon in cultivated soils as part of the CIRCASA project (Horizon 2020 – 2017-2020).

The SRIA is primarily dedicated to public and private research funders, international research organizations, scientists from soil science, experts in monitoring and modelling, economists and social scientists. It is also of interest for stakeholders designing carbon certification and associated MRV systems or soil health strategies. It is particularly relevant for funding agencies participating in the Soil Carbon Futures consortium.

The priorities listed herein are objective and impartial, but they are accompanied by commentary that justifies them. On this basis, users can establish their own priorities based on the issues specific to their context or their qualifications (e.g., agencies that finance fundamental or applied research projects, etc.).

2 Methodology

In order to establish a list of priorities for soil carbon research in the years to come, post-2025, we built up on six elements:

(i) the regional context and priorities which may have an impact on the topic of SOC (political, social, economic, environmental…), identified in close connection with the regional ambassadors of the ORCaSa project;

(ii) the collection of existing SRIA and roadmaps to detect shared priorities versus understudied topics, with an emphasis on SRIAs produced by under-studied regions/topics (i.e., urban soil, non-Western countries…) and on socio-economic considerations. Our starting point was the Strategic Research Agenda (SRA) on soil carbon sequestration in agricultural soils produced during the EC funded project CIRCASA (Horizon 2020 – 2017-2020);

(iii) the knowledge gaps identified in some major review papers recently published in the literature, in particular those gathered in the ORCaSa project (Scientific evidence component of Impact4Soil platform);

(iv) the organization of workshops worldwide, with the support of ORCaSa regional ambassadors to collect research needs from the ground;

(v) the dissemination of online surveys on ORCaSa social media and in scientific networks;

(vi) the solicitation of the scientists involved in the Thematic Annual Programming built in the ORCaSa project to react on the SRIA.

2.1 Building on existing strategic research and innovation agendas related to SOC

We collected 19 roadmaps on soil organic carbon or more generally on soil, with mention of actions regarding SOC. Most of them are agendas from Western countries, but we collected a couple of agendas in Brazil and Africa (see Table 1).

Table 1 Strategic Research and Innovation Agendas collected on the 25th of August 2025

Roadmap name	Release date	Region
Action plan for the preservation of forest soils	2025	France
Preparing the ground for healthy soils: Building capacities for engagement, outreach and knowledge. PREPSOIL	2025	Europe
Preliminary assessment of the knowledge gaps to conserve and increase soil organic carbon stocks. Soils for Europe. SoLo	2024	Europe
A roadmap for upscaling carbon farming in Flanders (Belgium)	2023	Belgium
the Australian Soil Plan Action for 2023-2028	2023	Australia
Global assessment of soil carbon in grasslands – From current stock estimates to sequestration potential - FAO	2023	Global
CCARBON 2023	2023	Brazil
Preservation and Restoration of Forest Soils in West Africa. Synthesis Report of the International Seminar - Abidjan	2023	West Africa
Roadmap of the CaSa network (Carbone des Sols pour une agriculture durable en Afrique)	2023	Africa
Blueprint for Forest Carbon Science in Canada	2023	Canada
Accelerating decarbonization in the USA : technocolgy, policy, and societal dimension	2023	USA
Soil Mission Support	2022	Europe
Global Peatlands Assessment: The State of the World's Peatlands	2022	Global
TSARA "Sols et Climat"	2022	France - Africa
Embrapa on the Climate Change project portfolio.	2022	Brazil
EJP Soil Deliverable 2.4: « Roadmap for the European Joint Programme SOIL"	2021	Europe
Strategic Research Agenda (SRA) on Soil Carbon (CIRCASA)	2020	Global
Negative Emissions Technologies and reliable sequestration : a research agenda	2019	USA
4p1000 Research priorities	2017	Global

Most of these agendas focus on cropland, but there are also a few agendas specific to forest, grassland, and wetland.

In North America, our regional ambassadors also recommended consulting websites of on-going programs to collect complementary priorities (see Table 2).

Table 2 On-going research programs consulted for collection of priorities

On-going Program visions
Soil Health Institute (https://soilhealthinstitute.org)
CalRecycle (https://calrecycle.ca.gov/)
Solutions from the Land (SfL) Network (https://www.solutionsfromtheland.org/network/)

2.2 Building on the scientific literature

Major efforts have been made in recent years to deliver some synthetic overviews about the status of knowledge on soil organic carbon and identify the key challenges for research and innovation. We selected recent reviews of the literature in the broadest sense (systematic reviews, meta-analyses, papers identifying research priorities or knowledge gaps) and compiled their content (see Table 3).

Table 3- Selected scientific publications

Scientific publications	Release date
Wellbrock et al. Annals of Forest Science. There is a need to better take into account forest soils in the planned soil monitoring law of the European Union.	2024
Vermeulen et al. Nature Sustainability. A global agenda for collective action on soil carbon.	2023
Beillouin et al. Nature Communications. A global meta-analysis of soil organic carbon in the Anthropocene.	2023
Rumpel et al. Ambio. The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy.	2020
Mayer et al. Forest Ecology and Management. Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis.	2020
Pellerin, Bamière et al. INRA study. Stocker du carbone dans les sols français, Quel potentiel au regard de l'objectif 4 pour 1000 et à quel coût ?	2020

In particular, the publications by Beillouin and his collaborators provided a robust basis for the SRIA building.

They conducted a global and systematic synthesis of meta-analyses of SOC stocks or concentrations and their related original studies in the form of an evidence map (e.g., Beillouin et al., 2019; Chausson et al., 2020), to get a clear understanding and a critical assessment of current research efforts on the determination of changes in soil carbon. The aims of an evidence map are (i) examining the extent, range, and nature of research activities on a particular topic; (ii) summarizing and disseminating research findings; and (iii) identifying research gaps in the existing literature (Anderson et al., 2008; Arksey & O'Malley, 2005; Colquhoun et al., 2014; Levac et al., 2010). Beillouin et al. (2022a) compiled a comprehensive database of published meta-analyses (217 meta-analyses) of SOC stocks or concentrations and retrieved their original studies (13,623 studies). Based on the evidence map, they identified knowledge gaps, which are among the building blocks of this SRIA. The methodology is briefly described in Figure 1. Unlike a meta-analysis, an evidence map does not allow to calculate a mean effect across a pool of collated studies. To bridge this limitation, Beillouin et al. (2023) carried out a second order meta-analysis based on an update of the above-mentioned comprehensive database of published meta-analyses. Indeed, their analysis combined 230 first-order meta-analyses, that synthesized the results of more than 25,000 primary studies and 190,200 paired comparison data. This second order meta-analysis includes over 220 specific drivers of SOC change, representing the direct and indirect effects of human interventions including land-use change, land management, and climate change. To our knowledge, this is the first of its kind and most comprehensive effort to synthesize global data on SOC and assess the impact of SOC change drivers. The quantitative results of this second order meta-analysis feed the identification of knowledge gaps and is another building block of this SRIA.

The detailed methodologies related to the evidence map and the second order meta-analysis are available respectively in Beillouin et al. (2022a), Beillouin et al. (2022b) and Beillouin et al. (2023). Additionally, the comprehensive database of published meta-analyses is available: https://doi.org/10.18167/DVN1/KKPLR834. Finally, these data are displayed in the "Scientific evidence" component of Impact4Soil platform https://www.impact4soil.com/scientific-evidence/

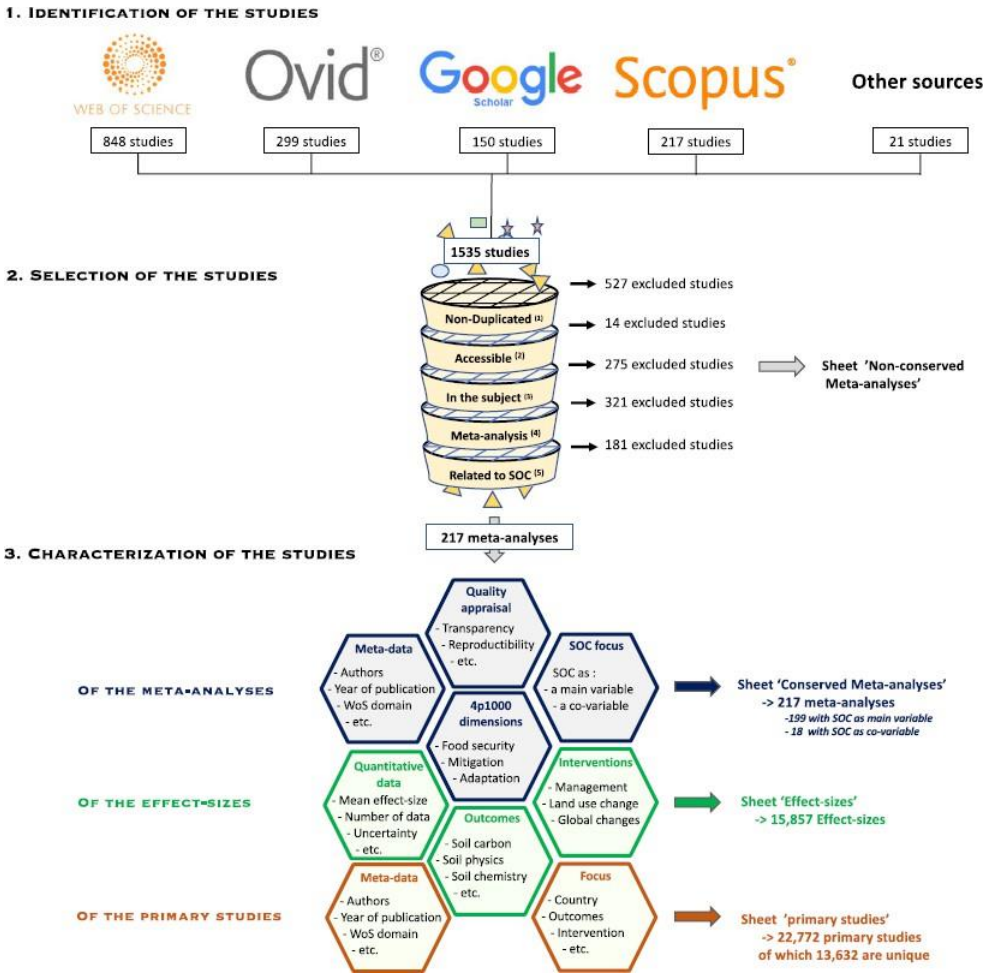

Figure 1- Methodological framework used to identify and characterize the data included in the database. Criteria for study selection are (1) duplicates are removed; (2) only studies published in English (non-English studies: n = 7) with available text (studies with non-available text: n = 7) are considered; (3) studies not dealing with SOC are excluded; (4) only meta-analyses are included; (5) the meta-analysis present at least one effect-size, i.e. a quantitative measure on SOC (or one effect-size described for different levels of SOC contents, i.e. SOC as a covariable). The hexagons represent the different characteristics analyzed in the meta-analyses or in the primary studies.

2.3 Organizing workshops worldwide

The collection of priorities already published in the literature or in the existing roadmaps for research on SOC has been completed by the organization of 12 workshops worldwide to collect priorities from the ground, especially in under-represented regions or soil uses.

Table 4 List of dedicated workshops

Date	Workshop type and place
2024 April	MRV workshop in Oceania (in Australia and in Fiji)
2024 August	Economics and social sciences "pre-workshop"
2024 October	5 workshops in Africa (Cameroun, Democratic Republic of Congo, Benin, Madagascar, Morocco), based on Impact4Soil (ca 150 attendees)
2024-2025 Winter	Workshop at the ISMOM conference in Japan, focus on processes controling SOC dynamics (ca 150 attendees)
2025 May	Workshop in SE Asia, based on Impact4Soil (20 participants)
2025 May	MRV workshop in the USA (ca 40 attendees)
2025 June	Workshop in Kenya, based on Impact4Soil (ca 40 attendees)
2025 October	Workshop on anthropogenic soils at the SUITMA conference in Italy

Depending on the timeslot available, we proposed two kinds of activities: either short questions asking about the main priorities of the participants concerning future research on SOC and the justification of the priorities, or a 1.5-hour activity, collecting priorities as well as informing on the Impact4Soil platform, and using it to get more in detail into the research needs (see Appendices).

The economic and social sciences (ESS) section was often rudimentary or lacking in the existing agendas and roadmaps we collected and analyzed, and specific attention has been paid to collect more items on this topic. As we wished to get inputs from ESS experts, we decided to conduct separate workshops on ESS topics linked to soil carbon, when possible. Priorities mentioned in this field often tend to mix actions to be undertaken and challenges to be met with research gaps. This is why we designed the ESS workshop a bit differently to sort out research priorities from actions, complete and update the research needs in economics and social sciences on the soil carbon issue. There is still a need to reach the ESS communities in the regional nodes and among partners and this work will continue within the Soil Carbon Futures association.

2.4 Disseminating on-line surveys

Finally, we created on-line surveys using google forms or the EU survey tools and disseminated them using ORCaSa social media and our networks.

2.5 Methodology for synthesizing priorities into a shortlist

As mentioned in the introduction, the ORCaSa strategic research and innovation agenda (SRIA) will be used by funding agencies to select relevant research topics for national, regional or international calls for projects. This is why it is important to identify and separate "theoretical and applied research items" from "action items". Only challenges and "theoretical and applied research" items were included, along with a justification on why they are relevant in this region or for this land use type.

We then categorized each priority by major topic (monitoring, tools, practices, processes, climate change, land-use change, ecosystem services, economics and social sciences, capacity building), by geographical area(s) concerned (e.g., Africa, Asia, Europe, Latin America, North America, and Oceania), and by land use type(s) (i.e., cropland, grassland, forest, wetlands, urban land). For each of the major regions of the world, we analyzed and summarized the priorities by topic and land use. In this summarizing phase, we paid more attention to priorities recorded in agendas or collected during workshops than to priorities raised in online surveys. They were considered more relevant due to the discussions among scientists/stakeholders that accompanied the identification of priorities in the

first two activities. Finally, for each region, the local Ambassador reviewed and validated the priorities' summary.

Note that there are some differences in the summary phase between soil sciences and economic and social sciences. Within the "economic and social sciences" and the "capacity building" topics, we first grouped priorities by broad items, to facilitate the comparison of the various regions afterwards, and provided more detailed explanations in the spreadsheet.

Broad items and regional-related knowledge gaps are provided in Appendices 7 to 7.7, and in a mind-map on the Soil Carbon Futures website (See MIND MAP in Soil Carbon Futures website in the "Resources" section for an overview).

3 The ORCaSa Strategic Research and Innovation Agenda on SOC

3.1 Presentation of global priorities

A number of priorities, often highlighted in global agendas or literature reviews and meta-analyses, are shared by all regions of the world. They are categorized into five sections: SOC measurement and associated tools, impact of natural and anthropogenic pressures (management practices, land-use changes, climate change) on SOC stocks, process-oriented research, SOC-dependent ecosystems services, economics policy and social sciences, as well as capacity building.

See Excel Table for the list of priorities in Appendix 7, also represented in the form of a mind-map available online on the Soil Carbon Futures website (see Soil Carbon Futures website in the "Resources" section for an overview).

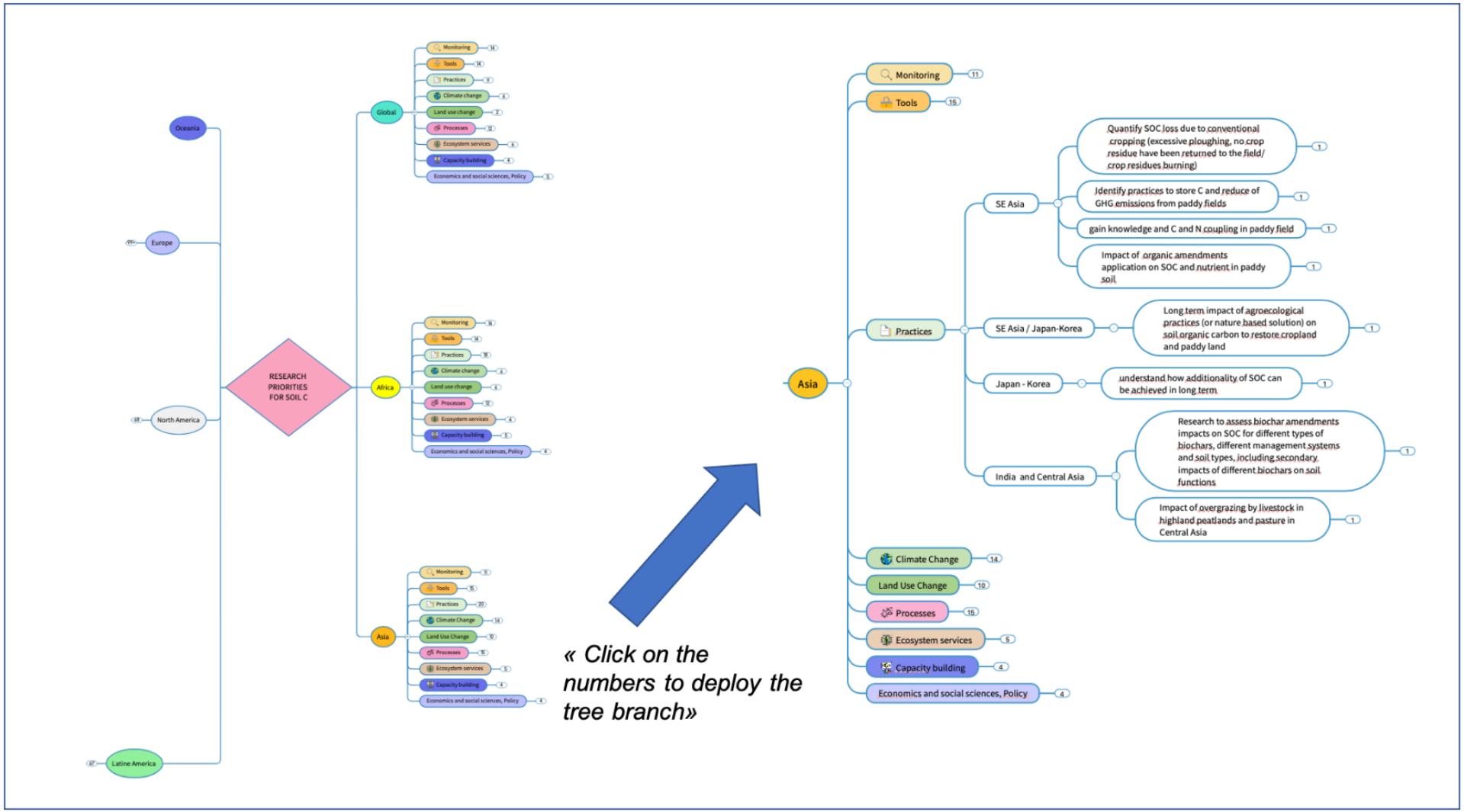

Figure 2- Mind-map of research priorities, available on the Soil Carbon Futures website. Priorities are detailed by region of the world and broad topics (monitoring, tools, practices, climate change, land-use change, processes, ecosystem services, capacity building, and economics and social sciences), along with an explanation of why it is a priority. They can be further detailed by type of land use or sub-region. Users can develop only the branches that interest them.

3.1.1 Monitoring and tools' development

Figure 3, taken from the meta-analysis by Beillouin et al. (2023), illustrates the significant regional disparities in the distribution of studies investigating SOC change. Africa was the least investigated continent, while the highest number of studies on SOC change were conducted in the United States and China, followed by Brazil, Canada, Australia, India, and some European countries (the United Kingdom, Germany, Spain and Italy). Enhancing the SOC monitoring of under-represented regions worldwide is then essential. If territorial boundaries are not considered, the under-investigated soils include highly weathered soils in tropical regions, drylands, wetlands and remote mountainous or subarctic areas, as well as degraded soils and soils in urban, industrial, traffic, mining and military areas (SUITMA). Sample collection in deep soil horizons should also be strengthened. Ideally, monitoring would follow a harmonized protocol and be supplemented by additional data on soil properties, management and ecosystem functioning (e.g., plant production, soil fertility...).

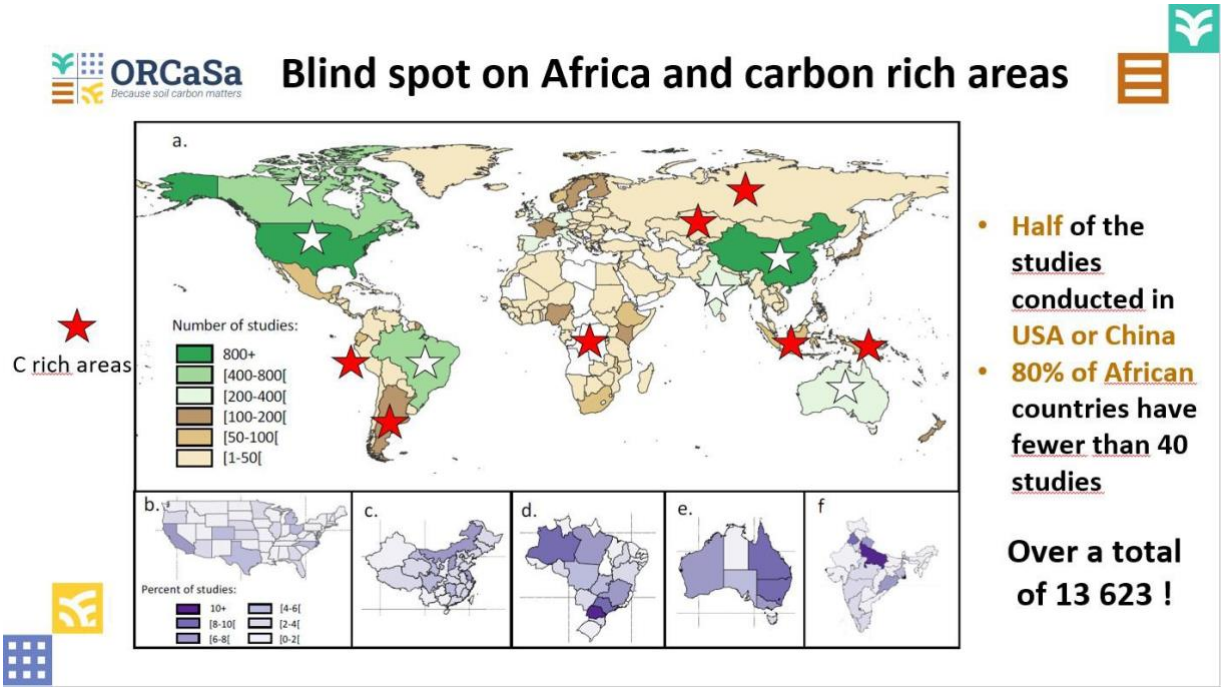

Figure 3- Locations of the original studies included in the meta-analysis by Beillouin et al. (2023).

Another important global priority is to identify the most promising sites for additional carbon storage if best management practices are applied and maintained, and to develop monitoring in SOC hotspots (SOC-rich areas), which could be sensitive to climate change and land-use change or management practices. For example, this could be done in Kazakhstan, Papua New Guinea, Peru, Oceania, and Africa, especially in the Congo Basin (see Beillouin et al., 2022a and Figure 3).

Finally, setting up and supporting long-term experimental observatories should be prioritized. Enhancing the SOC monitoring of under-represented regions worldwide is essential. This includes highly weathered soils in tropical regions, drylands, wetlands, remote mountainous or subarctic areas, as well as degraded soils and soils in urban, industrial, traffic, mining, and military areas (SUITMA).

Monitoring should be supported by the development of novel tools that diversify the options and methods for acquiring data, whether low-cost and high-throughput (notably for measuring GHG emissions) or based on digital technologies. This diversification of acquisition tools should be supported by the development of harmonized recommendations for SOC monitoring, reporting, and verification, which are essential for carbon credit certification in particular. Georeferenced databases should be created and shared worldwide to provide a robust foundation for further analysis. Models of SOC dynamics should be improved by introducing equations to report the impact of practices, coupling with climate or hydrological models, etc. Finally, SOC monitoring should be complemented by developing robust and repeatable methodologies to isolate C pools serving as proxies for vulnerability/persistence (e.g., OM in association with minerals is currently being promoted as a proxy for pluri-decadal stable SOM). However, the concept is not supported by a robust protocol, and furthermore the persistence of C in this pool still needs to be precisely quantified in a variety of contexts).

3.1.2 Impact of natural and anthropogenic pressures on SOC

3.1.2.1 Impact of practices on SOC

Global knowledge gaps about the impact of practices have been recorded in the publications by Beillouin et al., 2022a and 2023, based on the meta-analysis of meta-analyses they conducted. They are presented and justified in Table 5. (Note that many knowledge gaps are related to both a limited number of observations and a high variability in SOC change impact).

Table 5- Land use-specific knowledge gaps, according to Beillouin et al., 2023

Land use type	**Research priority on** management practices for their impact on SOC change and GHG balance	**Rationale**
Croplands	perennial crops/orchards, perennial energy crops, crop rotation, plastic film mulching, species mixture, liming, crop diversification, irrigation, deep-rooted annual crops, application of crushed silicate rocks.	- limited number of observations - relevant practices for agroecological practices or adaptation to climate change - putative mitigation potential
Croplands	biochar, organic amendments vs. mineral fertilizers, organic amendments, mineral fertilization.	- high variability on SOC change impact - putative high mitigation potential
Forest lands	species mixtures, intensity of harvesting, conifer vs. hardwood stands, litter removal, prescribed fire.	- limited number of observations - relevant practices for adaptation to climate change - putative mitigation potential
Forest lands	intensity of harvesting, conifer vs. hardwood stands, forest degradation, prescribed fire	- limited number of observations - relevant practices for adaptation to climate change - putative mitigation potential

Land use type	**Research priority on** management practices for their impact on SOC change and GHG balance	Rationale
Grasslands	organic amendments, biochar, agroforestry, species mixtures, liming, litter removal, intensity of grazing.	- limited number of observations - relevant practices for adaptation to climate change - putative mitigation potential
Grasslands	organic amendments, agroforestry, intensity of grazing.	- high variability on SOC change impact and limited number of observations - relevant practices for adaptation to climate change - putative mitigation potential
Wetlands	wetland degradation.	- limited number of observations - relevant practices for adaptation to climate change - putative mitigation potential
Wetlands	mineral fertilization.	- high variability of impact on SOC change and limited number of observations - relevant practices for adaptation to climate change - putative mitigation potential
Wetlands	wetland restoration	- limited number of observations - relevant practices for adaptation to climate change - putative mitigation potential

3.1.2.2 Impact of climate and land-use change on SOC

The work conducted by Beillouin et al., 2022a and 2023 (see Table 6) reveals the need to better investigate the impact of rainfall reduction, wildfire, snow-cover and freeze-thaw on SOC dynamics. They also highlighted the critical need for more in-depth exploration of the combined effects of climate change (e.g., summer drought together with a change in the rainfall regime). As SOC and soil water appear to be closely linked, it is important to carry out more research that explores the SOC-water nexus. Other resources we gathered also emphasized the importance of conducting region-specific studies on the impact of increased soil carbon on the resilience and adaptation of ecosystems to climate change. Such studies would provide land stewards with guidance on management strategies to maintain productivity in the face of a changing climate.

Concerning the impact of land-use change, the compilation of research priorities worldwide indicates the lack of knowledge on the impact of restoring soils degraded by human activities (e.g., restoration of drained peatlands, of deforested areas for intensive crop cultivation...). As the rate of C accrual is slower than the rate of C loss that was induced by human activity, it is necessary to repeatedly monitor the SOC content of the soil being restored over several decades.

Table 6- List of research priorities related to climate change and land-use change impact on SOC according to Beillouin et al (2022, 2023)

Research priority and description	Rationale
Need for more in-depth exploration of the combined effects of climate change (temperature, precipitation, CO_2 enrichment) on SOC (8% of the meta-analyses in Beillouin et al. 2022a). More specifically, only a limited number of observations on the impacts of rainfall reduction, wildfire, snow-cover and freeze-thaw, are currently available.	limited number of observations & impact on 100 % of land surface
Need to develop studies on the effect of wetlands conversion (8% of the meta-analyses in Beillouin et al. 2022a) and wetlands restoration on SOC (no meta-analysis).	limited number of observations & high annual potential of mitigation (1 $GtCO_{2e}$/y Bossio et al. 2020)
Need to carry out more research exploring the nexus SOC-water outcomes (i.e. water quality and soil water regulation) especially for the impacts of climate change and land-use change (see Beillouin et al. 2022a).	limited number of observations & limiting factor of water for biomass production & adaptation potential
Need to develop studies on the impacts of climate change, land-use change (LUC) or land management practices on SOC hotspots (SOC-rich areas).	limited number of observations & high vulnerability to climate change and LUC & SOC hotspots (and potential impacts of future population growth)

3.1.2.3 Process understanding

There are research priorities on SOC arising worldwide relating to the acquisition of knowledge on biotic and abiotic processes. It is widely acknowledged that control factors of SOC cycling such as climate, soil properties, nutrient and water availability vary considerably, and that research digging deeper into process understanding should account for this variability and be stratified by pedoclimate. It is important to determine the hierarchy of mechanisms affecting SOC persistence (decomposer activity, mineral protection, plant residues quality...) as a function of pedological and climatic contexts, practices, etc. Gaining insight into processes and factors controlling C association to mineral phases and turnover time of organo-mineral associations appears critical, and a widely shared research objective is to improve predictions of carbon storage and vulnerability and to resolve the current controversy related to the existence of C saturation on mineral phases. Finally, the way biodiversity controls SOC dynamics is still poorly understood and requires much more research.

3.1.2.4 SOC-related provision of ecosystem services

Soil health has become a central issue in recent years. For this reason, investigating the synergies between soil carbon sequestration and other ecosystem functions and services provided by soil is a worldwide priority. The ecosystem functions and services that attract the most attention are:

(i) soil fertility, which reduces dependence on fertilizers and water pollution caused by nutrient

leaching, depending on the region of the world;

(ii) food production;

(iii) biodiversity, which is under threat;

(iv) the impact on ecosystem resilience (adaptation to climate change and the reversal of soil degradation).

3.1.2.5 SOC in economics and social sciences

In economics and social sciences, further research is first needed to comprehensively assess the costs and benefits of land management practices in the various production systems and pedoclimatic conditions, i.e., to account not only for SOC stocks/storage and GHG emissions but also for other environmental issues, including Sustainable Development Goal targets (in relation with SOC-related provision of ecosystem services 3.1.2.4). The impact of SOC increases on productivity and resilience is of particular importance. All this information is useful to (better) design and assess policies, and to facilitate the adoption of cost-effective practices that are relevant to the local context.

Given the specificities of carbon storage in soils, the cost-effectiveness of various types of incentives and policy instruments still needs to be investigated to support decision makers. The investigation should address the distribution of the costs, risks, and benefits of implementation among stakeholders, and extend to the impacts of existing non-climate policies on SOC levels, as well as on food security and other SDGs.

Research is also needed to further identify the barriers, drivers, and levers to the (long-term) adoption of carbon-friendly practices, by drawing lessons from existing case studies and policies.

3.1.2.6 Capacity building on SOC

Needs for capacity building collected in the agendas correspond to actions rather than research questions. They mainly focus on networking farmers with other stakeholders to facilitate knowledge exchange and data collection through participatory approaches, and on providing training programs for policymakers, NGOs, and extension officers on SOC integration into national policies.

3.2 Presentation of region-specific priorities

The priorities presented in this section are region-specific. They were either mentioned in the local agendas we had access to, or in the responses of local people to our online and on-site surveys. The respondents were asked to explain how critical the priorities are in the local context. The priorities then differ across regions due to geographical, environmental but also political and socio-economic contexts. As the priorities reported in each region are shaped by existing local agendas and local stakeholder contributions, the resulting lists of local priorities should not be considered exhaustive. In addition, priorities identified in one region but absent in others may nevertheless hold significant relevance or limited applicability elsewhere, depending on contextual factors.

This regional breakdown of priorities carried out in ORCaSa is a new feature compared to CIRCaSa. This is a first step that will be further developed by regional nodes within the framework of Soil Carbon Futures. The collection of

regional priorities must be continued for certain topics that have not been explored exhaustively. It would also be very interesting to address sub-regional diversity and refine context-specific priorities tailored to smaller regions and land use systems.

3.2.1 Africa, and Near East

We collected 82 priorities through workshops organized in May 2025 with Fara in Kenya and in winter 2024-2025 in Madagascar, Cameroun, Benin, Morocco and Democratic Republic of Congo with the support of the CaSA network. They were completed by priorities from the CaSA network agenda and the synthesis report on the seminar on “Preservation and Restoration of Forest Soils in West Africa”. We also included 91 priorities collected from global agendas or resources, which were considered applicable to the African context. Finally, the list of priorities was completed with responses from online surveys. A dozen responses coming from the Near East were also reported, due to similarities between the context of the Near East countries and North Africa countries.

3.2.1.1 Geographical, economic, and political elements of the regional context with implications on SOC

Food security and poverty remain pressing challenges for Africa’s growing population. Increasing agricultural production and securing farmers’ livelihoods, while avoiding further deforestation, have therefore become urgent priorities.

In many deforested regions, intensive biomass extraction and excessive pesticide use have severely depleted soil organic carbon, degraded soil health, and reduced soil ability to sustain crop yields. To restore these soils and maintain productive agriculture, fertilization alone is not enough. Urgent action is needed to adopt practices that rebuild SOC levels and harness the benefits of soil organic matter to improve overall soil health.

At the same time, African farmers are facing a sharp decline in development aid and often struggle to navigate relationships with multiple international partners. They seek a new and independent voice grounded in their own knowledge and experience, while also calling for greater support from policymakers and investors.

3.2.1.2 Priorities for Africa

See Excel Table for the list of priorities in Appendix 7.2 and the online mind-map on the Soil Carbon Futures website.

(a) Monitoring and tools’ development

With regards to the African context, and to the limited knowledge about SOC stocks and storage in Africa mentioned previously, the overarching key priorities for research and innovation across Africa include a strong necessity for improved and accurate monitoring of SOC as well as long-term monitoring of the effects of practices (expected to improve SOC sequestration, but mainly food production and soil fertility). It is also important to intensify the monitoring effort in tropical peatlands, notably in the DR Congo Basin, which represent a major SOC hotspot, highly sensitive to climate change. Ideally, SOC data collection should be done according to a region-specific collection scheme.

This effort for data collection should be accompanied by the development of new low-cost and high throughput tools to measure C stocks and soil properties as a priority, with a harmonized methodology. This is a general need across

land uses, but specific attention should be paid to forest soils (in conservation, degraded by intensive cocoa production or restored areas), to urban soils, as urban areas expand rapidly and to soil in mining areas, due to the importance of this activity.

The assessment of C fluxes (GHG emissions and input to soil) would also be an important objective. In parallel, it is essential to set up long-term experiments to monitor SOC dynamics in Africa, as they are currently a crucial missing element.

(b) Impact of practices on SOC

Because of the rapid growth of population in Africa and the yield gap for many crops, agricultural production systems must produce more food, without compromising the environment. The key priority is then to locally measure the impact of sustainable management practices expected to increase SOC content and soil fertility (e.g., biochar application, crop residues restitution, plant cover, liming, slash burning, optimum fertilization, reduced tillage, crop rotation, species association, agroforestry, perennial forage, organic waste recycling...) on SOC stock and plant production. Taking the local data to consider the specificity of the pedoclimate and the agricultural practices would be a key point to foster the adoption of these practices.

Due to their widespread usage and the lack of information on their impact on SOC, the traditional practices implemented for cash crop cultivation (e.g., pineapple, cotton, peanut) or market gardening should also be investigated.

(c) Impact of climate and land-use change on SOC

In Africa, the manifestations of climate change vary geographically. In North Africa, severe drought has been observed and sudden intense rainfall events cause dramatic soil erosion. In sub-Saharan regions, climate change is characterized by delayed rainfall and shifting seasons leading to an unpredictable timeframe for the crop-growing season. Globally the impact of climate change on the frequency of wildfires and their subsequent role on SOC are not known. Knowledge is also lacking about how SOC may contribute to soil resilience when facing these extreme climatic events.

Due to the very high demand for food production, cropland is expanded at the expense of forest and grassland, but information on how this affects C stocks is sparse and should be improved, taking into account local pedoclimatic conditions. More knowledge on how the major expansion of urban area and the development of mining activities impact SOC is also required. One respondent from the Near East pointed out the need to assess the effects of war and bombs on soil functioning and SOC dynamics.

(d) Process understanding

Africa is also characterized by very specific soils. Further research is required to facilitate a more comprehensive understanding of the biotic and abiotic processes that govern the cycling of soil organic carbon in highly weathered soil. This research should specifically address the impact of macrofauna, nutrient limitation, the quality of organic matter input (plant cover, root/shoot ratios), and pedoclimate. The impact of salinity and sodicity on C dynamics should also be better investigated in arid regions around the Mediterranean Sea.

(e) SOC-related provision of ecosystem services

As previously mentioned, Africa is facing challenges in supplying a fast-growing population with food and restoring the fertility of degraded soil. It is therefore crucial to explore the co-benefits of SOC storage on nutrient supply and crop yield, in the short and the long-term and in relation with water management. However, storing SOC needs biomass, and biomass management could be challenging. For this reason, it is also important to evaluate the trade-offs between SOC storage and food/fibers production. Finally, it was not mentioned by people who attended the

workshops in Africa, but knowledge on the impact of increased soil carbon on adapting to climate change and arresting or reversing land degradation would be a major research output in the coming years.

(f) SOC in economics and social sciences

In Africa, few regional-specific research needs were expressed in the fields of economics and social sciences, the others coming from agendas at the global level. But this does not mean that there are actually no needs on the costs and benefits assessment of practices, or on the types of incentives or policies to be enforced to increase the adoption of SOC-friendly practices and preserve soil health. The former is included in the need to produce data and exchange knowledge (in general), and the latter two are often related to policy advocacy and funding that are frequently mentioned. This constitutes a barrier to the wide adoption of “positive” practices. In this sense, it seems very important to provide comprehensive information to farmers and stakeholders on all the (long-term) benefits and costs of changing land management and land use (see ecosystem services and practices). For example, when it comes to forest conservation, SOC data is needed alongside flora biodiversity data to provide further support for forest protection. The influence and economic interests of the various stakeholders, in particular of the agro-industries, in policy design and development must be accounted for.

(g) Capacity building on SOC

Capacity building of all stakeholders is an important regional challenge. This can be done by promoting participatory approaches and encouraging links between theory and practice, between scientists including technical personnel, non-governmental organizations, agricultural advisors, and farmers. Researchers' and technical staff's capacity building on the issue of soil carbon, across disciplines and for various types of soils and land uses, by training and networking, is also specifically mentioned. Acculturation to carbon credit schemes is also important for farmers to make decisions with full knowledge of what is at stake. Finally, policy advocacy and a sociocultural change of attitude are also required to make things change in the long-term.

3.2.2 Asia

We were unable to find any detailed research agendas specific to this area. This may be because prospective activities are not as common as they are in Europe. As a result, the priorities listed in the SRIA originate from the activities that we had the opportunity to propose at the International Symposium on the Interactions of Soil Minerals with Organic Matter and Microbes (ISMOM), which was organized by Tsukuba University in Japan in October 2024, and at the quadripartite meeting organized by the regional ambassador of ORCaSa in Southeast Asia that brought together around thirty partners from Laos, Cambodia, Thailand and Vietnam in a meeting organized at the Soil and Fertilizer Institute (SFI, Hanoi) with the co-support of the French Institute of Research for Development (IRD) in May 2025. Twenty-two items were collected from the Japanese symposium and twenty-three from the Southeast Asian workshop.

Additionally, we attended a large meeting on biochar in India in February 2025. We summarized the research questions on biochar in soil arising during the meeting into one priority.

Despite our efforts, we were unable to collect priorities from China. Our initial survey using Google Forms was not accessible to Chinese colleagues. We then proposed an alternative survey using EU forms but received no responses.

Due to the current international context, we did not contact our Russian colleagues.

Given the significant heterogeneity of Asian contexts, we have chosen to differentiate the priorities for Japan and

South Korea (22 items) from those of Central Asia (4 items) and Southeast Asia (26 items). We also included 84 priorities collected from global agendas or resources which were considered applicable to the Asian context.

With minimal contributions from India and no contribution from China or Russia, we acknowledge that the Asian SRIA is still very incomplete and will require amendment in the coming years. Nevertheless, it could be of high interest for international collaboration with countries in Southeast and East Asia.

3.2.2.1 Geographical, economic, and political elements of the regional context with implications on SOC

Asia is a vast continent encompassing a great deal of geographical, political, economic, and social diversity. It is characterized by diverse landscapes, ranging from mountainous uplands to fertile plains, volcanic areas and salt-affected coastal zones, which shape a wide variety of land use systems. Probably the largest commonality in many parts of South, South-East and East Asia is a monsoon climate (hot and wet summer) under which people developed the rice paddy production system, presumably a few thousand years ago – but other crops such as cassava, maize, and rubber are also widely cultivated. Sustainability of the terraced rice paddy system is well known. The terrace building to collect/keep water was an amazing ancient technology, and its important function includes trapping soil particles and nutrients eroded from the upper parts of the landscape. There is ample evidence of higher SOC storage in the paddy system than the upland systems under the same climate and soil type, but now the big question is the trade-off with CH_4 emissions. Other important aspects are biodiversity and trace metal biogeochemistry. Controlling wet/dry or redox conditions in paddy soil is a sensitive issue not only for biodiversity but also for human health, as the degree of rice uptake of toxic metals (such as cadmium and arsenic) is very sensitive to redox and pH conditions.

Other challenges also include shifting cultivation and upland maize farming that often accelerate soil erosion and SOC depletion; while the expansion of rubber and other plantations frequently drives deforestation, reducing SOC stocks in natural ecosystems. Ensuring a balance between agricultural productivity and sustainable land management is therefore critical to maintaining SOC, supporting climate change mitigation, and safeguarding long-term soil fertility.

Legislation and engagement in international programs for carbon sequestration remain highly uneven across the region. Proactive steps align with global climate agreements, piloting carbon market mechanisms, and promoting sustainable agricultural practices, while initiatives such as REDD+ and voluntary carbon projects are likely to offer interesting perspectives in the future. This diversity reflects contrasting governance capacities, economic priorities, and levels of integration into international climate frameworks.

3.2.2.2 Priorities for Asia

See Excel Table for the list of priorities (Appendix 7.3) and online mind-map on the Soil Carbon Futures website.

(a) Monitoring and tools' development

With regards to the above-mentioned context, in SE Asia, there is a critical need to increase SOC measurements and acquisition of activity data to better understand the impacts of changes in farming practices either degrading SOC stocks or sustaining them. It requires continuing the development of accurate and cost-effective methods for SOC assessment, but also for the measurement of non-CO_2 GHGs since paddy fields are responsible for large

GHG emissions. Workshop participants emphasized the need to collect data on ecosystem services such as food production, soil fertility, and biodiversity and on the socio-economic aspects associated with farmers' decisions, as critical components of decisions on soil management.

A couple of survey responses came from Mongolia and related the difficulty to scale up soil carbon measurements when the amount of data is sparse and the diversity in landscapes (from mountain steppe to arid semi-desert steppe), soil types, land uses, and level of degradation due to intensive grazing locally is great. They pointed to the potential of remote sensing technology and AI to resolve this issue.

In Japan and South Korea, the density of SOC measurements is much better than in the other Asian regions. Monitoring efforts should rather concentrate on enhancing the types of data collected together with bulk SOC measurements such as assessment of C pools, measurement of microbial activity, knowledge about management history… so as to gain a better understanding of processes controlling SOC. Priorities also include the need to explore SOC in diverse pedoclimates and to sample the subsoil. The need for the development of digital soil mapping to facilitate knowledge transfer to managers and decision makers was also mentioned in Japan and South Korea.

(b) Impact of practices on SOC

As mentioned above, rice is an important component of the agricultural production system in South and East Asia. Paddy fields are often poorly fertile and are responsible for large non-CO_2 emissions. It is therefore critical to identify sustainable practices to store more C, reduce GHG emissions, and minimize fertilizer use. Understanding the coupling of the C and N cycles in paddy fields would facilitate progress in this area.

Progress must also be made in quantifying SOC loss due to conventional cropping methods such as excessive ploughing and not returning crop residues to the field or burning crop residues. The impact of sustainable management practices and nature-based solutions that are expected to increase SOC content and soil fertility must also be measured. This would foster their adoption. Particular focus should be given to characterizing the impact of biochar amendment on SOC for different types of biochar, management systems, and soil types, including the secondary impacts of different types of biochar on soil functions. Biochar production would indeed be an efficient practice for eliminating large quantities of crop residue and preventing air pollution caused by burning it.

(c) Impact of climate change and land use on SOC

Asia is severely affected by climate change, and there is an urgent need to implement regional studies. In Southeast Asia, the focus should be on the impact of drought, heavy rainfall, and flooding on erosion and SOC loss while in the plateaus and mountains of Central Asia the focus should be on global warming – which could also be an opportunity for cropland development where water is available.

China and South Asia currently have the fastest growing populations and urban expansion in the world. It is crucial to investigate the impact of city development on SOC storage and other soil functions. The impact of air pollution on SOC must also be assessed, as some of the world's largest polluted cities are located in Asia. Deforestation is also a critical issue. There is a lack of knowledge about how SOC evolves after the conversion of deforested and degraded soils into commercial croplands. Efforts should also be undertaken to better integrate the multifunctionality of agroecosystems and the role of ecological heterogeneity and landscape complexity. This includes addressing the maintenance of ecological corridors, groves, or forest patches.

(d) Process understanding

There is critical need to increase the knowledge of several key components of carbon cycling in soil. The interaction between SOC and plants must be better understood, and research into novel varieties with increased root

production must be conducted to assess their impact on SOC storage. The influence of the taxonomic and functional diversity of decomposers should also be addressed, as should the reciprocal interactions between soil organic matter and the dynamic physical structure of soil. Specific attention must be given to mineral-associated organic matter (MAOM), which is poorly studied outside temperate soils or subsoils and is expected to be highly specific to tropical soils and volcanic soils in Japan, for example. Knowledge is needed on the mechanisms governing its dynamics and on quantifying the residence time of carbon in it. Research effort should also focus on understanding the temporal dynamics of soil physical structure and its mechanistic relations with SOC dynamics and association with minerals.

(e) SOC-related provision of ecosystem services

As previously mentioned, Asia is facing challenges in restoring degraded soil and sustaining a fast-growing population. In this regard, research and innovation must not only consider SOC but also address soil health. It is crucial to explore the benefits of SOC storage for ecosystem services, as well as the possible trade-offs related to biomass use (e.g., food security versus C storage in soil), and how these change over time.

(f) SOC in economics and social sciences

In Asia, no regional-specific research needs were expressed in the fields of economics and social sciences and capacity building in the survey or workshop activities. But this does not mean that there are no needs, it only reflects the background of the workshop participants and the possible absence of regional agendas.

For this reason, we still mention priorities, coming either from global agendas or survey answers from other parts of the world that we found applicable to Asia.

In economics and social sciences, further research is first needed to comprehensively assess the costs and benefits of land management practices in the various production systems and pedoclimatic conditions, i.e., to account not only for SOC stocks / storage and GHG emissions, but also for other environmental issues pertaining to the Sustainable Development Goals. The impact of SOC increases on productivity and resilience is of particular importance. All this information is useful to (better) design and assess policies, and to facilitate the adoption of cost-effective practices that are relevant to the local context.

Given the specificities of carbon storage, the cost-effectiveness of various types of incentives and policy instruments still needs to be investigated to support decision makers. The investigation should address the distribution of the costs, risks, and benefits of implementation among stakeholders, and extend to the impacts of existing non-climate policies on SOC levels, food security and other SDGs.

Research is also needed to further identify the barriers, drivers, and levers to the (long-term) adoption of carbon-friendly practices, by drawing lessons from existing case studies and policies.

Finally, in SE Asia participants in the regional workshop consider carbon credits and carbon market as important prospects, even if it seems complicated to implement in agriculture.

(g) Capacity building on SOC

In Asia, no regional-specific research needs were expressed in the fields of economics and social sciences and capacity building in the survey or workshop activities. But this does not mean that there are no needs, it only reflects the background of the workshop participants and the possible absence of regional agendas.

For this reason, we still mention priorities, coming either from global agendas or survey answers from other parts of the world that we found applicable to Asia.

Needs for capacity building correspond to actions rather than research questions. They focus on networking farmers

with other stakeholders to facilitate knowledge exchange and data collection through participatory approaches, and on providing training programs for policymakers, NGOs, and extension officers on SOC integration into national policies.

The perspective of Pascal Jouquet (IRD), co-Ambassador for Southeast Asia

The Soil-Doctor program (https://www.fao.org/global-soil-partnership/programme-projects/programmes/global-soil-doctors-programme/en/) represents an innovative and inspiring approach to information management and farmer training. Initiated in Thailand, the system has been adopted and further developed in Laos and Vietnam with support from FAO and other international organizations, such as Australian cooperation, and is currently being expanded in Cambodia. Its main limitation is that it requires a structured organizational framework and continuous support for training stakeholders and monitoring soil health.

3.2.3 Europe

The Europe-specific SRIA includes 279 original priorities on the physical basis of research on SOC, summarized into 59 items, as well as 77 original priorities for economics and social sciences and capacity building issues. We identified 7 research agendas (delivered in the EJP Soil program, the Soil Mission Support, PREPSOIL, SoLo and CIRCASA EU projects, and in a couple of French and Belgium roadmaps). 188 individual priorities were found in the agendas. They were completed by 84 responses to an online survey and also 65 contributions from other sources (scientific literature, reports…).

3.2.3.1 Geographical, economic, and political elements of the regional context with implications on SOC

Europe comprises a high diversity of pedoclimatic conditions, ranging from Mediterranean drylands to temperate croplands, boreal forests, and northern peatlands, which result in widely diverse soils. European soils have also been shaped by a legacy of millennia of agricultural use, while industrialization and urbanization left a footprint of contamination and sealing. Recent JRC assessments state that 62% of European soils are unhealthy, being affected by at least one type of soil degradation, such as erosion, sealing, contamination, salinization, compaction, soil organic matter loss or biodiversity decline. Regarding organic soils, half of European peatlands are being degraded by drainage for agricultural use.

At the same time, Europe is at the forefront of soil policy development with the EU Soil Monitoring and Resilience Directive proposal, the Nature Restoration Law, the Carbon Removals and Carbon Farming Certification Regulation and the CAP eco-schemes, which place soil carbon at the heart of climate, biodiversity, and food security strategies. Europe is also characterized by: a relative richness in soil data, although not fully harmonized yet; remarkable infrastructures, such as the LUCAS-soil and national soil monitoring systems, the European Soil Data Center (ESDAC and now the European Soil Observatory (EUSO); and in the near future, a wide range of living labs. These provide a unique platform for developing and testing soil health indicators and MRV systems. Europe is also rich in societal debates on livestock management, sustainable diets, bioeconomy, circularity, and the agroecological transition, that are related to soil carbon.

3.2.3.2 Priorities for Europe

See Excel Table for the list of priorities (Appendix 7.4) and online mind-map on Soil Carbon Futures website.

(a) Monitoring and tools' development

Europe is data-rich but harmonization, which has progressed, must continue. About half European countries have already set up a soil quality monitoring network, measuring carbon stocks with varying inventory densities, sometimes with several campaigns available. Europe also has its own soil monitoring system (LUCAS: Land Use/Cover Area frame statistical Survey). However, some types of land use are under-sampled (e.g., soils in city or mining areas) and protocols are not homogenous across countries, so it is necessary to increase data collection for under-represented soil and to further harmonize sampling protocols and further, the sampling strategy should pay specific attention to soil heterogeneity in non-ploughed soils, such as those found in forests, cities…. It is also critical to enhance the types of data measured in conjunction with soil organic carbon content, in order to assess C fluxes (and not only stocks), investigate the factors controlling carbon dynamics, and evaluate synergies with soil functions. The monitoring of SOC fractions appears also as a priority when fractions can be used as proxies for C persistence/vulnerability in soil. It should be noted that the implementation of the Soil Monitoring and Resilience Directive will push all these priorities.

The deployment of Living Labs and Lighthouses, as promoted by the Mission Soil, is another important priority to raise knowledge and awareness on the importance of long-term soil health for land managers, industries, consumers, and society at large and to fight against ongoing soil degradation in Europe. Such entities will offer opportunities for interactions between stakeholders and scientists, knowledge sharing and co-learning.

The need to continue developing accurate, easy-to-use, low-cost, high-throughput methods, as well as advanced sensors, satellite imaging, and AI-driven analytics, was mentioned on several occasions, notably to provide robust MRV systems for SOC.

It was also mentioned that the development of interoperable and reusable databases for knowledge development should continue. This involves creating data connections (APIs) and a data infrastructure in accordance with GDPR principles, to provide access to models and digital maps, for example. In addition, it is recommended that the models and digital maps are continually improved and enriched to better guide stakeholders in their decision-making. The models must also be improved to better integrate certain flows and specific practices, and to enable coupling with climate, hydrological, or vegetation models. Given the diversity of methods and models available for measuring or estimating soil organic carbon stocks, it seems necessary to provide stakeholders with a decision tree to guide them in choosing the most appropriate method and to work on providing the associated uncertainty, and how it varies with soil type/use.

It has been acknowledged that soil properties, climate, and management type have a significant impact on soil functioning and SOC dynamics. Therefore, a key priority is to provide SOC benchmark values, emissions factors, and indicators that link SOC to ecosystem services, categorized by soil type, climate, and land use.

(b) Impact of practices on SOC

With regard to the impact of practices on SOC and on GHG emissions, the research priority for cropland is to intensify studies of sustainable practices and systems such as organic residue recycling, biochar production and use, conservation agriculture, regenerative agriculture, etc., as results vary, and to develop an impact matrix for farmers' use. More long-term studies on innovative practices (mineral amendments, digestate inputs, etc.) are also recommended. What also appears critical is investigating the impact of combinations of practices (e.g., tillage and crop rotation). In Europe, there is an increasing awareness of the dangers of plastic use (as an alternative to

herbicides, to protect the soil and prevent evaporation): research must investigate their impact on soil C stocks and find more sustainable agricultural practices. The impact of livestock management practices on SOC must also be addressed further.

In forestry, a better understanding is needed of the activities performed during harvesting, such as the intensity of harvesting and the removal of residues, as well as activities related to vegetation management, such as the choice of trees species, of monoculture vs. mixed forest, and the disturbance caused by machinery. In wetlands, it is important to investigate management practices that conserve organic matter while generating income for landowners, such as agriculture on restored peatlands. Research into SOC management in SUITMA is also in its infancy, with much still to be studied, for example the impact of mineral/organic waste application and the impact of methods to deploy urban agriculture.

It also appears important to consider not only SOC storage in studies on the effects of practices, but also non-CO_2 GHG emissions and soil health in general.

(c) Impact of climate and land-use change on SOC

The manifestations of climate change and their intensity vary greatly across Europe. The Mediterranean region experiences more fires and droughts, which can locally lead to the salinization of ecosystems (e.g., in Spain), while the north is mainly experiencing warming that favors agricultural development. In this context, the collected priorities highlight the need to investigate the role of soil organic carbon in soil resilience to climate change, and to explore the effects of climate on SOC stocks and cycling mechanisms in more depth (particularly plant inputs and the activity of decomposer communities). It is important to implement long-term experiments on climate-smart management options to assess their long-term impact on SOC.

It is also essential to integrate regional climate scenarios into models that predict changes in soil carbon stocks, in order to strengthen predictions and estimate the potential for offsetting GHG emissions by storing carbon in the soil. Research priorities regarding the impact of land-use change in Europe highlight the need to characterize more precisely the effect of soil degradation and erosion on soil carbon stocks and to focus on the effects of afforestation on the entire soil profile rather than just the topsoil. The expansion of agriculture (organic and sustainable as well as intensive) at the expense of natural ecosystems, e.g., forest or restored peatlands, must also be investigated as SOC losses are expected and possibly exacerbated with climate change. Soils that have undergone recent anthropization also require further investigation to understand the effect of sealing, the rehabilitation of former mining sites, and the effect of the military conflict in Ukraine.

(d) Process understanding

It is recognized that organic matter turnover processes are not the same everywhere but vary depending on the context. It is important to determine the hierarchy of mechanisms affecting organic matter persistence (decomposer activity, mineral protection, plant residues quality...) as a function of pedological and climatic contexts, practices, etc. Research should be done to assess whether the local control variables evolve over time and depth and what may affect this hierarchy. Further progress is needed to complete our understanding of the mechanisms of organic matter cycling. Elucidating soil-plant interactions appears to be a major obstacle. This involves understanding the influence of the quality and location of plant inputs. Belowground inputs play a major role in the formation of soil carbon stocks, but they are difficult to quantify. Another important issue is the question of synchrony between the nutrient requirements of growing plants and the availability of nutrients from the mineralization of organic matter. The development of -omics tools has enabled us to gain new insights and propose a new conceptual vision of organic matter decomposition processes, placing decomposers at the heart of the process. Nevertheless, much work remains to be done to understand the role of taxonomic and functional biodiversity in the carbon cycle in soils.

There is still no consensus on the mechanisms of MAOM formation and disruption, even though this compartment is considered to be more stable and less vulnerable to hazards than free plant residues. Reaching a consensus on the formation and disruption of MAOM (by soil type and management) is also a priority in the coming years. A significant area for future research is understanding organic-inorganic carbon interactions, given that much of Europe's soil is calcareous. Expanding the scope of research to include connections with aquatic systems and element exchange is another area that requires further investigation.

(e) SOC-related provision of ecosystem services

Further research programs in Europe should investigate the trade-offs and co-benefits between C accumulation in soil and food security, biodiversity...; this should be done at different time scales as interactions between C storage and soil functions are expected to change over time. In connection with this point, our survey respondents expressed the need to create indicators that would enable the quantity of SOC in soils to be related to the ecosystem services provided by SOC, depending on climate and soil type. Finally, it appears critical to carry out an estimation of GHG emissions that goes beyond what happens in the soils, and that takes into account the entire value chain (transport, fate of the products, etc.).

(f) SOC in economics and social science

A huge majority of topics come from local agendas and workshops (75%). They focus mainly on the cost-effectiveness of policies and instruments, the barriers and levers to the adoption of positive practices, policy coherence, and governance issues. More comprehensive research is still to be carried out on the cost-effectiveness of various land management practices, accounting for the heterogeneity of production conditions and systems, and including all environmental impacts. Compared to other world regions, the design and financing of carbon credit schemes, including carbon markets, are more often mentioned.

While there is already a substantial body of work in Europe on the abatement costs of agricultural practices, this is not the case for all land uses. In the case of peatlands, sustainable soil management practices that conserve organic matter in the soil while still generating a viable income for farmers still need to be investigated. In the forestry sector, studies mainly focus on carbon storage in the biomass. Additional monitoring/experimentation of forestry work still needs to be carried out to acquire technical and economic knowledge on recommended practices for SOC storage that also limit the impact on soil compaction and erosion; to ensure that the recommendations are operational; and to assess the additional economic costs. Another area for improvement concerns cost-benefit analyses, which must take into account all co-benefits - synergies and trade-offs- of “positive” practices, the short- and long-term effects of an increase/decrease in SOC levels at farm level, the cost of risk associated with changes in practices, as well as regional specificities, pedoclimatic context, and farming systems.

While economic and social sciences have already compared the efficiency of different policy instruments for addressing environmental externalities, there is still work to be done to account for the specificities of SOC storage (which is a long-term process, finite and non-permanent, and surrounded by uncertainty). The comparison of the cost-effectiveness of various instruments, including second-best instruments, is useful for policy design and can be done with, e.g., economic modelling and "field experiment" approaches. It is worth investigating the trade-offs of funding schemes, including carbon farming payment schemes, as well as funding in less effective measures. Ex-post impact evaluation of carbon credit schemes, in relation with MRV, is necessary to investigate the real efficiency and effectiveness of such tools and improve policy design. And, indeed, ex-post analysis of the effectiveness of existing schemes and policies, e.g., EU soil protection policies and financial incentives for sustainable farming, is of utmost importance to guide decision makers and improve the policy design.

When assessing policies and instruments, one must address the following questions: What incentives can be used

to encourage the adoption of alternative production strategies in the long term, given that the costs are immediate while the benefits and return on investment may only come several years later? Who bears the risk associated with change? How is the land rent shared between land managers and landowners? How is the economic surplus shared between farmers/forest managers and operators/intermediaries within carbon farming projects?

Assessing the impacts of existing policy instruments - not necessarily climate-related, e.g., EU Common Agricultural Policy payments, bioenergy demand, on soil carbon sequestration is useful to address policy coherence issues and can be done by modelling the removal of existing instruments. Inversely, it is important to measure the impacts of large-scale implementation of carbon farming (schemes) on prices and food security, as well as on other environmental impacts and SDGs, using economic modelling.

Even if the costs and benefits of land use/management practices are known and cost-effective policy instruments are identified ex-ante, it does not mean that they are actually adopted or successfully implemented. This is why research is still needed on the barriers and motivations of land managers to adopt sustainable or new practices, the most effective ways to overcome barriers, and the type of enabling environment to be put in place. It includes, among others, attitude towards change and risk acceptance, the complexity and cost of MRV systems associated with carbon farming schemes, access to funding, but also policy coherence across sectors and at different scales as well as governance.

In Europe, questions are raised on the consistency between adaptation to climate change, soil conservation, and sustainable land management policies, also accounting for the bio-based energy demand, on how carbon farming credits should be coordinated with carbon markets in other sectors (e.g., sectoral quotas) and on what scale. Political economy can help understanding the building of carbon policy at international scale.

For peatlands, where rewetting has a high opportunity cost, building a narrative on carbon sequestration and co-benefits, exploring paludiculture opportunities, and building a governance structure with a clear mandate and clear vision for the long term, is essential to ensure adoption.

Concerning carbon farming schemes generating carbon credits, questions remain on the best way to deal with the impermanence of carbon storage and the appropriate MRV system(s) to deal with cost-accuracy and additionality, hence creating trust in the quality of the credits. In this respect, we lack reliable public data on individual carbon credit projects and carbon credit transactions (including selling price) along the value chain, to help characterize the demand and willingness to pay for such credits depending on their quality. Information on how costs, benefits, and environmental and financial risks are distributed among land managers, operators/intermediaries, and buyers in carbon farming projects is also useful for effective carbon market design.

(g) Capacity building on SOC

Concerning farmers' capacity building, there is a lack of regional and pedoclimatic-specific guidelines on measures to maintain (i.e., prevent degradation) and increase SOC, including socio-economic effects for different farming systems, and a lack of science-based and objective information available to field users concerning the use of biochar and its impacts.

Participatory approaches, such as soil health Living Labs, Lighthouses, and knowledge hubs, are put forward to connect stakeholders, facilitate knowledge exchange, and design effective solutions. For instance, creating a knowledge hub on the technical aspects of carbon farming, such as the impact of practices on carbon sequestration, co-benefits, trade-offs, models, data infrastructure, tools, measuring protocols, quantification methods, and regional baselines, would create trust in the carbon farming ecosystem. Indeed, stakeholders need to be sure that project outcomes are quantified accurately and are comparable between carbon farming schemes. Raising awareness among stakeholders on the need to plan ahead for the management of forest sites after a storm or pest infestation

is also mentioned, in order to protect soils and their carbon stocks, as huge volumes of wood need to be mobilized and access to plots is a problem.

The need for education that increases awareness and knowledge of society as a whole on carbon fluxes, the conservation of soil organic carbon stocks, and sustainable soil management, is underlined. There is currently a lack of awareness and appreciation of the multiple benefits of increasing and maintaining soil carbon stocks, and a poor understanding of the trade-offs and synergies between soil carbon and other environmental and socio-economic objectives.

3.2.4 Latin America

44 of the priorities listed in the SRIA have been collected from the CCARBON Center and the Embrapa 2022 roadmaps, which are Brazilian roadmaps. In the coming years, this Latin America-specific agenda will require additional contributions from countries other than Brazil.

We also obtained 6 answers to the online survey and completed the list of priorities with 91 priorities from global agendas that we considered applicable to Latin America, that were validated by our regional node correspondent.

3.2.4.1 Geographical, economic, and political elements of the regional context with implications on SOC

Latin America and the Caribbean encompass a wide range of land use systems, from tropical forests to agricultural and urban landscapes, each exerting distinct influences on soil carbon dynamics. High-carbon ecosystems such as the Amazon and Atlantic Forest act as critical carbon reservoirs, and their conservation is essential to prevent substantial CO_2 emissions. In contrast, large-scale agriculture dominated by soybean and maize cultivation has historically depleted soil carbon stocks through the removal of native vegetation, although conservation practices such as no-tillage and crop rotation have demonstrated potential to mitigate these losses. Extensive livestock grazing, prevalent in regions such as the Cerrado and Pampas, can either enhance or diminish soil carbon depending on pasture management strategies. Agroforestry systems and smallholder farming often maintain or increase soil carbon through greater species diversity and nutrient cycling. Conversely, urban expansion and mining activities lead to soil sealing or exposure, severely reducing carbon storage capacity.

Soils across Latin America and the Caribbean exhibit substantial heterogeneity, reflecting the region's diverse climatic regimes and complex geological histories. In the Brazilian Cerrado, oxisols and ultisols predominate; these are deep, well-drained, highly weathered soils with low natural fertility, requiring liming and nutrient amendments to sustain intensive agricultural production. In the Amazon Basin, similar soil orders are likewise nutrient poor, with fertility concentrated in a thin surface horizon enriched by organic matter, maintained through rapid nutrient cycling in the forest ecosystem. In the Andean highlands, shallow, stony soils are widespread in mountainous terrains, whereas volcanic landscapes support fertile andisols that facilitate terrace-based cultivation. In Mexico, the arid northern regions are dominated by sandy and calcareous soils of low productivity, while the southern regions contain nutrient-rich volcanic and alluvial soils. In Central America and the Caribbean, volcanic soils underpin the production of key crops; however, calcareous soils, particularly prevalent on island landscapes, are typically shallow and highly susceptible to erosion.

Between 1990 and 2025, Latin America and the Caribbean underwent profound land-use transformations, with deforestation emerging as one of the principal drivers of environmental loss. In the 1990s, the region exhibited some of the highest deforestation rates globally, driven by the expansion of the agricultural frontier, extensive cattle ranching, logging, often illegal, and the development of infrastructure in forested areas. The Amazon, spanning

multiple countries, was the epicentre of this loss, but other biomes, such as the Brazilian Cerrado, the Argentine and Paraguayan Chaco, and the tropical forests of Central America, also experienced intense pressure. Now, the annual deforestation rate is approximately 2 million hectares of native forest destroyed each year, according to the FAO. The relative reduction compared to the 1990's was the result of conservation policies, the establishment of protected areas, international agreements, and advances in satellite monitoring. However, illegal logging, land grabbing, and the conversion of forests to agriculture and pasture have continued to undermine progress, particularly in countries with weak enforcement capacity. Beyond the loss of vegetation cover, deforestation has contributed to soil degradation. In 2025, a study by the University of São Paulo estimated that 38% of soils in Latin America and the Caribbean are degraded, because of the combined effects of deforestation, inadequate land management, and climate change. The most critical conditions are found in arid and savanna regions, while humid equatorial zones show better indicators, although the Amazon is already exhibiting signs of vulnerability. It is important to note that without the integration of environmental, agricultural, and climate policies, and without effective action against illegal activities, the goal of halting deforestation in Latin America and the Caribbean by 2030 will remain at serious risk.

Some facts about SOC stocks and deforestation in Latin America

Soil organic carbon stocks vary considerably across different land uses in Latin America and the Caribbean, as well as within each category, depending on soil type, climate, and management practices. Natural ecosystems, such as tropical forests, maintain high average SOC stocks, reaching 48–50 tons of carbon per hectare to a depth of one meter, due to continuous vegetation cover and the constant input of organic matter. In pasturelands, SOC stocks vary according to management: well-managed pastures maintain between 30 and 40 t C/ha, whereas degraded pastures hold only 20 to 30 t C/ha, primarily due to organic matter loss and erosion. Conventional agriculture reduces SOC stocks to 20–35 t C/ha, although conservation practices can stabilize or even increase soil carbon levels. Agroforestry systems sustain relatively high SOC stocks, between 35 and 45 t C/ha, owing to species diversity and permanent soil cover. Urban and mining areas exhibit very low SOC stocks, generally below 20 t C/ha, due to soil sealing and exposure. The majority of SOC in the region is stored in preserved native ecosystems. Brazil alone is estimated to hold approximately 37 gigatons (Gt) of SOC, with nearly two-thirds located in areas of stable native vegetation (the Amazon, the Atlantic Forest and Pampa biomes).

Between 2000 and 2015, some countries, such as Brazil and Costa Rica, achieved significant reductions in deforestation rates, while others, including Bolivia, Paraguay, and Nicaragua, recorded increases, often linked to soybean cultivation, cattle ranching, and the expansion of oil palm plantations. Deforestation also intensified in savanna and dry forest ecosystems, which are generally less protected than tropical rainforests.

3.2.4.2 Priorities for Latin America

See Excel Table for the list of priorities (Appendix 7.5) and online mind-map on Soil Carbon Futures website.

(a) Monitoring and tools' development

With regards to the strong necessity to restore the quality of degraded soils, the first priority is to characterize them by enhancing the monitoring of C and N stocks as well as GHG emissions, in particular in areas deforested into pasture and conventional cropping, and to document additional data on current soil conditions and implemented management. Improving the monitoring of C storage and fluxes in peatlands in also important to complete GHG inventories, despite the difficulty in accessing peatlands located in mountainous regions or in central Amazonia.

Densifying soil monitoring at the country or continent scale, with large spatial and temporal heterogeneities, will

require the development of novel remote or proximal sensing techniques. Digital platforms to store and share data in a harmonized, interoperable and reusable format should be jointly developed. The development of long-term experiment (LTE) observatories should be continued and LTEs must organize themselves into a network.

Another key technical development to implement is the production of a new generation of models accounting for Latin America-specific agricultural practices and processes.

(b) Impact of practices on SOC

A substantial proportion of degraded lands in Brazil results from unsustainable agricultural and livestock practices, including excessive soil use without crop rotation, inadequate pasture management, prior deforestation without re-establishing vegetative cover, and intensive use of chemical inputs on poorly fertile soils. These factors lead to soil compaction, erosion, loss of organic matter, and reduced soil biodiversity, thereby compromising productivity and encouraging the opening of new areas, perpetuating the deforestation cycle.

The recovery of such land demands a set of integrated strategies whose impact on SOC and GHG emissions must be assessed. These include the adoption of agroforestry systems, crop–livestock–forest integration, green manuring, riparian forest restoration, and the introduction of adapted species that improve soil structure and fertility, or the inoculation of legumes with rhizobia and mycorrhizal fungi. The impact of various livestock management systems on SOC and GHG must also be assessed.

(c) Impact of climate and land-use change on SOC

Climate change has severe repercussions in Latin America, with serious impact on plant production. There is an urgent need for regional studies to identify agricultural systems adapted to the novel climatic conditions, with positive effects on climate mitigation by enhanced C storage in soil. Studies must also better characterize the vulnerability of SOC to climate change. Restoring degraded areas within productive lands while preventing new deforestation is among the most pressing socio-environmental and economic challenges currently faced in Latin America, particularly in Brazil. It requires a delicate balance between restoring the productive capacity of soils, ensuring food security, and preserving remaining ecosystems.

(d) Process understanding

Concerning improvement of process understanding, current listed priorities focus on the role of biodiversity on SOC cycling, which is poorly known out of temperate regions, in relation with the search for sustainable biological-based practices. Better understanding of mineral-organic associations in highly weathered tropical soil is also needed. There is a willingness to make progress on the quantification of CO_2 consumed by rock weathering for the C capture credit market. Application of rock powder available from mining activity to soil could improve soil fertility and provide additional profits to farmers.

(e) SOC-related provision of ecosystem services

It is also important in Latin America to examine the synergy between soil carbon sequestration and ecosystem services. Particular attention must be paid to the effect of increased C stocks on the restoration of degraded soils and the resilience to climate change.

(f) SOC in economics and social sciences

In Latin America, a few regional-specific research needs were expressed in the fields of economics and social sciences and capacity building, others coming from the survey answers and agendas at the global level. The few specific elements do not mean that there are no other needs, it only reflects the background of the workshop participants and the limited number of regional agendas.

In economics and social sciences and in the region, there is a need to assess the cost-effectiveness of native ecosystems restoration in Brazil, and to make this information available in different formats to support the design of relevant policies. The impacts of low carbon farming systems on the resilience and adaptive capacity of agriculture, on food security, and on the rest of the economy, compared to current systems and in the face of climate change, also need further investigation. Additional information on the socio-economic and environmental impacts of the products generated by integrated systems (ILP and ILPF) along the value chain is useful to increase their visibility and capture added value as well as to design relevant incentives. The development of tools and indicators integrated into a digital platform to characterize the sustainability of agricultural, livestock, and forestry systems in the face of climate change would make it possible to evaluate, validate, or even adapt public policies, actions, and programs. A regional agenda (CCARBON, 2024) also mentions the need to build a narrative on C sequestration and co-benefits (i.e., guiding principles to adhere to) and to provide a trajectory and transition pathway toward the narrative, so that it makes sense for farmers and land managers to adopt low carbon practices or systems.

The perspective of the IRC Ambassador for Soil Carbon in Latin America and the Caribbean at EMBRAPA

Restoration of native ecosystems alone is insufficient. It is essential to create conditions that prevent producers from reverting to deforestation. This requires consistent public policies, such as payments for environmental services (PES) that financially reward the maintenance or recovery of native vegetation, dedicated credit lines for productive restoration, and market mechanisms that value products originating from restored or deforestation-free areas.

The challenge is also cultural and logistical. Many producers still perceive land clearing as a faster and cheaper solution than investing in the recovery of degraded soils. Changing this mindset necessitates expanding technical assistance, demonstrating long-term economic gains, and developing value chains that reward sustainable production. Restoring degraded areas in productive lands while preventing new deforestation requires a dual-front approach. Simultaneously recovering what has been lost and removing the incentives that drive further land conversion. This entails aligning science, public policy, economic incentives, and social awareness to transform restoration into a driver of sustainable development, rather than merely an emergency response to degradation.

Small farmers' poverty is also an issue in Latin America. Research institutes and agribusiness companies are joining forces to develop advice on best practices and simple tests to assess the level of soil degradation, so that farmers can learn about the state of their plots and what they need to do to restore or maintain their fertility. Researchers are also working on new economic models with a systemic approach. For example, for agroforestry and agro-pastoralism, how can trees be used for construction (enabling carbon storage) rather than for making paper tissues?

(g) About SOC and capacity building

Needs for capacity building correspond to actions rather than research questions. They focus on networking farmers with other stakeholders to facilitate knowledge exchange and data collection through participatory approaches, and on providing training programs for policymakers, NGOs, and extension officers on SOC integration into national policies. This is also emphasized in a Latin American agenda (CCARBON, 2024), along with the need for compiled information and data available to all stakeholders on native ecosystems restoration.

The perspective of the IRC Ambassador for Soil Carbon in Latin America and the Caribbean at EMBRAPA

Local and Indigenous knowledge plays a strategic role in enhancing soil carbon sequestration in Latin America and the Caribbean, as it is rooted in land management practices that have maintained soil fertility, vegetation cover, and biodiversity for centuries, often more efficiently and resiliently than conventional systems. These contributions manifest in several ways.

Traditional land management techniques, such as swidden-fallow systems with appropriate fallow periods, agroforestry, and diversified polycultures, help maintain soil organic matter, thereby promoting carbon accumulation. Protection of intact ecosystems is another key contribution: studies show that forests within Indigenous territories in the Amazon act as significant carbon sinks, removing hundreds of millions of tons of CO_2 from the atmosphere between 2001 and 2021. Agrobiodiversity, through the selection and preservation of locally-adapted plant varieties, increases the resilience of production systems and reduces dependence on external inputs, avoiding emissions associated with their production and transport. Integration of trees and crops in traditional agroforestry systems, common in Indigenous and rural communities, increases carbon stocks in both aboveground biomass and soils, while improving water infiltration and reducing erosion. Community-based governance, characteristic of many Indigenous societies, supports the maintenance of native vegetation and the sustainable use of resources, thereby preserving and enhancing carbon stocks. Deep ecological knowledge, encompassing understanding of natural cycles, keystone species, and environmental indicators, enables adaptive management to maximize natural regeneration and soil carbon accumulation.

Empirical evidence, such as research conducted in the Poyanawa Indigenous Territory in Acre, Brazil, demonstrates that changes in land use practices within villages have reduced deforestation and created opportunities for generating carbon credits, linking conservation with income generation. Another assessment indicates that 58% of Amazonian biomass carbon is located within Indigenous lands and protected areas, underscoring their essential role in climate regulation. Integrating local and Indigenous knowledge into climate change mitigation policies and sustainable agriculture programs is not only a matter of cultural justice but also a practical and effective strategy to increase soil carbon sequestration and maintain ecosystems as active allies in addressing the climate crisis.

3.2.5 North America

The North America-specific SRIA includes 100 original priorities on the biophysical research on SOC, summarized into 24 items, and 27 original topics in the field of economic and social sciences. We identified two important research agendas delivered by the National Academy of Sciences and used a few program roadmaps (from the SfL Network, CalRecycle, Soil Health Institute). Agendas' priorities were completed by 65 contributions collected during a MRV workshop hosted by Colorado State University.

We recognize the dominance of MRV-related questions and priorities here, which is partly a reflection of the sources used so far. The roadmap has been completed and benefited from contacts established in Canada during a week-long visit by some ORCaSa delegates in September 2025.

3.2.5.1 Geographical, economic, and political elements of the regional context with implications on SOC

North America is characterized by its vast territories, some of which are sparsely populated.

We only had the opportunity to examine the agri-food sector in Quebec in more detail. The main agricultural activities are dairy production and forestry. Cattle are kept in sheds, while much of the cultivated land is used to grow corn

or soybeans for animal feed. The growing season is short due to the climate, and the first agricultural activities at the end of winter are affected by waterlogged soils following snowmelt, which makes soil highly sensitive and leads to nutrient losses through leaching. Soils are relatively young there, and some are characterized by a sandy texture and a low fertility, making farmers highly dependent on fertilizers. Contrary to many regions in the world, climate change and global warming may be an opportunity in Quebec, enabling cropland expansion at the expense of forest. Nevertheless, climate change is a serious source of threats for forest ecosystems, particularly due to the increase in extreme events and fires, which not only destroy standing biomass but also affect soil C, especially in the surface organic layer.

Farmers are organized into cooperatives, and agricultural practices' advice is provided by companies doing business in the agricultural sector. Since the 2000s, pressure from civil society has prompted a shift towards silvicultural practices that ensure the soil sustainability. The federal administration and the administration of Quebec have embarked on an ambitious and proactive policy to reduce GHG emissions, supported by subsidies. This government policy is complemented by the non-regulated, voluntary carbon market. As a result, stakeholders are strongly looking for MRV certification and assessment frameworks.

It is worth noting that Quebec decision-makers express an interest in collaborating with French-speaking countries, notably in Africa.

In the USA the recent federal administration has pulled back initiatives related to GHG mitigation, climate change, land use practices, and soils. Nevertheless, there remains strong interest in addressing such questions within the research community, as well as among landowners, industry, NGOs and in the administration of certain states.

Today, less than 5% of cropland in the U.S. is managed using the basic soil health practice of cover cropping. More research is needed to provide a scientific foundation that will encourage farmers and ranchers to grow quality food, fiber, and fuel using soil health systems that sustain farms and rural landscapes, promote a stable climate and clean environment, and improve human health and well-being

3.2.5.2 Priorities for North America

> See Excel Table for the list of priorities (Appendix 7.6) and online mind-map on the Soil Carbon Futures website.

(a) Monitoring and tools' development

SOC and SOC-change monitoring is already an active area of work in the USA and Canada, except in remote peatland areas where it should be improved. Nevertheless, there is still a need to improve the current monitoring network by aiming at periodic, high-quality re-measurements, which would allow on-farm monitoring systems to augment the existing national inventories. SOC inventories should be completed by data collected on soil properties, practices, biodiversity... The measurement of non-CO2 greenhouse gases (GHGs) should also be expanded to improve the GHG inventory international reporting. Monitoring of C pools at low cost also appears as a priority when they can be used as proxies for C persistence/vulnerability in soil. Finally, deploying of Long-Term Agricultural Field Experiments in underrepresented cropping systems, regions, climates, and soil types is also listed as an important priority.

Concerning methodologies and tools, one key point is to standardize the measurement and re-measurement, reporting and verifying to create trust in the carbon farming system. This requires reducing the uncertainty associated with existing proximal and remote sensing SOC monitoring methodologies. A decision tool should be produced to inform stakeholders on the most adapted methodology for them. A harmonized SOC data portal should

also be developed, hosting national or even international public and private data to make data available for further analyses (knowledge enhancement, practices' promotion) and evaluation (carbon payment schemes). As SOC is closely related to soil health, the development of ecosystem service indicators as a function of soil type, climate, and land use is also one of the listed priorities.

(b) Impact of practices, climate and land-use changes on SOC

Research should be conducted in priority to quantify the impact of adopting conservation/regenerative management practices on SOC, and to compare their performance to conventional systems under different pedoclimatic conditions. Another priority is to explore ways to improve N fertilizer efficiency to reduce N leaching in Canada in waterlogged soil after snowmelt, and to reduce N_2O emissions. With regards to soil fertility and C balance, another important avenue for research is to investigate the effects of biochar amendment application and the recycling of organic waste from biogas production. In Canada, in the field of forestry it is important to identify species adapted to a warmer climate and to characterize the vulnerability of SOC and understand its drivers. It is also critical to gain knowledge on the single or combined effects of extreme climatic events and ongoing changing climatic conditions on SOC. Due to the strong interest of society for C markets and C-smart practices, more knowledge is needed to understand the rate of C storage after afforestation, reforestation, or agroforestry adoption.

(c) Process understanding

One important knowledge gap to fill is to identify the drivers of C persistence versus abundance stratified by pedoclimate. It is important to gain a better understanding on interactions between soil porosity and SOC and their temporal dynamics, critical for SOC availability to decomposers. It is necessary to quantify C persistence and nutrient availability in MAOMs. It is also critical to understand the drivers of SOC vulnerability and loss by leaching or erosion enhanced by climate change. Investigations are also needed to improve the level of knowledge on the influence of taxonomic and functional diversity on C dynamics. Finally, more research should be engaged to advance understanding of carbon cycling processes in peatland and permafrost soils of North America.

(d) SOC-related provision of ecosystem services

Future research in North America should continue to make progress on quantifying the benefits of SOC on ecosystem services and soil health and develop indicators as a function of soil type and climate. This will connect SOC storage to agricultural and forestry systems' resilience, water quality, food production and not just mitigation, and increase stakeholder's interest. As mentioned previously, the emissions of non-CO_2 greenhouse gases associated with additional C storage practices must be quantified to generate a comprehensive greenhouse gas accounting.

(e) SOC in economics and social sciences

In North America, about a third of research needs expressed in the fields of economics and social sciences were region-specific, the others coming from agendas at the global level. Local agendas and workshops mainly focus on the long-term impacts of policies, including permanence of practices, (in)equity between landowner classes, and on the barriers/levers to adoption at scale and in the long-term.

There is a lack of knowledge on the long-term impacts of incentives/policies, especially on the permanence of practices and SOC storage, on how the various types of landowners respond to incentives, and on incentives' impact in terms of equity among landowner classes. There is also a need to (better) assess the growing demand for meat and dairy substitutes and its impacts on land use (change), in terms of areas that could be freed up for instance to provide services in reforestation or sequestration.

First there is a need to quantify indicators that influence adoption of regenerative agricultural practices, e.g. economic costs/benefits, social barriers, and equity issues. Then, economic and behavioral research can help investigate approaches to improve policy design and landowner responses to incentives, to address inequities in participation in conservation incentive programs, and to project the potential for upscaling of soil-based carbon removal and GHG reduction approaches as climate mitigation strategies. There is also the question of which type of governance structures are needed to better engage the private sector in pursuing demand-side carbon removal activities.

Finally, in addition to increased transparency, developing a common set of standards for offset accounting could allow for harmonization across different registry systems and offset market participants. There is still a need for research on the trade-off between the cost of decreasing uncertainty surrounding net carbon removal quantification and the potential increase in the offset value for both buyer and seller. The question of the ownership of the carbon credits generated and its impacts on the adoption of certain practices and the distribution of the economic surplus is raised and needs to be further investigated, for instance in the case of biochar or biodigesters' digestates application.

(f) Capacity building on SOC

Concerning farmers' capacity building, there is both a need for improved outreach and training and a need for technical services' provision and access to finance for all farmers−including small producers and discriminated producers− to assist farmers and ranchers in (successfully) adopting regionally-tailored technologies and conservation practices and to help them participate in programs. This implies transferring research findings and technologies to practitioners, farmers, and forest managers through extension and outreach educational programs. Sharing experiences of success and failure and identifying solutions to overcome barriers to adoption is necessary to accelerate programs across regions and scale up agricultural sequestering practices. And, indeed, policy advocacy and clear guidance to commercial companies is required that encourage adoption and real removals.

In Canada, there is a need to develop participatory approaches including Indigenous-led research that is centered on Indigenous voices and experiences and application of Indigenous Knowledge systems, to improve understanding of forest carbon. The maintenance and further development of researchers' capacity in the field of forest carbon science is also required to address forest carbon policy issues and analytical needs at multiple levels.

3.2.6 Oceania

The Oceania-specific SRIA includes 27 original priorities summarized into 22 items. As most priorities were collected during workshops dedicated to SOC monitoring, reporting, and verification, there is an urgent need to complete the list of region-specific priorities by considering practices' impacts, process understanding... Nevertheless, priorities applicable anywhere in the world apply in Oceania.

3.2.6.1 Geographical, economic, and political elements of the regional context with implications on SOC

The Pacific region presents a complex interplay of geographic isolation, fragile ecosystems, and diverse socio-political contexts that deeply influence SOC dynamics' management. Addressing SOC issues in the Pacific thus requires integrated approaches that respect cultural values, strengthen institutional frameworks and build resilience to climate and economic shocks.

3.2.6.2 Priorities for Oceania

See Excel Table for the list of priorities (Appendix 7.7) and online mind-map on Carbon Futures website.

(a) Monitoring and tools' development

In the Australian context, there has been substantial investment in the measurement–modelling space of SOC over the past five years. These programs have compiled large volumes of high-quality, landscape-scale data that underpin further development of SOC monitoring, reporting, and verification (MRV), including the CSIRO-led Soil Organic Carbon Monitoring (SOC-M) project. The key priority for the coming years is to develop monitoring over a long timescale. In the Pacific Region, there is need for enhanced long-term monitoring across diverse island contexts. Data in tropical peatlands and mangroves are also very scarce. This should be performed with the development of robust harmonized databases to store SOC and related data. Long-Term Experiments should also be supported.

In Australia, there has been significant development and deployment of proximal sensing technologies to reduce measurement costs while maintaining integrity and these developments should continue, together with other high through-put and low-cost methods.

Australia uses a locally calibrated IPCC Tier-3 framework model (FullCAM: Full Carbon Accounting Model)—for annual land-sector accounting, including SOC dynamics for 0–30 cm depth. These estimates inform Australia's reporting obligations under the UNFCCC. But research should continue to improve models and promote a modular modeling approach (crop, regional climate, etc. modules). Another priority is to better assess the uncertainty associated with measurements and predictions.

(b) Impact of practices, climate and land-use changes on SOC

A key priority is to identify practices adapted to local conditions in Australia and Pacific Islands Territories (tropical/arid soils), for building/maintaining soil organic carbon in small-holder farming systems that are undergoing rapid management changes due to mechanization, intensification, and climate change. There is a strong interest in practices increasing C inputs to SOM in water and nutrient-limited environments, while limiting GHG emission risk from N_2O. Research is essential to understand how climate change affects soil organic carbon in Australia and the Pacific. Climate variables like temperature, precipitation, and CO_2 impact SOC decomposition and storage, while changes in productivity, land use, and technology further influence these dynamics. Developing land capability scenarios that factor in future climate, land shifts, and SOC is crucial for both carbon stock and soil function assessment.

(c) Process understanding

One important priority is to characterize soil carbon forms by integrating particle size fractionation with thermal analyses of SOC. This combined framework improves attribution of stabilized SOC pools, quantifies their vulnerability to land-use and climatic change, and constrains the capacity of attainable mineral-associated SOC (MAOM) stocks.

(d) SOC-related provision of ecosystem services

Soil organic carbon mineralization plays a critical role in maintaining soil fertility across Australia and the Pacific by facilitating nutrient cycling, which supports both agriculture and environmental health. The integration of ecosystem services, particularly nutrient cycling, alongside robust soil carbon monitoring, reporting, and verification (MRV) frameworks, is vital in future research projects for advancing sustainable agricultural practices.

(e) SOC in economics and social sciences

In Oceania, about a third of research needs expressed in the fields of economics and social sciences were regional-specific, the others coming from agendas at the global level. Local agendas emphasize the need to provide information on all the costs and co-benefits of land management and practices, integrate this information in simple, robust, and science-based decision–making tools as well as in policy design and assessment, so as to align them. They suggest that soil be recognized as an environmental asset, hence research should account for this when designing or assessing laws and policies. Research is still needed on the type of agriculture and policies that can encourage good soil management while ensuring food production in the region in the long-term. And finally, the need for policy coherence across sectors and scales is underlined.

Note that the Australian government co-developed a voluntary carbon-crediting method, the 2021 Soil Organic Carbon Measurement and Modelling method (2021 SOC method), which enables landholders adopting materially different land-management practices to generate Australian Carbon Credit Units (ACCUs) for sale.

(f) Capacity building on SOC

Knowledge sharing and capacity building of all stakeholders is an important regional challenge, especially concerning measuring, monitoring, and verifying soil carbon, which is key to facilitate investment in sustainable land use practices as well as to incorporate C sequestration in the Nationally Determined Contribution to GHG emission reduction. Setting and aligning research priorities across the Pacific for measuring, monitoring and verifying soil carbon is therefore necessary, as is maintaining and building further soil expertise and capability in schools and universities. As changes take time, if Oceania is to meet existing and future soil challenges, it is essential that information and effective learning opportunities about improved land use and soil management practices are available and focused on the needs of the users and landholders. A robust system of networks and partnerships for knowledge-sharing across all soil types, conditions, and capacities would help. Finally, policy advocacy is required to integrate SOC data into national and regional climate and sustainable land management policies and to have soil recognized as an environmental asset in legislation and policies, to avoid further soil carbon decline.

3.3 Main messages about the region-specific SRIA

A crucial point for a Strategic Agenda on Research and Innovation is that studies on the role of soils in carbon storage and climate change mitigation must never be disconnected from the other functions performed by soils, in particular their role in feeding a growing population (which is particularly significant in the case of highly weathered and poorly fertile soils) and in supporting the resilience of soils facing degradation and/or climate change. In Western countries, interest in soil as a habitat for biodiversity is also growing, and the benefits of increasing carbon stocks should be carefully investigated.

3.3.1 Monitoring and tools

There is a shared need worldwide for enhanced monitoring and monitoring methodologies to collect accurate data on SOC and ideally also on other soil properties across diverse contexts, in a cost-effective manner. SOC monitoring is particularly weak in non-Western countries, as well as in remote and sparsely populated areas, and in non-productive soils (i.e. peatlands, urban soils). Nevertheless, this need is motivated by different reasons depending on the region of the world. In non-Western countries, this need is highlighted to demonstrate the effectiveness of certain practices in terms of additional carbon storage and the benefits in terms of soil fertility and crop yields. In

Western countries, progress on additional carbon storage monitoring is necessary to support and create truth in the implementation of carbon payment schemes (including carbon farming) that promote conservation and enhancement of SOC. One issue that remains critical regarding data acquisition is cost. Remote sensing methodologies are expensive. Laboratory measurements or proxy detection are less expensive in absolute terms, but the cost of sending personnel into the field then becomes the major expense.

Whatever the situation, new scientific knowledge will be produced from the novel data collected. In particular, we will learn more about how local conditions (climatic factors, soil properties, and practices) influence carbon stocks. This will identify where significant carbon gain is possible, and where carbon stocks are already high for local conditions and should be preserved.

Due to the non-permanence of organic carbon in soil, progress is needed everywhere to identify robust proxies for SOC vulnerability (to climate change events, land-use change or change in practices), and for slow-cycling carbon reservoirs, generally considered among the scientific community to be associated with soil mineral phases or in the form of burned residues.

Another means to assess and quantify C persistence in soil is to improve current models of SOC dynamics, notably by connecting them with other models (crop, climate…), adapting them to local conditions and providing a clear statement about uncertainty of model predictions.

Finally, it was repeatedly mentioned in Western countries that, for wetlands, monitoring of SOC stocks should be complemented by measuring of non-CO_2 greenhouse gas emissions and monitoring of dissolved organic C loss, to gain a complete balance of ecosystem functioning. The same priority was identified in the context of Asian paddy fields.

3.3.2 Impact of practices on SOC

It is now acknowledged than the carbon-smart practices are not the same everywhere. As practices promoted for their effect on additional carbon storage have often been tested in temperate climates of western countries, it is important to work on adapting the practices to other climatic contexts or investigating possible practices mobilizing the same principles (e.g., maintaining a permanent soil cover where intercropping is impossible, as on snow-covered soil.). Examining the practices implemented by indigenous peoples is a possible complementary strategy to identify practices favoring C storage in regions where this traditional knowledge has been set aside. At the country scale, examination of practices' efficiency on C storage in soil should also urgently be characterized for the various pedoclimatic conditions. Worldwide, there is a growing awareness of the harmfulness of the plastics increasingly used in agriculture (greenhouses, nets, haylage covers, mulching, irrigation pipes, coated fertilizers, etc.). They release microplastics and chemicals in the soil during their use and disposal. Research must work to investigate their impact on soil C stocks and find more sustainable agricultural practices.

Studying how crop residue management impacts soil carbon is a recurring priority around the world. However, it is emerging as a priority for a variety of reasons. In Asian countries that grow rice and in Latin American regions that grow sugar cane, large amounts of dry crop residue need to be disposed of in ways that do not involve burning, as this causes air pollution. There, residues transformation into biochar is currently advertised as an efficient means to sustain soil fertility and store carbon in the long-term, with the advantage of providing heat during combustion. In Western countries, the residual biomass generated by agriculture is not in excess, which may give rise to conflicts of use. In addition, an important proportion of this biomass may be wet, such as livestock effluents. The latter are more difficult to use in pyrolysis to convert them into biochar and are better suited to use in biogas plants via anaerobic processes. An increasing number of farmers are interested in this income-generating practice, because

often subsidized. Applying biochar or digestate (the by-product of biogas plants) to soil is recommended to enhance fertility and carbon storage. However, knowledge of how the quality of the residues, the method of biochar/biogas production, and the properties of the amended soil affect soil fertility and carbon storage is lacking. It is also unclear whether this is more beneficial than direct amendment with crop residues, livestock effluents, or inorganic fertilizer application. Additionally, for the biogas industry, a more systemic approach is required to properly evaluate impacts, as it involves changes to crops and associated technical itineraries that undoubtedly have a significant impact on soil functioning.

3.3.3 Impact of land use and climate change on SOC

Concerning land-use change, a repeated need is to gain knowledge on the impact of restoring soils degraded by human activities. Depending on the region, it could be drained peatlands or deforested areas intended for intensive crop cultivation. There is also a need for knowledge on the impact of urban expansion. Finally, to capture the true impact of land-use changes on SOC it is very important to conduct long-term research and monitoring.

In all regions of the world, climate change is being felt in increasingly dramatic ways. There is an urgent need for more research to understand the role of SOC in the resilience of ecosystems to ongoing changes and extreme climate events.

Regarding the impacts of climate change on soil C dynamics and stock changes, it is important to emphasize the need to examine the combined effects of several climatic constraints (i.e., summer heat waves and changes in precipitation patterns) and to study the cumulative effect over time of the changes currently underway. Strong efforts are needed in regions where the SOC reservoir is considered highly vulnerable to extreme events (e.g. pergelisols, forest ecosystems…).

3.3.4 Processes controlling SOC dynamics

We have collected more research priorities on understanding the mechanisms controlling C dynamics in soils in Western countries, due to the advanced analytical resources that may be required to carry out this type of work. Nevertheless, the same concerns are emerging from all regions of the world.

Firstly, based on the observation already stated that C dynamics are not the same everywhere but depend on environmental conditions, it appears necessary to make progress in the dominant main biotic and abiotic mechanisms and control factors as a function of pedoclimate (i.e., protection in the form of aggregates in fine-textured soils, energy limitation to decomposition in waterlogged soils, etc.). Knowledge must also be gained in understanding these mechanisms. For example, the way in which soil and plant biodiversity control C dynamics remains largely unknown. There are still many mechanisms to be investigated regarding the associations between mineral phases and organic matter, with practical implications: is there any C saturation on mineral phases? Does this association of organic C with mineral phases negate the consumption of atmospheric C linked to enhanced mineral weathering? How long will C remain in the soil depending on the processes involved?

3.3.5 SOC-related provision of ecosystem services

Priorities concerning the need to link C storage with soil functioning and the services it provides was repeatedly mentioned in research agendas worldwide, but discussions during the workshops underlined the importance of not dissociating soil carbon storage from other soil functions/services. Soil health has become a central issue in recent

years. For this reason, investigating the synergies and trade-offs between soil carbon sequestration and the ecosystem services provided by soil is key. The ecosystem services that attract the most attention are: soil fertility, which reduces dependence on fertilizers and water pollution caused by nutrient leaching; food production; biodiversity, which is under threat; and ecosystem resilience, which involves adaptation to climate change and the reversal of soil degradation. Soil fertility and food production receive more attention in non-Western countries.

3.3.6 SOC in economics and social sciences

The need for science-based information on the cost-effectiveness of "positive" land management practices is present in all regions of the world to varying degrees, depending on whether research has already been conducted. Costs and benefits of land management practices must be comprehensively assessed for the various production systems and pedoclimatic conditions, to account not only for SOC and GHG emissions, but for a wide range of environmental and socio-economic impacts (e.g., sustainable development goals). The impact of SOC increases and low-carbon systems on productivity, food security, and resilience and adaptive capacity of agriculture and forestry, compared to current systems and in the face of climate change, is of particular importance.

In Europe, while there is already a substantial body of work on abatement costs of agricultural practices in agriculture, it is not the case for other land uses (e.g., urban land, peatlands, and soil carbon in forests). Systemic approaches, accounting for all and long-term co-benefits, synergies, and trade-offs between practices, and the cost of risks associated with changes in management practices, are further required.

All this information is useful to (better) design, assess, and adapt policies, and to facilitate the adoption of cost-effective practices that are relevant to the local context.

While economic and social sciences have already compared the efficiency of different policy instruments for addressing environmental externalities, there is still work to be done to support decision makers. The cost-effectiveness of various types of incentives and policy instruments needs to be further investigated, accounting for the specificities of carbon storage (which is a long-term process, finite and non-permanent, and surrounded by uncertainty) and addressing the distribution of the costs, risks, and benefits among stakeholders. The analysis must be extended to other benefits as well as to the impacts of existing non-climate policies (e.g., agricultural and energy policies) on SOC levels.

"Western" regions focus more on addressing: the long-term effects of policies; (in)equity issues between landowner classes; how the land rent is shared between land managers and landowners; the distribution of the economic surplus; how to preserve existing soil carbon stocks, while increasing SOC levels where they are low; the trade-offs between the existing funding schemes; and the funding of the low carbon transition. The impact of food regimes and demand, especially substitutes to meat and milk products, is often mentioned. Indeed, ex-post analysis of the effectiveness of existing schemes and policies (e.g., EU soil protection policies and financial incentives for sustainable farming) is important to guide decision-makers and improve policy design. Representatives from Oceania suggest that soil be recognized as an environmental asset, hence research should account for this when designing or assessing laws and policies.

Even if the costs and benefits of land uses/management practices are known and cost-effective policy instruments are identified ex-ante, it does not mean that they are actually adopted or successfully implemented. This is why research is still needed on the barriers and motivations of land managers to adopt sustainable or new practices (in the long-term), the most effective ways to overcome these barriers, and the type of enabling environment that should be put in place. It includes, among others, attitudes towards change and risk acceptance, the complexity and cost of MRV systems associated with carbon farming schemes, access to funding, but also policy coherence across

sectors and at different scales as well as effective governance structure. Several regions mention the need to build a narrative on carbon sequestration and associated benefits (i.e., guiding principles to adhere to), and to provide a trajectory and transition pathway toward the narrative, so that it makes sense for land managers to adopt low carbon practices or systems. It is important to draw lessons from existing case studies and policies.

Carbon credit scheme design and financing issues, including carbon markets, are most often raised in “western” regions of the world, i.e., where they already exist. Questions remain on the best way to deal with impermanence of carbon storage; a common set of standards for offset accounting to allow for harmonization across different registry systems and offset market participants; the appropriate MRV system(s) to deal with cost-accuracy and additionality, hence creating trust in the quality of the credits; and trade-offs between the cost of decreasing uncertainty surrounding net carbon removal quantification and the potential increase in the offset value for both buyer and seller. Indeed, information on how costs, benefits, and environmental and financial risks are distributed among land managers, operators/intermediaries, and carbon credit buyers in carbon farming projects is useful for achieving effective carbon market design.

3.3.7 Capacity building on SOC

In all regions of the world, there is a need for:

- Information and effective learning opportunities on improved land use and soil management practices that are available with focus on the needs of the users and landholders.
- Participatory approaches, such as soil health Living Labs, Lighthouses and knowledge hubs, to connect stakeholders, facilitate knowledge exchange and data collection, and design effective solutions.
- Providing training programs for policymakers, NGOs, and extension officers on SOC integration into national policies.
- Education to increase awareness and knowledge of society as a whole on carbon fluxes, the conservation of soil organic carbon stocks, sustainable soil management, and the trade-offs and synergies with other environmental and socio-economic objectives.

But there are also some specificities. In Africa, connecting farmers and researchers as well as increasing researchers’ and technical staff’s capacity building on the issue of soil carbon (across disciplines and for various types of soil land uses) is put forward. North America insists on the need for improved outreach and training to transfer research findings, technical services’ provision, and access to finance for all farmers. Europe focuses more on the need for knowledge hubs on the technical aspects (e.g., impact of practices, trade-offs, models, data infrastructure, quantification methods, and regional baselines) to create trust in the carbon farming system. Additionally, the need to establish and align MRV research priorities across the Pacific, as well as to maintain and further develop soil expertise and capabilities in schools and universities is emphasized in Oceania.

4 Expected impact

The SRIA is intended for a wide audience, enabling them to discover the research priorities identified, particularly for the scientists who contributed to it. However, it is primarily aimed at public and private funders who will be able to leverage funding in order to finance the research gaps, thereby removing the barriers to the implementation of sustainable practices and climate impact. The ORCaSa Strategic Research and Innovation Agenda is available to everyone *(having an interest in soil carbon)* on the Soil Carbon Futures website.

The SRIA aims are:

- to foster international collaboration and networking, by support funding agencies in defining action plans and new research calls, either jointly or simultaneously on the same topic;
- to support scientific creativity by ensuring the relevance of novel research proposals and helping to identify regions and international partners that could have a similar interest in conducting studies on a novel topic.

The agenda is a dynamic document, intended to be updated regularly by regional nodes within the Soil Carbon Futures association. Developments on SOC in urban, industrial, traffic, mining, and military areas (SUITMA) as well as in pasture lands must be actively monitored. The agenda could also benefit from contributions from countries such as Russia, China, and India. Regarding India, a new Regional Node is being developed between Soil Carbon Futures and BAIF Development Research Foundation, acting as an ambassador. To sum up, this agenda is a major building block of the Soil Carbon Futures association that will enable discussions with research funding agencies around the world to turn this strategy into action.

Two funding agencies have already signed the letter of interest to join Soil Carbon Futures: Ministry of Agriculture and Forestry of Finland and National Research Foundation of South Africa.

Professor Adrian Unc from Memorial University of Newfoundland, Canada and Affiliated Faculty of McGill University, suggested to publish the SRIA in the peer review journal “Soil Use and Management” (British Soil Science Society & Wiley) as a special issue where members of the Soil Carbon Futures consortium can contribute.

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7 Appendices

7.1 Global priorities

Global research needs (1st column) and their rationale (2nd column) gathered by major topics (monitoring, tools, practices, processes, climate change, land-use change, ecosystem services, economics and social sciences, capacity building).

MONITORING PRIORITIES	
Enhance the harmonized monitoring of SOC and additional data on soil properties and management, particularly in under-represented regions. If possible collect also data on subsoil	To improve knowledge
Improve the monitoring of SOC and SOC sequestration as well as CH_4 emissions in wetlands (paddy fields, peatlands and mangroves)	Little data while wetland areas are under pressure and must be preserved. High potential for climate mitigation. It is therefore necessary to have data according to the practices to best conserve them or even restore them.
Monitoring of SOC in Soils of Urban, Industrial, Traffic, Mining and Military Areas	SUITMA soils poorly known in comparison to other land uses
Improve monitoring in highly weathered tropical soils, in drylands, in degraded soils	Limited knowledge
Need to develop studies on the impacts of climate change, land-use change (LUC) or land management practices on SOC in SOC hotspots, and more specifically Kazakhstan, Papua New Guinea, DR Congo and Peru (see Beillouin et al. 2022a).	Limited number of observations. SOC hotspot to preserve
Identify most promising sites for additional C storage.	Very contrasted pedoclimatic conditions affecting storage capacity. Apply or maintain best management practices in these promising sites

TOOLS' DEVELOPMENT PRIORITIES	
Support the development of harmonized SOC monitoring, reporting and verifying methods	For carbon credit certification
Develop low-cost and high throughput tools to measure GHG emissions	Better measurement and monitoring of a comprehensive greenhouse gas accounting (i.e., include non-CO_2 emissions such as N_2O, CH_4) are needed to encourage the implementation of sustainable practices.
Promote the use of digital tools for SOC data acquisition	To gain knowledge where data on SOC is sparse; for Verification & Carbon Markets Integration
Mapping of soil organic carbon (SOC) stocks, as well as other soil properties	To better support land managers' and stakeholders' decisions
Improve models of SOC dynamics (include practices' impact, better account for below-ground inputs, deep soil layers, coupling with hydrological models or regional climate models)	To improve predictions and better support stakeholders' decisions
Assess the vulnerability of SOC stocks and the persistence of SOC in relation to soil type, pedoclimatic conditions and climate change. Search for proxies, e.g., test POM and MAOM fractions	To gain more knowledge

PRACTICES' IMPACT PRIORITIES	
Impact of sustainable C management practices for improving SOC content, soil health and plant production while reducing fertilizer use: biochar application, crop residues restitution, plant cover, liming, slash burning, optimum fertilization, reduced tillage, crop rotation, species association, agroforestry, perennial forage, organic waste recycling...(see Beillouin et al. 2023). Also investigate the impact of conventional monoculture for reference.	Limited number of observations / high variability
Gain knowledge on systems that integrate livestock and agriculture to promote organic matter (OM) transfers.	To optimize fertilizer application and SOC storage
Improve the understanding of water and nutrient constraints on SOC sequestration	To optimize fertilization or irrigation strategies
Better explore the impacts of the following forestry practices on SOC and GHG balance: species mixtures, intensity of harvesting, conifer vs. hardwood stands, litter removal, prescribed fire (see Beillouin et al. 2023).	Limited number of observations/high variability. Relevant practices for adaptation to climate change and with a putative mitigation potential.
Better explore the impacts of the following grassland management practices on SOC and GHG balance: organic amendments, biochar, agroforestry, species mixtures, liming, litter removal, intensity of grazing (see Beillouin et al. 2023).	Limited number of observations/high variability. Relevant practices for adaptation to climate change and with a putative mitigation potential.
Gain knowledge on how plastic film mulching impacts biological activity and SOC cycling (see Beillouin et al. 2023), as well as soil health in general	Increasing evidence of the harmful effects of plastics in soil

CLIMATE CHANGE IMPACT PRIORITIES	
Perform region-specific studies about the effects of increased soil carbon on ecosystem resilience and adaptation to climate change.	Increase of drought events, delay or lack of rainfall, season shifts, heavy rainfall causing soil erosion. Essential to guide climate -resilient soil and land management strategies to maintain productivity under future climate.
Need to explore more in-depth the single and combined effects of climate change (rising temperature, change in precipitation, drought, CO_2 enrichment, climate extremes) on SOC stocks and cycling mechanisms (8 % of the meta-analyses in Beillouin et al. 2022a). More specifically, currently a limited number of observations on the impacts of rainfall reduction and wildfire	Limited number of observations and impact on 100 % of land surface
Need to carry out more research exploring the nexus SOC-water outcomes (i.e. water quality and soil water regulation) especially for the impacts of climate change and land-use change (see Beillouin et al. 2022a).	Limited number of observations. Limiting factor of water for biomass production. Adaptation potential
Assess temperature sensitivity in situ and not in the laboratory	To improve knowledge on climate change impacts

LAND-USE CHANGE IMPACT PRIORITIES	
Better investigate the impact of wetland degradation, conversion into other land uses and restoration on SOC and GHG emissions	Limited number of observations x high annual potential of mitigation (1 GtCO2e/y -- Bossio et al. 2020)

PRIORITIES FOR BETTER UNDERSTANDING OF SOC PROCESSES	
Unravelling the influence of taxonomic and functional diversity of decomposers (macro/meso/micro-organisms) on C dynamics and how it is affected by soil type and climate change	Lack of knowledge on processes in tropical and arid soils
Impact of abiotic factors (soil type, pedoclimate, OM-mineral interactions) on C dynamics and storage	Lack of knowledge on processes in tropical and arid soils
Impact of salinity and sodicity on C dynamics and crop production	Critical in arid areas, but lack of knowledge
Impact of OM input quality on C additional storage and its residence time in soil	Lack of knowledge on processes in tropical soil, important for conservation programs
C residence time in POM and MAOM fraction	Limited knowledge, while these fractions could provide insight into SOC vulnerability to climate and practice changes
Investigate N, P, water constraints on SOC sequestration.	Lack of knowledge on processes in tropical and arid soils. Important for arid soils to limit the use of fertilizers

PRIORITIES RELATED TO SOIL HEALTH AND ECOSYSTEMS SERVICES	
Effects of carbon sequestration on food production and soil fertility (and soil health in general)	Population is growing rapidly. More food should be produced but without compromising the environment. Restoring soil fertility and reducing farmer's expense for fertilizer
Effects of increased soil carbon on ecosystem resilience (i.e., adapting to climate change, arresting or reversing land degradation…)	Increase of drought events, delay or lack of rainfall, season shifts, heavy rainfall causing soil erosion
Research on how SOC restoration influences microbial diversity, pollinators, and soil fauna	Biodiversity is also at stake. Knowledge needed on SOC-biodiversity interactions

PRIORITIES RELATED TO CAPACITY BUILDING	
Farmers' and land managers' capacity building: training, guidance, and advice to farmers and land managers on how to increase SOC, the positive practices and their impacts; networks to facilitate knowledge	Develop regional farmer-led SOC research networks.
Policy advocacy	
Stakeholders' capacity building: connecting researchers, NGOs, land managers, policy makers, etc. to facilitate knowledge exchange and the design of effective solutions ton increase and monitor SOC. This includes, e.g., participatory approaches, living labs, lighthouses, and knowledge hubs.	Encourage participatory soil monitoring approaches where farmers collect and report SOC data. Provide training programs for policymakers, NGOs, and extension officers on SOC integration into national policies.
Raising awareness on soil organic carbon and soil health in society as a whole: education on the issues at stake, on good practices, socio-cultural change in attitude, etc.	
Researchers' and technical staff's capacity building: on the issue of soil carbon, across disciplines and for various types of land uses, by training and networking.	

PRIORITIES RELATED TO ECONOMICS AND SOCIAL SCIENCES	
Costs and benefits of "positive" practices: science-based information, indicators, and (decision-making) tools to support land managers and policy-makers, concerning the impacts of land management practices and land use (changes) on SOC, carbon storage, net-GHG budget, but also on all other environmental and SDGs aspects, including the co-benefits' synergies and tradeoffs, accounting for uncertainty; cost-uncertainty/accuracy tradeoffs of baseline/impact assessment of various M(RV) methodologies.	Lack of comprehensive assessment of the costs and benefits of land management practices in the various production systems and pedoclimatic conditions, i.e., to account not only for SOC stocks/storage and GHG emissions but also for other environmental issues, including Sustainable Development Goals. Lack of knowledge on the impact of SOC increases on productivity and resilience, on well-being and resilience of farming communities.
Types of incentives / instruments to be enforced and comparison of their cost-effectiveness and/or cost-efficiency: this also includes the impacts of existing climate and non-climate policies on carbon sequestration, but also on other environmental and SDGs aspects (e.g., resilience, land value/rent, how the economic surplus is shared along the value chain).	Further investigation of the cost-effectiveness of various types of incentives and policy instruments, accounting for the specificities of carbon storage in soils, to support decision makers. The investigation should address the distribution of the costs, risks, and benefits of implementation among stakeholders, and extend to the impacts of existing non-climate policies on SOC levels, as well as on food security and other SDGs.
Barriers, levers, and enabling environment for the adoption of "positive" practices and cost-effective instruments, as well as policy issues and governance: the latter include policy coherence issues at different scales and across sectors, the building of a narrative on carbon sequestration and co-benefits, the provision of a trajectory and transition pathway towards this narrative, etc.	Research needed to further identify the barriers, drivers, and levers to the (long-term) adoption of carbon-friendly practices, by drawing lessons from existing case studies and policies.
Carbon credits schemes and financing: carbon credit schemes design (to deal with the impermanence of C storage, financing of existing C stocks, clarity of MRV implementation, ...), public-private funding of carbon finance and carbon market design (to ensure that costs, benefits, and environmental and financial risks are fairly distributed among participants).	

7.2 Summarized priorities for Africa and Near East

Africa and Near East research needs (1st column) and their rationale (2nd column) gathered by major topics (monitoring, tools, practices, processes, climate change, land-use change, ecosystem services, economics and social sciences, capacity building).

MONITORING PRIORITIES	
Enhance the harmonized monitoring of SOC and additional data on soil properties and management. If possible, collect data on subsoil	Too few observations
Improve SOC monitoring in forest submitted to on-going changes: natural forest conservation or restoration program, forest degradation	Few quantified monitoring efforts on forest restoration projects or conservation programs. Limited knowledge on forest degradation, fire impact or litter export
Improve the monitoring of SOC and SOC sequestration as well as CH_4 emissions in wetlands (paddy fields, peatlands and mangroves)	Little data while areas under pressure and must be preserved. High potential for climate mitigation. It is therefore necessary to have data according to the practices to best conserve them or even restore them
Monitoring of SOC in Soils of Urban, Industrial, Traffic, Mining and Military Areas	Limited observations on urban soils (while strong expansion), mining soil during exploitation or after restoration. SUITMA soils poorly known in comparison to other land uses
Improve monitoring in under-represented areas, highly weathered tropical soil,s in drylands, in degraded soils and in SOC hotspots such as the Democratic Republic of Congo	Limited knowledge and demand for agricultural intensification
Validate the use of POM and MAOM fractions as proxies for the vulnerability of SOC to climate change and practices and improve their monitoring.	Current controversy about the use of POM and MAOM proxies for C vulnerability/persistence. Would improve prediction of C storage
Set up and support long-term experimental research observatories	Long-term experiments are a critical missing element to monitor SOC in Africa countries
Identify most promising sites for additional C storage.	Very contrasted pedoclimatic conditions and storage capacity in Africa. Apply or maintain best management practices in these promising sites

TOOLS' DEVELOPMENT PRIORITIES	
Support the development of harmonized SOC monitoring methods, as well as the monitoring of plant yield and fertility.	To established link between soil carbon and plant yield and soil health in general, what will ultimately determine the practice choice (e.g., decrease the use of fertilizers). Also, for carbon credit certification (reporting and verification)
Develop low-cost and high throughput tools to measure GHG emissions	Better measurement and monitoring of a comprehensive greenhouse gas accounting (i.e., include non-CO_2 emissions such as N_2O, CH_4) are needed to encourage the implementation of sustainable practices.
Creating and sharing georeferenced databases.	For knowledge improvement
Promote the use of digital tools for SOC data acquisition	To gain knowledge where data on SOC is sparse
Mapping of soil organic carbon (SOC) stocks, as well as other soils	To better support land managers and stakeholders' decisions
Improve models of SOC dynamics (include practices 'impact, better account for below-ground inputs, deep soil layers, coupling with hydrological models or regional climate models)	To improve prediction and better support stakeholders' decisions

PRACTICES' IMPACT PRIORITIES	
Impact of cash crops (pineapple, oil palm, cashew, cotton, peanut, teak, acacia, Melina) as well as market gardening… on SOC change depending on the size of the farms	Little data while widespread usage
Impact of sustainable C management practices for improving SOC content, soil health and plant production while reducing fertilizer use: biochar application, crop residues restitution, plant cover, liming, slash burning, optimum fertilization, reduced tillage, crop rotation, species association, agroforestry, perennial forage, organic waste recycling... Also investigate the impact of conventional monoculture for reference	Limited number of observations / high variability on poorly fertile soils under climatic and human pressure with the development of cultivation areas in Africa. Shifting from conventional monoculture systems to diversified systems like agroforestry and forage integration constitutes a significant land-use change. This will encourage the implementation of sustainable practices
Impact of cocoa production on previous forested soil on SOC	Increases deforestation, decreases soil fertility
Gain knowledge on systems that integrate livestock and agriculture to promote organic matter (OM) transfers.	To optimize fertilizer application and SOC storage
Develop a common "Carbon preservation" referential on practices that do not increase C in soil but maintain it on highly weathered African soils	Limited knowledge and demand for agricultural intensification
Improve the understanding of water and nutrient constraints on SOC sequestration	To optimize fertilization or irrigation strategies
Impact of tree harvest intensity on SOC stock in forest	Little data

CLIMATE CHANGE IMPACT PRIORITIES	
Perform region-specific studies about the effects of increased soil carbon on ecosystem resilience and adaptation to climate change (e.g., drought, heavy rains...).	Increase of drought events, delay or lack of rainfall, season shifts, heavy rainfall causing soil erosion. Essential to guide climate resilient soil and land management strategies to maintain productivity under future climate.
Need to explore more in-depth the single and combined effects of climate change (rising temperature, change in precipitation, drought, CO2 enrichment, climate extremes) on SOC stocks and cycling mechanisms (8 % of the meta-analyses in Beillouin et al. 2022a). More specifically, currently a limited number of observations on the impacts of rainfall reduction, and wildfire	Limited number of observations and impact on 100 % of land surface
Need to carry out more research exploring the nexus SOC-water outcomes (i.e., water quality and soil water regulation), especially for the impacts of climate change and land-use change (see Beillouin et al. 2022a).	Limited number of observations. Limiting factor of water for biomass production. Adaptation potential

LAND-USE CHANGE IMPACT PRIORITIES	
Need to develop studies on the impacts of land conversion to cropland on SOC in Africa, such as forest conversion to cropland or cocoa production, grassland conversion to cropland (see Beillouin et al. 2022a).	Limited number of observations and high variability. The conversion is driver by population growth Moreover, after several years of cropping, the soil loses its fertility and erosion occurs.
Monitoring of grassland conversion into forest	This change has been little studied but is practiced with national conservation/climate commitment plans, or to increase farmers' incomes (wood, honey, etc.). But livestock and high grassland biodiversity issues at stake. Agroforestry could be an intermediate practice for which it would be useful to have data.
Investigate the impact of accelerated soil erosion on SOC	Poorly known
What did bomb change in soil characteristics and SOC	War in Near East
Better investigate the impact of wetland degradation, conversion into other land uses and restoration on SOC and GHG emissions	Limited number of observations, high annual potential of mitigation (1 GtCO2e/y -- Bossio et al. 2020)

PRIORITIES FOR BETTER UNDERSTANDING OF SOC PROCESSES	
Unravelling the influence of taxonomic and functional diversity of decomposers (macro/meso/micro-organisms) on C dynamics and how it is affected by soil type and climate change	Lack of knowledge on processes in tropical and arid soils
Impact of abiotic factors (soil type, pedoclimate, OM-mineral interactions) on C dynamics and storage	Lack of knowledge on processes in tropical and arid soils
Impact of salinity and sodicity on C dynamics and crop production	Critical in arid areas, but lack of knowledge
impact of OM input quality on C additional storage and its residence time in soil	Lack of knowledge on processes in tropical soil, important for conservation Programs
C residence time in POM and MAOM fraction	Limited knowledge and controversy about the use of POM and MAOM proxies for C vulnerability/persistence. Could improve prediction of C storage.
Investigate N, P, water constraints on SOC sequestration.	Lack of knowledge on processes in tropical and arid soils. Important for arid soils to limit the use of fertilizers

PRIORITIES RELATED TO SOIL HEALTH AND ECOSYSTEMS SERVICES	
Effects of carbon sequestration on food production and soil fertility (and soil health in general)	Population is growing rapidly. More food should be produced but without compromising the environment. Restoring soil fertility and reducing farmer's expense for fertilizer
Examine tradeoff between SOC storage and food production.	Storing SOC needs biomass, and management of the biomass could be challenging.
Effects of increased soil carbon on ecosystem resilience (i.e., adapting to climate change, arresting or reversing land degradation...)	Increase of drought events, delay or lack of rainfall, season shifts, heavy rainfall causing soil erosion

PRIORITIES RELATED TO CAPACITY BUILDING	
Farmers' and land managers' capacity building: training, guidance, and advice to farmers and land managers on how to increase SOC, positive practices and their impacts; networks to facilitate knowledge exchange.	Lack of knowledge of (and information available to) farmers and land managers about their soils. Acculturation of farmers to carbon credit schemes, for them to make decisions with full knowledge of what is at stake.
Policy advocacy	To raise awareness among governments and politicians about certain issues and take action on them: land tenure security, infrastructure necessary to agriculture, access to credit, incentives for farmers to invest, reforestation, international negotiations, their national commitments (e.g., NDCs) etc., to facilitate the adoption of "positive" practices on soil carbon and increase SOC storage. Policy advocacy to support research and inventories.
Stakeholders' capacity building: connecting researchers, NGOs, land managers, policy makers, etc. to facilitate knowledge exchange and the design of effective solutions to increase and monitor SOC. This includes e.g., participatory approaches, living labs, lighthouses, and knowledge hubs.	Promoting participatory approaches and encouraging links between theory and practice, between scientists including technical personnel, non-governmental organizations, agricultural advisors, and farmers. Developing and promoting knowledge and data production. Drawing on the expertise of the Southern network of researchers regarding global change issues and their impacts on agriculture and sustainable development. Understanding and mastering the legal aspects of data in the context of open science.
Raising awareness on soil organic carbon and soil health in society as a whole: education on the issues at stake, on good practices, socio-cultural change in attitude, etc.	Need for a socio-cultural change of attitude.
Researchers' and technical staff's capacity building: on the issue of soil carbon, across disciplines and for various types of land uses, by training and networking.	Need to support African research that produces data, including supporting the training of technical staff. Encouraging research across disciplines and land uses.

PRIORITIES RELATED TO ECONOMICS AND SOCIAL SCIENCES	
Costs and benefits of "positive" practices: science-based information, indicators, and (decision-making) tools to support land managers and policy-makers, concerning the impacts of land management practices and land use (changes) on SOC, carbon storage, net-GHG budget, but also on all other environmental and SDGs aspects, including the co-benefits' synergies and tradeoffs, accounting for uncertainty; cost-uncertainty/accuracy tradeoffs of baseline/impact assessment of various M(RV) methodologies.	
Types of incentives / instruments to be enforced and comparison of their cost-effectiveness and/or cost-efficiency : this also includes the impacts of existing climate and non-climate policies on carbon sequestration, but also on other environmental and SDGs aspects (e.g., resilience, land value/rent, how the economic surplus is shared along the value chain).	
Barriers, levers, and enabling environment for the adoption of "positive" practices and cost-effective instruments, as well as policy issues and governance: the latter include policy coherence issues at different scales and across sectors, the building of a narrative on carbon sequestration and co-benefits, the provision of a trajectory and transition pathway towards this narrative, etc.	Need to account for the influence and economic interests of the various stakeholders, particularly the agro-industries, in policy design and development.
Carbon credits schemes and financing: carbon credit schemes design (to deal with the impermanence of C storage, financing of existing C stocks, clarity of MRV implementation, ...), public-private funding of carbon finance, and carbon market design (to ensure that costs, benefits, and environmental and financial risks are fairly distributed among participants).	

7.3 Summarized priorities for Asia

Asia research needs (1st column) and their rationale (2nd column) gathered by major topics (monitoring, tools, practices, processes, climate change, land-use change, ecosystem services, economics and social sciences, capacity building).

MONITORING PRIORITIES		Sub-region
Increase the monitoring of SOC and activity data, in particular in paddy fields and agroforestry systems in South and SE Asia, and after land-use change	Limited data	SE Asia
Better quantification of C stocks over the soil profile	Limited data	Japan - Korea
Increase the monitoring of SOC in Soils of Urban, Industrial, Traffic, Mining and Military Areas	Limited observations and understanding	Generic for Asia
Identify most promising sites for additional C storage.	Many soils are already well managed therefore presenting limited opportunities to increase SOC storage	Generic for Asia

TOOLS' DEVELOPMENT PRIORITIES		Sub-region
Improve the accuracy of SOC measurement, continue developing easy to use, high-throughput and low-cost methods to assess SOC content	To complete our knowledge on the C status of soils / to demonstrate the efficiency of sustainable practices on soil C and soil health, what will ultimately determine the choice of practices.	SE Asia / Central Asia
Unified methodologies for soil health assessment	To quantify the effect of SOC accumulation on ecosystem services such as production, biodiversity...	SE Asia / Japan-Korea
Develop mapping of SOC stocks, rate of change, potential for additional storage under future management and climate scenarios (together with mapping of specific indicators or thresholds, soil typology, ecosystem services, fire risk)	To facilitate decision-making by managers and operators in the field.	Japan - Korea
Investigate how to scale soil carbon measurements and C pools when the amount of data is sparse and the soil types vary greatly in the steppe of Central Asia (from mountain steppe to arid semi-desert steppe/different grazing regime and land use history)	The Mongolian nomadic lifestyle is unique in that the land belongs to the public, yet sustainable grazing patterns were long maintained through traditional culture and nomadic pastoralism. However, socio-economic transitions and climate change have disrupted these cultural institutions, leading to overgrazing, pasture degradation, and associated losses in soil carbon. Understanding how labile and stable soil carbon pools respond to these pressures is essential for both ecological restoration and the preservation of herder livelihoods. Given the vast extent of Mongolia's steppe, the potential for soil carbon sequestration is significant and must be strategically harnessed. Moreover, due to the diverse ecosystems (mountain steppe-meadow to Gobi Desert), land use histories (peatland grazing, etc.), and grazing practices (rotational grazing vs. semi-rotational) across Mongolia, the insights gained here can inform soil carbon strategies in other steppe and rangeland systems globally. From a commercial perspective, methodologies must be cost-effective and scalable across large, heterogeneous landscapes. From a scientific standpoint, they must remain repeatable, testable, and robust. Striking this balance is critical—yet dynamic—as technologies such as proximal sensing, remote sensing and machine learning continue to evolve. An adaptable framework that integrates affordability with scientific integrity is essential for real-world implementation.	Central Asia
Improve models of SOC dynamics (include practices' impact, better account for below-ground inputs, deep soil layers, coupling with hydrological models or regional climate models)	To improve prediction and better support stakeholders' decisions	Generic for Asia

PRACTICES' IMPACT PRIORITIES		Sub-region
Quantify SOC loss due to conventional cropping (excessive ploughing, no crop residues have been returned to the field/ burning of crop residues)	Provide an estimation of SOC decline if such practices are continued by farmers. It these practices cover a large surface area, if this can be solved it will impact on the soil fertility and the preservation of biodiversity.	SE Asia
Identify practices to store C and reduce of GHG emissions from paddy fields	Paddy fields responsible for large non-CO_2 emissions	SE Asia
Long-term impact of agroecological practices (or nature-based solutions) on soil organic carbon to restore cropland and paddy land	Limited knowledge	SE Asia / Japan-Korea
Gain knowledge on C and N coupling in paddy field	To optimize fertilizer application and SOC storage	SE Asia
Impact of organic amendments' application on SOC and nutrients in paddy soil	Important for paddy soil because many chemical fertilizers are applied and it might be important for biodiversity, stress control...	SE Asia
Understand how additionality of SOC can be achieved in the long-term	Carbon credit system is starting in Japan, and it is necessary to know how it can be gained by soils	Japan - Korea
Research to assess impact of biochar amendments on SOC for different types of biochars, different management systems and soil types, including secondary impacts of different biochars on soil functions	Crop burning to produce biochar is widely used to get rid of crop residues. High variability of biochar impacts. Relevant practices for agroecology or adaptation to climate change and with a putative mitigation potential	India
Impact of overgrazing by livestock in highland peatlands and pastures in Central Asia	Growing numbers of animals and the decreasing productivity of pastures on mineral soils in the current warming and drying climate (Joosten et al. 2012)	Central Asia

CLIMATE CHANGE IMPACT PRIORITIES		Sub-region
Region-specific investigations on the impact of soil erosion from heavy rain on the change of SOC in slope land	Essential to guide climate-resilient soil and land management strategies to maintain productivity under future climate scenarios.	SE Asia
Region-specific investigations on the effects of flood/drought on SOC	Essential to guide climate-resilient soil and land management strategies to maintain productivity under future climate scenarios.	SE Asia
Effect of global warming on SOC dynamics, especially in peatlands from northern latitudes (permafrost)	Global warming is progressing at an incredible speed. The soil environment is changing dramatically and there is a possibility that soil up to now will be washed out in large quantities all at once. In particular, Central Asia is more affected by global warming. The landscape encompasses high mountains very sensitive to it	Japan-Korea / Central Asia/ Northen Asia
Effect of air pollution and elevated CO_2 on SOC dynamics	Limited knowledge	Japan - Korea
Integrate SOC modeling with regional climate models for better scenario planning.	To improve model predictions	Generic for Asia

LAND-USE CHANGE IMPACT PRIORITIES		Sub-region
Impact of land-use change on SOC and other ecosystem services, over the long-term	Limited knowledge	SE Asia / Japan-Korea
Impact of deforestation on SOC – deforestation related to expanding agricultural and residential use.	Limited knowledge. After several years of growing, the soil becomes very poor in nutrition and erosion occurs.	SE Asia
Quantify SOC loss after conversion of degraded forest soil into cassava plantation	Limited knowledge. After several years of growing, the soil becomes very poor in nutrition and erosion occurs.	SE Asia
Better investigate the impact of peatland conversion for plantations,agriculture, and infrastructure development in SE Asia	Peat swamp forests in Southeast Asia have been subject to conversion for plantations, agriculture, and infrastructure development	SE Asia

PRIORITIES FOR BETTER UNDERSTANDING OF SOC PROCESSES		Sub-region
How plant-SOM interactions change across various environments. In particular, unravel the influence of below- ground C inputs of novel varieties with more root production on soil C stocks	1. Untapped potential: Root-derived carbon contributes 2-3x more to stable SOC than shoot residues, yet we barely consider this in crop improvement programs.2. Scalability: Once developed, improved varieties can be deployed across millions of hectares without requiring new equipment or farmer training.3. Economic compatibility: Unlike many carbon-focused practices that may reduce yields short-term, root-optimized varieties can maintain or increase productivity while building soil carbon. This also has a huge impact for "Livelihoods" 4. Climate resilience synergy: Enhanced root systems improve drought tolerance, nutrient uptake efficiency, and soil structure - creating multiple benefits.5. Breeding timeline urgency: Developing new varieties takes 10-15 years, so research must begin now to have climate-relevant impact by 2040.6. Integration opportunity: This approach can be combined with existing practices (cover crops, reduced tillage) for synergistic effects.	SE Asia / Japan-Korea
Unravelling the influence of taxonomic and functional diversity of decomposers (macro/meso/micro-organisms) on C dynamics	Limited knowledge	SE Asia
investigate the effect of soil management and pollution on soil organic matter decomposers	Limited knowledge	Japan - Korea
Dynamics of POM and MAOM, notably in deep soil	MAOM is poorly studied for temperate regions. Deep soil has a great potential to sequester SOC, but knowledge on mechanisms is required to make a method or policy	Japan - Korea
Assess residence time of C in charred material and MAOM	Important for the effectiveness of C sequestration	Japan - Korea
Investigate the temporal dynamics of soil physical structures: How SOM (quantity and quality) is involved in the mechanisms behind, how colloid and bacteria are trapped or circulate in the porosity depending on dry/wet cycles?	Limited knowledge about how it contributes to C storage/migration	Japan - Korea

PRIORITIES RELATED TO SOIL HEALTH AND ECOSYSTEMS SERVICES		Sub-region
Explore the co-benefits of SOC storage on ecosystems services such as biodiversity, soil fertility and crop production	Lack of knowledge	Generic for Asia
Explore the trade-offs related to biomass use: food security versus C storage in soil	Sustainability issue	Generic for Asia

PRIORITIES RELATED TO CAPACITY BUILDING		
Farmers' and land managers' capacity building: training, guidance, and advice to farmers and land managers on how to increase SOC, the positive practices and their impacts; networks to facilitate knowledge exchange.		
Policy advocacy		
Stakeholders' capacity building: connecting researchers, NGOs, land managers, policy makers, etc. to facilitate knowledge exchange and the design of effective solutions ton increase and monitor SOC. This includes e.g., participatory approaches, living labs, lighthouses, and knowledge hubs.		
Raising awareness on soil organic carbon and soil health in society as a whole: education on the issues at stake, on good practices, socio-cultural change in attitude, etc.		
Researchers' and technical staff's capacity building: on the issue of soil carbon, across disciplines and for various types of land uses, by training and networking.		
PRIORITIES RELATED TO ECONOMICS AND SOCIAL SCIENCES		
Costs and benefits of "positive" practices: science-based information, indicators, and (decision-making) tools to support land managers and policy-makers, concerning the impacts of land management practices and land use (changes) on SOC, carbon storage, net-GHG budget, but also on all other environmental and SDGs aspects, including the co-benefits' synergies and tradeoffs, accounting for uncertainty; cost-uncertainty/accuracy tradeoffs of baseline/impact assessment of various M(RV) methodologies.		
Types of incentives/ instruments to be enforced and comparison of their cost-effectiveness and/or cost-efficiency: this also includes the impacts of existing climate and non-climate policies on carbon sequestration, but also on other environmental and SDGs aspects (e.g., resilience, land value/rent, how the economic surplus is shared along the value chain).		
Barriers, levers and enabling environment for the adoption of "positive" practices and cost-effective instruments, as well as policy issues and governance: the latter include policy coherence issues at different scales and across sectors, the building of a narrative on carbon sequestration and co-benefits, the provision of a trajectory and transition pathway towards this narrative, etc.		
Carbon credits schemes and financing: carbon credit schemes' design (to deal with the impermanence of C storage, financing of existing C stocks, clarity of MRV implementation, ...), public-private funding of carbon finance, and carbon market design (to ensure that costs, benefits, and environmental and financial risks are fairly distributed among participants).		

7.4 Summarized priorities for Europe

Europe research needs (1st column) and their rationale (2nd column) gathered by major topics (monitoring, tools, practices, processes, climate change, land-use change, ecosystem services, economics and social sciences, capacity building).

MONITORING PRIORITIES	
Enhance the type of data collected together with soil carbon: soil type and properties, practices, OM inputs, CO_2 fluxes and other GHG emissions, taxonomic and functional biodiversity, compaction and erosion, etc.	To gain a better understanding of SOC balance, find causal relationships and improve models.
Develop harmonized protocols based on existing forest monitoring and reporting systems that include forest inventory data and take into account the whole rooting zone of trees, the spatial heterogeneity of forest soils and the sampling of the forest floor	Heterogeneity across forest and urban soils is a challenge, hence investigating the factors contributing to this heterogeneity is essential.
Develop/maintain long-term experiments and Living Labs where SOC can be measured depending on climate, soil type, biodiversity, land uses and management practices	To improve knowledge, C dynamics over long-term scale, learn more/quantify/model the links between soil/land management and SOC and all side effects
Collect data on SOC pools	To identify which carbon fractions are most relevant for stabilization of carbon, which are the most relevant for the many aspects of soil health. As carbon stocks in soils change slowly, there is a need for developing and/or more extensive testing of more dynamic proxies for carbon sequestration
Emphasis on monitoring in C-under-sampled regions, e.g., in the tropics or SUITMA soils (Soils of Urban, Industrial, Traffic, Mining and Military Areas)	Limited observations and understanding

TOOLS' DEVELOPMENT PRIORITIES	
Develop digital mapping of SOC stocks, rate of change, potential for additional storage (together with mapping of specific indicators or thresholds, soil typology, ecosystem services, fire risk) depending on pedoclimatic conditions and soil management	To facilitate decision-making by managers and operators in the field.
Continue developing accurate, easy to use, high throughput and low-cost methods to assess SOC content	To complete our knowledge on the C status of soils / to provide robust MRV systems (in-field and remote) and overview of the potential and current carbon stock of European soils, which will ultimately determine the practices choice
Developing advanced sensors, satellite imaging, and AI-driven analytics that can help monitor SOC and vegetation/soil conditions in real time	For Verification & Carbon Markets Integration / allowing for precise application of water, fertilizers
Improve models of SOC dynamics (include practices' impact, better account for below-ground inputs, deep soil layers, coupling with hydrological models, crop models or regional climate models)	To improve prediction and better support stakeholders' decisions
Develop a MRV system for MAOM (from GIS/Earth observation from inclusion in MRV accredited models)	The MAOM pool is considered as relevant for long-term C storage
Develop a SOC data portal that should be compatible with the EU Data Strategy24 and the EU data spaces and which should be a hub providing access to soil data coming from various sources, in the aggregated form (building on and upgrading the existing EU soil observatory). making data interoperable and reusable for knowledge development, creating data connections (APIs) and a data infrastructure (in respect of GDPR principles) and providing access to models and tools (using open access or an appropriate license).	To check all national data in a standardized manner and make them available in harmonized formats for further analyses and evaluations. to create trust in the carbon farming ecosystem, all stakeholders involved in the roadmap process have communicated a need to have sufficient certainty that project outcomes are quantified accurately and are comparable between carbon farming schemes. To deliver carbon payment schemes (incl. carbon farming) that promote conservation and enhancement of SOC, including wider economic impacts based on scientific research
Based on the knowledge, develop SOC baselines and indicators that correlate SOC with ecosystem services, emission factors, benchmark values and best management practices adapted for each soil type, climate and land use.	To support the development of a matrix of achievable objectives with sustainable practices and advice to land stewards, for national SOC stocks reporting and emissions trading. To deliver carbon payment schemes (incl. carbon farming) that promote conservation and enhancement of SOC including wider economic impacts based on scientific research. To provide an overview of the potential and current carbon stock of European soils
Determine the uncertainty associated with each soil carbon measurement/prediction method. Determine how variable this uncertainty is according to soil type and the quality of organic matter it contains	There are several methods of SOC assessment, either direct or indirect. The associated errors are rarely indicated. It can be difficult to compare the various methodologies. These errors can be large, whereas carbon storage values can be small. Does this error depend on soil type? For example, isn't it higher in calcareous soil?

Provide decision trees with harmonized and standardized methodologies (what methodology for who), and simple indicators for stakeholders.	To remove barriers to the adoption and help stakeholders
Improve methods to quantify rhizodeposition	Importance of below ground C inputs for SOC

PRACTICES' IMPACT PRIORITIES	
Develop the matrix of sustainable soil management options (deep-rooted and perennial crops, recycled waste and organic amendments vs. mineral fertilizers, agroforestry, regenerative agriculture, conservation agriculture, biochar...) on SOC under different pedoclimatic conditions	High variability. Relevant practices for agroecology or adaptation to climate change and with a putative mitigation potential
Need for more systematic long-term studies on "novel" practices, e.g., fertilizer strategies for more novel organic fertilizers (biogas digestates, fish sludge etc.), alternatives to plastic use, microbial inoculants; silicate rock amendments to enhance weathering processes	Limited number of observations. Relevant practices for agroecology or adaptation to climate change and with a putative mitigation potential. Increasing awareness on the toxicity of plastics.
Better understand and define drivers and impacts of C storage by combinations of management practices (e.g. tillage and crop rotation)	Most studies consider agricultural practices isolated and do not account for the diversity and complexity of cropping systems
Measuring and monitoring the effect of livestock management, intensive grazing, mowing, the duration and frequency of temporary grasslands in crop rotations on the evolution of SOC stocks and SOC pools in the long term	Limited number of observations. Relevant practices for adaptation to climate change. Putative mitigation potential
Gain a better understanding of the long-term impact of tree harvest management (litter and residues removal, stand age structure, stump uprooting, soil compaction ... on C stocks) depending on soil properties	The increased demand for wood, including wood energy, increases the harvest intensification of whole tree harvest. Meanwhile mechanization impacts soil properties. Lack of knowledge, "one-size-fits-all forestry" policy measures that deliver on all expectations at once should be avoided
Gain a better understanding of the long-term impact of forestry practices related to plant cover management (identity and diversity of tree species, tree mycorrhizal status, understory management, natural regeneration vs. plantation, stand density, duration of stand rotation, machinery-induced soil disturbance such as compaction or erosion) on C storage	Because these management changes are imposed by climate change and directly impact ecosystem services. Lack of knowledge, "one-size-fits-all forestry" policy measures that deliver on all expectations at once should be avoided
Improve long-term understanding of biophysical and biochemical constraints on SOC sequestration (N, P, water)	To optimize fertilization/irrigation strategies
Investigate sustainable soil management practices in peatlands that conserve the organic matter in the soil while still creating a viable income for the farmers (such as paludiculture = wetland agriculture on restored peatland)	To enhance both the natural environment, climate mitigation as well as the local and viable value chain.
In urban areas, test and apply organic waste recycling (accounting for their diversity), urban agriculture, bioengineering techniques (e.g., geotextiles, vegetated retaining walls) to enhance SOC stocks while considering urban constraints.	Limited number of observations x relevant practices for adaptation to climate change x putative mitigation potential
Quantification and prediction of non-CO_2 greenhouse gas emissions associated with additional C storage practices.	Need for comprehensive greenhouse gas accounting (i.e. include non-CO_2 emissions such as N_2O, CH_4)

CLIMATE CHANGE IMPACT PRIORITIES	
How does OM contribute to soil resilience to drought conditions or heavy rainfall events?	Increase of drought events, delay or lack of rainfall, season shifts, heavy rainfall causing soil erosion
Need to explore more in-depth the single and combined effects of climate change (rising temperature, change in precipitation, increased drought frequency, wildfire, CO_2 enrichment, climate extremes) on SOC stocks and cycling mechanisms (in particular, plant inputs and activity of decomposer communities)	Limited number of observations and impact on 100 % of land surface
Implement long-term experiments on climate-smart management options (e.g. irrigation, breeding of more resilient varieties with larger root systems, longer-lasting plant covers) to assess long-term impact on SOC	Limited number of observations
Integrate SOC modeling with regional climate models for better scenario planning.	To improve model predictions
Can storing carbon in the soil offset greenhouse gas emissions?	Numerous studies show that carbon storage in the soil cannot compensate for emissions. However, offsetting is an important part of corporate strategies. How far can this strategy go?
Does salinization have an impact on soil carbon storage, other than through the impact of salt on primary production?	Lack of knowledge: Salinization is a growing threat to soils as a result of climate Change

LAND-USE CHANGE IMPACT PRIORITIES	
Investigate peatland restoration impact on C sink (e.g. avoided forestry on formerly drained peatlands, paludiculture=wetland agriculture on restored peatland)	To enhance both the natural environment, climate mitigation as well as the local and viable value chain.
Investigate the effect of soil degradation and erosion	Soil degradation and erosion directly threaten the vital functions and processes of soils. Healthy forest soils are essential for sustaining plant productivity, resilience, and their capacity to deliver key ecosystem services. Understanding and mitigating soil degradation is therefore critical for long-term food security, environmental sustainability and climate stability.
better quantify the afforestation impacts on deep soil C (below 30 cm) and on highly organic soils	Reviews to date on the magnitude and direction of change of soil C stocks in organo-mineral soils after afforestation were inconclusive
increase knowledge on C storage in SUITMA (e.g. sequestration potential and C vulnerability in urban soils and post-industrial, mining areas; impact of soil sealing; soils affected by military impacts in Ukraine...)	SUITMA soils poorly known in comparison to other land uses
Impact of transformation of natural areas into organic agriculture.	Consumer demand for organic products will continue to grow driven by food safety concerns and increasing affluence, but due to lower yields in organic farming, natural ecosystems may be increasingly converted to agroecosystems to meet the demand with less well-known consequences for the environment.

PRIORITIES FOR BETTER UNDERSTANDING OF SOC PROCESSES	
Unravelling the influence of plant input quality (plant cover diversity, forest age, forest floor compartment) on above & below ground C inputs to soil and soil C dynamics	Lack of knowledge; importance of below-ground C for SOC stocks
Unravelling the influence of taxonomic and functional diversity of decomposers (macro/meso/micro-organisms) on C dynamics. Investigate the energetic constraints on decomposer-mediated SOM turnover.	Lack of knowledge; to facilitate decision-making by managers and operators in the field
Is there a hierarchy of processes regulating carbon dynamics (OM quality, decomposer activity, mineral protection...), as a function of soil type and climate? Do the control factors (geochemical, geophysical/topographical, climatic, biotic, managemental) vary in time?	Understanding biophysical controls on SOC pool sizes across diverse landscapes and land uses is paramount. Only if we have a good, quantitative understanding of named controls, we can design and implement tailored monitoring and management options. Specifically, this includes the interplay between soil minerals, soil life and soil structure in controlling SOC at the soil profile to the landscape scale.
SOC and soil inorganic carbon (SIC) interactions	Lack of knowledge about SOC dynamics in calcareous soils. Not all carbon is organic; inorganic carbon could release large amounts of CO_2 with temperature rise or microbial activity
Synchronicity between plant nutrient needs and mineralization of SOM (being dependent on water availability) (the C-nutrient-water nexus)	Not much studied so far, especially in agroecological systems
More investigation on the processes to store carbon deeper in the soil, more stable carbon, are needed.	Subsoil still understudied, expected potential to accommodate more carbon
Sensitivity of specific mechanisms controlling soil C storage to climate change (as a function of soil type and pedoclimatic conditions)	Increasing impact of climate change
Reach a consensus on MAOM formation/disruption mechanisms (by soil type and management)	MAOM=largest fraction in soil, retention time>100yrs vs. POM retention time in general <10yrs. Storage (POM) vs. sequestration (MAOM)
Connectivity across terrestrial aquatic interfaces: how do soil processes affect watershed nutrients and C export?	

PRIORITIES RELATED TO SOIL HEALTH AND ECOSYSTEMS SERVICES	
Lack of knowledge about the short and long-term effects and co-benefits of SOC on ecosystems services (stop soil degradation, improve soil fertility, climate resilience, biodiversity.....)	
Understand the potential trade-offs between food security, soil biodiversity and C accumulation for a balanced ecosystem management to meet multiple goals	If we only focus on management to increase C sequestration for climate mitigation, we risk harming soil biodiversity, while biodiversity influences soil processes, nutrient cycling, and ecosystem functioning, climate resilience. Food production will also be impacted. It is important to understand whether multiple effects/services can be obtained in the same stands/sites or whether they should be optimized across differently managed ecosystems. The time scale is also important to consider
Quantification and prediction of non-CO_2 greenhouse gas emissions associated with additional C storage practices. For example, questioning timber production: is wood-biomass sustainable when growing on drained peat still emitting greenhouse gases? Is forest bioenergy sustainable?	Need for comprehensive greenhouse gas accounting (i.e. include non-CO2 emissions such as N2O, CH4)
Develop indicators that correlate SOC storage, stability with other ecosystem services, as a function of soil type and climate	To improve the adoption of practices favoring SOC accumulation. Despite efforts, many European soils remain unhealthy

PRIORITIES RELATED TO CAPACITY BUILDING	
Farmers' and land managers' capacity building: training, guidance, and advice to farmers and land managers on how to increase SOC, the positive practices and their impacts; networks to facilitate knowledge exchange.	Lack of regional and pedoclimatic-specific guidelines on measures to maintain (e.g., avoid degradation) and increase SOC, including socio-economic effects for different farming systems. Lack of science-based and objective information available to field users concerning the use of biochars and its impacts.
Policy advocacy	-
Stakeholders' capacity building: connecting researchers, NGOs, land managers, policy makers, etc., to facilitate knowledge exchange and the design of effective solutions to increase and monitor SOC. This includes, e.g., participatory approaches, living labs, lighthouses, and knowledge hubs.	E;g., creating a knowledge hub on the technical aspects of carbon farming, such as the impact of practices on carbon sequestration, co-benefits, trade-offs, models, data infrastructure, tools, measuring protocols, quantification methods, and regional baselines, to create trust in the carbon farming ecosystem. Lack of stakeholders' trust on project outcomes, quantification and comparability between CF schemes. Forest: need to plan ahead for the management of forest sites after a storm or pest infestation to protect soils and their carbon stocks, as huge volumes of wood need to be mobilized and access to plots is a problem.
Raising awareness on soil organic carbon and soil health in society as a whole: education on the issues at stake, on good practices, socio-cultural change in attitude, etc.	Lack of awareness and knowledge of society as a whole on carbon flows, the conservation of soil organic carbon stocks, and sustainable soil management. Lack of awareness and appreciation of the multiple (co)benefits of increasing and maintaining soil carbon stocks, and poor understanding of the trade-offs and synergies between soil carbon and other environmental and socio-economic objectives.

PRIORITIES RELATED TO ECONOMICS AND SOCIAL SCIENCES	
Costs and benefits of "positive" practices : science-based information, indicators, and (decision-making) tools to support land managers and policy-makers, concerning the impacts of land management practices and land use (changes) on SOC, carbon storage, net-GHG budget, but also on all other environmental and SDGs aspects, including the co-benefits' synergies and tradeoffs, accounting for uncertainty; cost-uncertainty/accuracy tradeoffs of baseline/impact assessment of various M(RV) methodologies.	Peatlands: sustainable soil management practices that conserve organic matter in the soil while still generating a viable income for farmers still need to be investigated. Forest: studies mainly focus on biomass storage, lack of monitoring/experimentation to acquire technical and economic knowledge on recommended practices for SOC storage (also limiting the impact on soil compaction and erosion), to assess additional economic costs and ensure that recommendations are operational. In general: Lack of cost-benefit analyses accounting for all co-benefits - synergies and tradeoffs- of "positive" practices, the short- and long-term effects of an increase/decrease in SOC levels at farm level, and the cost of risk associated with changes in practices, while taking into account regional specificities, pedoclimatic context, and farming systems.
Types of incentives / instruments to be enforced and comparison of their cost-effectiveness and/or cost-efficiency: this also includes the impacts of existing climate and non-climate policies on carbon sequestration, but also on other environmental and SDGs aspects (e.g., resilience, land value/rent, how the economic surplus is shared along the value chain).	Lack of comparison of the cost-effectiveness of various instruments on SOC storage, while accounting for its specificities (long-term process, finite and non-permanent, and surrounded by uncertainty). Lack of assessment of the impacts of existing (non) climate policies (e.g., EU Common agricultural policy, bioenergy demand) on soil carbon sequestration. Lack of assessment of the impacts of carbon farming (schemes) large-scale implementation on prices and food security, as well as on other environmental impacts and SDGs, using economic modelling. Lack of ex-post evaluation of impacts and effectiveness of existing schemes and policies (e.g., carbon credit schemes in relation with MRV, EU soil protection policies, financial incentives for sustainable farming), to improve policy design.
Barriers, levers, and enabling environment for the adoption of "positive" practices and cost-effective instruments, as well as policy issues and governance: the latter include policy coherence issues at different scales and across sectors, the building of a narrative on carbon sequestration and co-benefits, the provision of a trajectory and transition pathway towards this narrative, etc.	To improve policy coherence and better design policies: address consistency between climate mitigation, adaptation, soil conservation, and sustainable land management, also accounting for medium-term bio-based energy demand; analysis of carbon policy building at international scale (using game theory, political economy); address how carbon farming credits/schemes should be coordinated with carbon markets in other sectors and on what scale. Peatland : need for a narrative and a governance structure with a clear mandate and long-term vision, and to explore paludiculture opportunities as rewetting has a high opportunity cost.
Carbon credits schemes and financing: carbon credit schemes' design (to deal with the impermanence of C storage, financing of existing C stocks, clarity of MRV implementation, ...), public-private funding of carbon finance, and carbon market design (to ensure that costs, benefits, and environmental and financial risks are fairly distributed among participants).	Lack of knowledge on the best way to deal with the impermanence of carbon storage, on the appropriate MRV system(s) to deal with cost-accuracy and additionality, both for the climate and to create trust in the quality of the credits. Lack of reliable public data on individual carbon credit projects and carbon credit transactions (including selling price) along the value chain, to help characterize the demand and willingness to pay for such credits depending on their quality. Lack of information on how costs, benefits, and environmental and financial risks are distributed among land managers, operators/intermediaries, and buyers in carbon farming projects, which is also useful for effective carbon market design.

7.5 Summarized priorities for Latin America

Latin America research needs (1st column) and their rationale (2nd column) gathered by major topics (monitoring, tools, practices, processes, climate change, land-use change, ecosystem services, economics and social sciences, capacity building).

MONITORING PRIORITIES	
Enhance large-scale monitoring of C and N stocks and additional data on current soil conditions, accounting for the diversity of agricultural production systems (e.g. coffee production, regions of the Amazon Basin & Andes deforested into pasture and cropland...)	Heterogeneity of soils is a challenge, hence investigating the factors contributing to this heterogeneity is essential.
Enhance the monitoring of changes in methane and N_2O emissions following pasture intensification to understand the environmental impacts of such an intervention on the full system	Pasture intensification, achieved by increasing fertilization, yield and animal feeds has a large impact on methane emissions and other GHG fluxes
Enhance the monitoring of peatland distribution, carbon storage and GHG fluxes	Peatland research is much less developed in Latin America than in the northern hemisphere or in Southeast Asia. There are still knowledge gaps regarding peatlands distribution and extent, particularly in mountainous regions where peatlands form in small, isolated patches or in remote locations where fieldwork is difficult (e.g., central Amazonia). Mapping peatlands in Latin America is challenging as some ecosystems, considered 'peat-forming', do not always accumulate peat. More efforts are also needed to understand to what extent peatlands have been altered and how disturbance alters GHG fluxes.
Identify most promising sites for additional C storage.	e.g. for Bofedales and Vegas in the Andes (Izquierdo et al. 2022), *M. flexuosa* swamps in Amazonia (Hastie et al., 2022) or Mallines in Patagonia. Therefore, maps of peatlands only indicate potential peatlands. The presence of peat can only be validated by ground-truthing, which requires substantial funding and major efforts to access remote and inaccessible locations
TOOLS' DEVELOPMENT PRIORITIES	
To assess SOC content and SOC change: continue developing easy to use, high throughput and low-cost but accurate methods, as well as advanced sensors, satellite imaging, and AI-driven analytics	To complete our knowledge on the C status of soils / to demonstrate the efficiency of sustainable practices on soil C and soil health, that will ultimately determine the practices' choice
Develop a digital platform with geographical information, soil data, practices' history...for agricultural, livestock and forestry systems as well as ecosystem restoration. Data should be interoperable and reusable for knowledge development.	To guide the planning of practices promoting conservation and enhancement of SOC, to check all national data in a standardized manner and make them available in harmonized formats for further analyses and evaluations.
Organize a Long-term Experiments network and digital platform	To improve knowledge
Develop mapping of SOC stocks, rate of change, potential for additional storage under future management and climate scenarios (together with mapping of specific indicators or thresholds, soil typology, ecosystem services, fire risk)	To facilitate decision-making by managers and operators in the field.
Improve and "tropicalize" models of SOC dynamics (include practices' impact, better account for below-ground inputs, deep soil layers, coupling with hydrological models, crop models or regional climate models)	To improve prediction and better support stakeholders' decisions. Current models are designed to report temperate soil processes/practices
How to scale up microscale processes at the soil profile, landscape level, which are highly heterogeneous	Landscape dynamics include spatial and temporal heterogeneity but in theory, they can be modelled from microscale analysis

PRACTICES' IMPACT PRIORITIES	
Explore the impacts of livestock and grazing management as well as the use of N fertilizer on soil carbon and GHG emissions at country and farm levels.	In Brazil, animal production from pastures is carried out on 159 million hectares (45% of the agricultural area of the country) which support the second largest cattle herd of the world, exceeding 230 million bovines (IBGE, 2017). Further, animal production from pastures is the main economic activity on 2.5 million rural properties around the country (IBGE, 2017) and it represents approximately 4% of Gross Domestic Product (CEPEA, 2018).
Development and testing of innovative and sustainable practices adapted to highly weathered and poorly fertile tropical soils to improve soil quality and increase SOC (organic waste management such as sustainable production and use of biochar, introduction of N-fixing species, production and inclusion of bioenergy crops in crop rotations, exploitation of the soil-plant-insect pest microbiome instead of employing pesticides, plant breeding adapted to changing climatic conditions with a more developed root system...)	Most of current practices are similar to the ones implemented in Europe and are often not adapted to Latin America, where most soils are highly weathered and poorly fertile. The climate is also very different, with a lot of rain. Soil quality correction currently based on the use of chemical fertilizer, liming and machinery should rather rely on biological-based management. Additionally burning of crop residues is forbidden, innovation and research are needed to improve efficiency of their recycling
Develop a common "Carbon preservation" referential on practices that do not increase C in soil but maintain it	Many soils are already well managed therefore presenting limited opportunities to increase SOC storage

CLIMATE CHANGE IMPACT PRIORITIES	
Increasing the adaptive capacity and resilience of agricultural production systems (management and planning) to water stress, heat waves and pests intensified by climate change with greater SOC accumulation, economic impact and relevance to food security	Many of the current agricultural production systems have low adaptive capacity and low resilience to the impacts of climate change. Assessing the risks of productivity loss in agricultural systems*, based on zoning and current scenarios and projections of future scenarios, which take into account the impacts of climate change on biotic and abiotic production factors, makes it possible to take decisions to adopt preventive measures, promote loss reduction, the formation of risk transfer mechanisms and the expansion of agricultural insurance. It also makes it possible to identify vulnerable areas and prioritize them in adaptation policies and actions (*agricultural systems, livestock, forestry and their integrations).
Investigate vulnerability of SOC content and persistence to climate change (drought, rain, more frequent and intense fires) in relation to soil type	To increase the adaptive capacity and resilience of SOC and agricultural production as fire, water stress, heat and changes in the dynamics of phytosanitary problems, are intensified by climate change
Need for in-depth exploration of the combined effects of climate change (temperature, precipitation, CO_2 enrichment) on SOC	Essential to guide climate resilient soil and land management strategies to maintain productivity under future climate scenarios.
Integrate SOC modeling with regional climate models for better scenario planning	To improve model predictions

LAND-USE CHANGE IMPACT PRIORITIES	
Can land-use change such as forest regeneration, commercial tree plantations, construction of smart-C technosol or restoration of degraded soil and mining area mitigate GHG emissions from agriculture	One promising opportunity to mitigate GHG emissions from agriculture and other sectors is to reforest marginal lands for intensive agriculture, where naturally regenerating or planted trees could sequester much larger amounts of C than other land uses. Understanding the potential of different tree planting and regeneration approaches across agricultural landscapes is then critical to design integrated and effective tropical agri-environmental schemes and policies. In addition, soil degradation is closely linked to a decrease in soil organic carbon content and to an increase in soil GHG emissions (Damian et al., 2021; Santos et al., 2021). Thus, soil restoration strategies can both increase soil C content and help mitigate climate change and GHG emissions
Investigate carbon flux in highly biodiverse but deforested regions of the Amazon Basin & Andes (South America)	Lack of knowledge
Need to develop studies on the effect of wetlands conversion (8 % of the meta-analyses in Beillouin et al. 2022a) and wetlands restoration on SOC (no meta-analysis).	Limited number of observations x high annual potential of mitigation (1 $GtCO_2e/y$ Bossio et al. 2020)

PRIORITIES FOR BETTER UNDERSTANDING OF SOC PROCESSES	
Understand the role of biodiversity in C sequestration and fluxes in deforested and agricultural systems of Latin America, in particular in highly weathered tropical soils from the Amazon Basin or from the Andes	The living part of soils has been recently recognized as an active part of the system, supplying services for both soil quality and plant growth efficiency. Poorly investigated out of temperate regions
Investigate OM-minerals interactions: characteristics in tropical soils, impact of rock weathering, make progress on quantification of C capture by rock weathering for C credit market	Limited knowledge

PRIORITIES RELATED TO SOIL HEALTH AND ECOSYSTEMS SERVICES	
Investigate if there synergies between soil carbon sequestration and soil health and other ecosystem services?	Depending on management practices, agricultural systems can also be the source of numerous disservices, including nutrient runoff, water contamination, pest proliferation, soil erosion and GHG emissions. Therefore, the tradeoffs and synergies that may occur among different categories of ecosystem services should be evaluated in terms of spatial and temporal scales to design sustainable management systems and offer public policy recommendations
Effects of increased soil carbon on ecosystem resilience (i.e., adapting to climate change, arresting or reversing land degradation...)	A lot of soils in Latin America have been degraded by expansion of agro-pastoral lands into native ecosystems. It is critical to restore them to support production and adaptation to climate change

PRIORITIES RELATED TO CAPACITY BUILDING	
Farmers' and land managers' capacity building: training, guidance, and advice to farmers and land managers on how to increase SOC, the positive practices and their impacts; networks to facilitate knowledge exchange.	Need for technical knowledge sharing: showcase, peer-to-peer learning, demonstration, mapping tools, projects, extension services, local to global policies.
Policy advocacy	-
Stakeholders' capacity building: connecting researchers, NGOs, land managers, policy makers, etc. to facilitate knowledge exchange and the design of effective solutions ton increase and monitor SOC. This includes e.g., participatory approaches, living labs, lighthouses, and knowledge hubs.	Lack of compiled information and data available to all stakeholders on native ecosystem restoration. Need for technical knowledge sharing.
Raising awareness on soil organic carbon and soil health in society as a whole: education on the issues at stake, on good practices, socio-cultural change in attitude, etc.	-
Researchers' and technical staff's capacity building: on the issue of soil carbon, across disciplines and for various types of land uses, by training and networking.	-

PRIORITIES RELATED TO ECONOMICS AND SOCIAL SCIENCES	
Costs and benefits of "positive" practices : science-based information, indicators, and (decision-making) tools to support land managers and policy-makers, concerning the impacts of land management practices and land use (changes) on SOC, carbon storage, net-GHG budget, but also on all other environmental and SDGs aspects, including the co-benefits' synergies and tradeoffs, accounting for uncertainty; cost-uncertainty/accuracy tradeoffs of baseline/impact assessment of various M(RV) methodologies.	Need to assess the cost-effectiveness of native ecosystems restoration in Brazil, and to make this information available in different formats, to support the design of relevant policies. Lack of knowledge on the impacts of low carbon farming systems on the resilience and adaptive capacity of agriculture, on food security, and on the rest of the economy, compared to current systems and in the face of climate change. Lack of information on the socio-economic and environmental impacts of the products generated by integrated systems (ILP and ILPF) along the value chain, useful to increase their visibility and capture added value as well as design relevant incentives. Lack of tools and indicators integrated into a digital platform, to characterize and quantify the sustainability of agricultural, livestock, and forestry systems in the face of climate change, useful to evaluate, validate or even adapt public policies, actions, and programs.
Types of incentives / instruments to be enforced and comparison of their cost-effectiveness and/or cost-efficiency: this also includes the impacts of existing climate and non-climate policies on carbon sequestration, but also on other environmental and SDGs aspects (e.g., resilience, land value/rent, how the economic surplus is shared along the value chain).	
Barriers, levers, and enabling environment for the adoption of "positive" practices and cost-effective instruments, as well as policy issues and governance: the latter include policy coherence issues at different scales and across sectors, the building of a narrative on carbon sequestration and co-benefits, the provision of a trajectory and transition pathway towards this narrative, etc.	Need to build a narrative on C sequestration and co-benefits (i.e., guiding principles to adhere to), and to provide a trajectory and transition pathway toward the narrative, so that it makes sense for farmers and land managers to adopt low carbon practices or systems.
Carbon credits schemes and financing: carbon credit schemes design (to deal with the impermanence of C storage, financing of existing C stocks, clarity of MRV implementation, ...), public-private funding of carbon finance, and carbon market design (to ensure that costs, benefits, and environmental and financial risks are fairly distributed among participants).	

7.6 Summarized priorities for North America

North America research needs (1st column) and their rationale (2nd column) gathered by major topics (monitoring, tools, practices, processes, climate change, land-use change, ecosystem services, economics and social sciences, capacity building).

MONITORING PRIORITIES	
Enhance SOC monitoring and the type of data collected together with soil carbon: soil type and properties, practices, OM inputs, CO_2 fluxes and other GHG emissions, taxonomic and functional biodiversity, compaction and erosion, etc.	To gain a better understanding of SOC balance, find causal relationships and improve models.
Improve current monitoring network by establish a permanent, national-scale, high-quality soil monitoring network, to allow for a periodic (re-) measurement of soil C stocks and soil health indicators. allow on-farm monitoring system to augment the existing national inventories	Required for a robust monitoring program, to improve accuracy and reduce uncertainty in regional to national soil C stocks quantification; lack of data on rates and uncertainty bounds of soil C accrual for some practices in certain systems and geographies
Expand the measurement of non-CO_2 greenhouse gases, particularly soil N_2O and enteric CH_4 emissions on both existing and new sites	To quantify impacts of adopting conservation/regenerative management practices and contrasting their performance with conventional systems.
Build Long-Term Agricultural Field Experiments in underrepresented cropping systems, regions, climates and soil types	To quantify impacts of adopting conservation/regenerative management practices and contrasting their performance with conventional systems.
Improve SOC monitoring in remote Sub-arctic and Arctic peatlands, for some mountain territories and forested peatlands	To refine estimates of peatland C for North America
Improve SOC monitoring at depth	Data are lacking where significant stores lie at depth

TOOLS' DEVELOPMENT PRIORITIES	
Develop a SOC harmonized data portal (national, or even international) with public and also private data from C removal projects	To increase knowledge, to check all data in a standardized manner and make them available in harmonized formats for further analyses and evaluation. to deliver carbon payment schemes (incl. carbon farming) that promote conservation and enhancement of SOC including wider economic impacts based on scientific research.
Reduce the uncertainty associated with proximal or remote sensing monitoring methodologies to improve data quality. Determine how variable this uncertainty is according to soil type and the quality of organic matter it contains?	There are several methods of SOC assessment, either direct or indirect. The associated errors are rarely indicated. It can be difficult to compare the various methodologies. These errors can be large, whereas carbon storage values can be small. Does this error depend on soil type? For example, isn't it higher in calcareous soil?
Provide decision trees with harmonized and standardized methodologies (what methodology for who), and simple indicators for stakeholders.	To remove barriers to the adoption and help stakeholders
Improve models of SOC dynamics (include practices impact, better account for below-ground inputs, deep soil layers, coupling with hydrological models, crop models or regional climate models). develop a model platform	To improve prediction and better support stakeholders' decisions
Standardization in the measurement, reporting and verifying of sources, and in protocols for offset use by the private sector: establish appropriate control areas for a statistically representative sample of treatment areas within first 2 years of IRA/projects, resurvey them 5 years later	To create trust in the carbon farming ecosystem, all stakeholders involved in the roadmap process have communicated a need to have sufficient certainty that project outcomes are quantified accurately and are comparable between carbon farming schemes.
Develop indicators of ecosystem services, by drawing a growing database of on-farm results as a function of soil type and climate	Today, less than 5% of cropland in the U.S. is managed using the basic soil health practice of cover cropping. To improve the adoption of sustainable practices favoring SOC accumulation and soil health, Interpretation of any soil health indicator requires defining what values are ideal
Develop methods to isolate vulnerable/persistent pools of C in soil	As carbon stocks in soils change slowly, there is a need for developing and/or more extensive testing of more dynamic proxies for carbon sequestration. This will improve predictions of C stock changes.

PRACTICES' IMPACT PRIORITIES	
Quantify impacts on SOC of adopting conservation/regenerative management practices and their performance compared to conventional systems under different pedoclimatic conditions	Under-studied practices compared to conventional system, though relevant for agroecology or adaptation to climate change and with a putative mitigation potential
Explore the impact on SOC of waste recycling and composting- in particular, assess impacts of amendment with biochar or digestate of biogas production, for different management systems and soil types, including secondary impacts on soil functions and larger impact due to changes in technical itineraries	Protecting environment and climate for the health and prosperity of future generations through the reduction, reuse and recycling of resources, and the transition from a disposable to a fully circular economy. High variability x relevant practices for agroecological practices or adaptation to climate change x putative mitigation potential
Explore solutions for urban agriculture and their impact on SOC	Urban and vertical farming saw remarkable growth in 2023, addressing the challenges of space constraints and the need for fresh produce in city centers.
Explore solutions to enhance fertilizer efficiency and decrease GHG emissions	To optimize fertilization strategy
Better explore the impacts of wetland degradation on SOC and GHG balance	Areas of peatland disturbed by a range of development pressures (e.g., roads, seismic lines, drainage for agriculture, ore mining industry, forestry, flooding by dams) are not well-known. In addition, the full impact of many disturbances, including agriculture, roads, infrastructure development and permafrost thaw, on peatland function (particularly GHG emissions) is not well-quantified
Better explore the impacts of the following forestry practices on SOC : site preparation, improved representation of harvesting approaches with various retention levels, the impact of thinning (commercial and pre-commercial) on carbon stocks and subsequent growth, impacts of harvesting on uneven-aged stands.	Limited or highly variable observations x relevant practices for adaptation to climate change x putative mitigation potential
Better explore how to preserve C stocks in forests (species selection, amount of vulnerable SOC...) with the threat of climate change	To preserve C stocks

CLIMATE CHANGE IMPACT PRIORITIES	
Investigate vulnerability of SOC content and persistence to climate change in relation to soil type	To increase the adaptive capacity and resilience of SOC and agricultural production as stresses such as water, heat and changes in the dynamics of phytosanitary problems, are intensified by climate change
Need more in-depth exploration of the combined effects of climate change (extreme events, and changing climatic conditions) on SOC	Essential to guide climate resilient soil and land management strategies to maintain productivity under future climate scenarios.
Develop models of climate-sensitive disturbance occurrence and intensity. Develop integrated models that quantify the impacts of individual disturbances and cumulative effects of multiple disturbances on carbon dynamics.	To improve model predictions

LAND-USE CHANGE IMPACT PRIORITIES	
Investigate the influence of afforestation, reforestation or agroforestry on C accrual, depending on initial soil carbon stock and on pedoclimate	It will improve forest sector GHG emission and mitigation estimates. Forest land managers and other stakeholders will have access to site- and landscape-level information on the impact of various human activities on current and future forest carbon dynamics. Important for C credit schemes

PRIORITIES FOR BETTER UNDERSTANDING OF SOC PROCESSES	
What are the drivers of C persistence vs. abundance stratified by pedoclimate	Needed for assessment of modeling and policy efforts
Unravelling the influence of taxonomic and functional diversity of decomposers (macro/meso/micro-organisms) on C dynamics	Lack of knowledge; to facilitate decision-making by managers and operators in the field
Gain a better knowledge on C persistence and nutrient availability in MAOM as a function of soil type	We seem to assume C is stable in MAOM yet we know that is not true (particularly in the case of redox). What percentage of it is stable, when is it vulnerable and why? Addresses the need for co-benefits/function
Gain a better understanding on interactions between soil porosity and SOC and their temporal dynamics	Lack of knowledge
Process-based studies are required to understand how physical, biological, and chemical mechanisms interact to determine decomposition, leaching, and erosion rates and their sensitivity to a changing climate	A thorough understanding is needed about the role of soil composition, geochemistry, environmental controls, natural disturbances, and soil community biodiversity in controlling biomass turnover, decomposition rates, and soil carbon stabilization processes.
Advance understanding of carbon cycling processes in peatland and permafrost soils of North America.	Advancing our understanding of carbon cycling processes in peatland and permafrost soils that are carbon-rich and climate-vulnerable will better allow us to predict the impacts these critical components have on national carbon emissions and removals.

PRIORITIES RELATED TO SOIL HEALTH AND ECOSYSTEMS SERVICES	
Quantify co-benefits of SOC accumulation in different systems (i.e. agronomic outcomes, water quality/quantity, biodiversity...) by conducting a benchmarking approach	Today, less than 5% of cropland in the U.S. is managed using the basic soil health practice of cover cropping. To improve the adoption of sustainable practices favoring SOC accumulation and soil health, Interpretation of any soil health indicator requires defining what values are ideal
Develop indicators of ecosystem services, by drawing a growing database of on-farm results as a function of soil type and climate	Today, less than 5% of cropland in the U.S. is managed using the basic soil health practice of cover cropping. To improve the adoption of sustainable practices favoring SOC accumulation and soil health, Interpretation of any soil health indicator requires defining what values are ideal

PRIORITIES RELATED TO CAPACITY BUILDING	
Farmers' and land managers' capacity building: training, guidance, and advice to farmers and land managers on how to increase SOC, the positive practices and their impacts; networks to facilitate knowledge exchange.	Need for improved outreach and training and a need for technical services' provision and access to finance for all farmers (including small producers and discriminated producers), to assist farmers and ranchers in (successfully) adopting regionally-tailored technologies and conservation practices and to help them participate in programs.
Policy advocacy	To provide clear guidance to policy makers and commercial companies undertaking efforts to encourage adoption and real removals.
Stakeholders' capacity building: connecting researchers, NGOs, land managers, policy makers, etc. to facilitate knowledge exchange and the design of effective solutions to increase and monitor SOC. This includes, e.g., participatory approaches, living labs, lighthouses, and knowledge hubs.	Transferring research findings and technologies to practitioners, farmers and forest managers through extension and outreach educational programs. Sharing experiences of success and failure and identifying solutions to overcome barriers to adoption is necessary to accelerate programs across regions and scale up agriculture sequestering practices. In Canada, there is a need to develop participatory approaches involving Indigenous-led research that is centered on Indigenous voices and experiences and application of Indigenous Knowledge systems, to improve understanding of forest carbon.
Raising awareness on soil organic carbon and soil health in society as a whole: education on the issues at stake, on good practices, socio-cultural change in attitude, etc.	-
Researchers' and technical staff's capacity building: on the issue of soil carbon, across disciplines and for various types of land uses, by training and networking.	In Canada, need to maintain and further develop researchers' capacity in the field of forest carbon science to address forest carbon policy issues and analytical needs at multiple levels.

PRIORITIES RELATED TO ECONOMICS AND SOCIAL SCIENCES	
Costs and benefits of "positive" practices : science-based information, indicators, and (decision-making) tools to support land managers and policy-makers, concerning the impacts of land management practices and land use (changes) on SOC, carbon storage, net-GHG budget, but also on all other environmental and SDGs aspects, including the co-benefits' synergies and tradeoffs, accounting for uncertainty; cost-uncertainty/accuracy tradeoffs of baseline/impact assessment of various M(RV) methodologies.	Lack of knowledge/data on the economic sustainability of regenerative/conservation agricultural practices (to ensure long-term maintenance of practices and increased soil C stocks). Lack of knowledge on the costs, benefits and cost-effectiveness of carbon-friendly practices and land management in the context of Quebec and Canada production systems and pedoclimate. Lack of knowledge on the relevant MRV system(s) for carbon farming in the local (Canadian) context, accounting for cost-accuracy and robustness.
Types of incentives / instruments to be enforced and comparison of their cost-effectiveness and/or cost-efficiency: this also includes the impacts of existing climate and non-climate policies on carbon sequestration, but also on other environmental and SDGs aspects (e.g., resilience, land value/rent, how the economic surplus is shared along the value chain).	Lack of knowledge on the cost-effectiveness (including other co-benefits) and cost-efficiency of various types of incentives; addressing the design of incentives that favor the adoption of positive practices at scale and in the long-term. Need to (better) assess the growing demand for meat and dairy substitutes and its impacts on land use (change), in terms of areas that could be freed up for instance to provide services in reforestation or sequestration. Lack of knowledge on the long-term impacts of incentives/policies especially on the permanence of practices and SOC storage, and the magnitude and time of subsequent release. Lack of research on how the various types of landowners respond to incentives and on incentives' impact in terms of equity among landowner classes.
Barriers, levers, and enabling environment for the adoption of "positive" practices and cost-effective instruments, as well as policy issues and governance: the latter include policy coherence issues at different scales and across sectors, the building of a narrative on carbon sequestration and co-benefits, the provision of a trajectory and transition pathway towards this narrative, etc.	Need to quantify indicators that influence adoption of regenerative agricultural practices. Economic and behavioral research can help investigate approaches to improve policy design and landowner responses to incentives, to address inequities in participation to conservation incentive programs, and to project the potential for upscaling of soil-based carbon removal and GHG reduction approaches as climate mitigation strategies. Lack of knowledge on the type of governance necessary to better engage the private-sector in pursing demand-side carbon removal activities.
Carbon credit schemes and financing: carbon credit schemes design (to deal with the impermanence of C storage, financing of existing C stocks, clarity of MRV implementation, ...), public-private funding of carbon finance, and carbon market design (to ensure that costs, benefits, and environmental and financial risks are fairly distributed among participants).	Need for research on the tradeoff between the cost of decreasing uncertainty surrounding net carbon removal quantification and the potential increase in the offset value for both buyer and seller. Need to further investigate the impacts of the ownership of carbon credits generated on the adoption of certain practices (esp. biochar and biodigesters' digestate application) and the distribution of the economic surplus. Developing a common set of standards for offset accounting could allow for harmonization across different registry systems and offset market participants, in addition to increased transparency.

7.7 Summarized priorities for Oceania

Oceania research needs (1st column) and their rationale (2nd column) gathered by major topics (monitoring, tools, practices, processes, climate change, land-use change, ecosystem services, economics and social sciences, capacity building).

MONITORING PRIORITIES	
Increase experiments and SOC measurement in Pacific islands territories	Little information
In Australia, the priority is the establishment of long-term monitoring sites	To inform farm-scale MRV
Increase SOC monitoring in peatlands, mangroves	Peatlands in Oceania are amongst the most threatened and least understood ecosystems. This is because they are rare and restricted in distribution. In the Pacific Islands, polar lowland peatlands have been the focus of more research than their tropical counterparts
TOOLS' DEVELOPMENT PRIORITIES	
Support the development of harmonized databases for SOC and related data	Consistent and accurate monitoring of change in SOC, reporting and verification is key to facilitate investment in sustainable land use practices as well as to incorporate C sequestration in Nationally Determined Contributions to GHG emissions reductions
Continue developing accurate, easy to use, high throughput and low-cost methods to assess SOC content	To complete our knowledge on the C status of soils / to provide robust MRV systems (in-field and remote) and overview of the potential and current carbon stock, that will ultimately determine the practices' choice.
Develop decision-making tools with integrated information relevant to land managers' context: simple, affordable, and evidence-based, including economic and environmental benefits.	To better support stakeholders' decisions
Improve models and promote modular modeling approaches (include practices impact, better account for below-ground inputs, deep soil layers, coupling with hydrological models, crop models or regional climate models)	To improve prediction and support stakeholders' decisions
Assess uncertainty associated with measurements/predictions	Consistent and accurate monitoring of change in SOC, reporting and verification is key to facilitate investment in sustainable land use practices as well as to incorporate C sequestration in Nationally Determined Contributions to GHG emissions reductions

PRACTICES IMPACT PRIORITIES	
Identify practices adapted to local conditions (tropical / arid soils) for building/maintain soil organic carbon in small holder farming systems that are undergoing rapid management changes due to mechanization and intensification and climate change. In particular, practices increasing C inputs to SOM in water- and nutrient-limited environments while limiting GHG emission risk from N_2O.	Limited knowledge
CLIMATE CHANGE IMPACT PRIORITIES	
Need more in-depth exploration of the single and combined effects of climate change (rising temperature, change in precipitation, drought, CO_2 enrichment, climate extremes) on SOC stocks and cycling mechanisms. More specifically, currently a limited number of observations on the impacts of rainfall reduction, and wildfire	Limited number of observations and impact on 100 % of land surface
Develop land capability scenarios with future climate, land shifts	To improve SOC change predictions
LAND-USE CHANGE IMPACT PRIORITIES	
No information	No information

PRIORITIES FOR BETTER UNDERSTANDING OF SOC PROCESSES	
Explore C fractionation (particle-size fractionation and thermal analysis) as proxies for stabilized SOC pools, quantifies their vulnerability to land use and climatic change, and constrains the capacity of attainable mineral-associated SOC (MAOM)	Need for proxies of vulnerable and stable carbon.

PRIORITIES RELATED TO SOIL HEALTH AND ECOSYSTEMS SERVICES	
Lack of knowledge about the short and long-term effects and co-benefits of SOC on ecosystems services (stop soil degradation, improve soil fertility, climate resilience, biodiversity .....)	To promote the adoption of sustainable practices

PRIORITIES RELATED TO CAPACITY BUILDING	
Farmers' and land managers' capacity building: training, guidance, and advice to farmers and land managers on how to increase SOC, the positive practices and their impacts; networks to facilitate knowledge exchange.	Need for a robust system of networks and partnerships for knowledge-sharing across all soil types, conditions, and capacities. As changes take time, if existing and future soil challenges are to be met, it is essential that information and effective learning opportunities about improved land use and soil management practices are available and focused on the needs of the users and landholders.
Policy advocacy	Policy advocacy is required i) to integrate SOC data into national and regional climate and sustainable land management policies and ii) to have soil recognized as an environmental asset in legislation and policies, to avoid further soil carbon decline.
Stakeholders' capacity building: connecting researchers, NGOs, land managers, policy makers, etc. to facilitate knowledge exchange and the design of effective solutions to increase and monitor SOC. This includes, e.g., participatory approaches, living labs, lighthouses, and knowledge hubs.	Need to share knowledge and build capacity in methodologies for measuring, monitoring, and verifying soil carbon, which is key to facilitate investment in sustainable land use practices as well as to incorporate C sequestration in Nationally Determined Contributions to GHG emissions reductions.
Raising awareness on soil organic carbon and soil health in society as a whole: education on the issues at stake, on good practices, socio-cultural change in attitude, etc.	-
Researchers' and technical staff's capacity building: on the issue of soil carbon, across disciplines and for various types of land uses, by training and networking.	Need to maintain and continue building soil expertise and capability in schools and universities, to meet current and future challenges. Across the Pacific there are a range of institutional capabilities and biophysical and cultural environments: support is needed to set and align research priorities across the Pacific for measuring, monitoring, and verifying soil carbon.

PRIORITIES RELATED TO ECONOMICS AND SOCIAL SCIENCES	
Costs and benefits of "positive" practices: science-based information, indicators, and (decision-making) tools to support land managers and policy-makers, concerning the impacts of land management practices and land use (changes) on SOC, carbon storage, net-GHG budget, but also on all other environmental and SDGs aspects, including the co-benefits' synergies and tradeoffs, accounting for uncertainty; cost-uncertainty/accuracy tradeoffs of baseline/impact assessment of various M(RV) methodologies.	Lack of information on all the costs and co-benefits of land management and practices, integrated in simple, robust, and science-based decision-making tools as well as in policy design and assessment, so as to align them.
Types of incentives / instruments to be enforced and comparison of their cost-effectiveness and/or cost-efficiency: this also includes the impacts of existing climate and non-climate policies on carbon sequestration, but also on other environmental and SDGs aspects (e.g., resilience, land value/rent, how the economic surplus is shared along the value chain).	Need for research on the implication of recognizing soil as an environmental asset in environmental legislation, planning policies, codes of practice and environment and socio-economic impact assessment; for soil is not sufficiently considered in public policy objectives while it supports Australia's economy, environment and social well-being. What type of agricultural and trade policies can encourage good soil management while ensuring food security in the region in the long-term.
Barriers, levers, and enabling environment for the adoption of "positive" practices and cost-effective instruments, as well as policy issues and governance: the latter include policy coherence issues at different scales and across sectors, the building of a narrative on carbon sequestration and co-benefits, the provision of a trajectory and transition pathway towards this narrative, etc.	Need to integrate SOC data into national and regional climate and sustainable land management policies. Lack of policy coherence across sectors and scales.
Carbon credits schemes and financing: carbon credit schemes' design (to deal with the impermanence of C storage, financing of existing C stocks, clarity of MRV implementation, ...), public-private funding of carbon finance, and carbon market design (to ensure that costs, benefits, and environmental and financial risks are fairly distributed among participants).	

7.8 Workshop supporting document: general

Your priorities for future research on soil organic C

Soil carbon is central of many societal issues relating to soil health, global warming mitigation and food security.

This survey is part of a scientific research project called ORCaSa (Horizon Europe project #101059863 - https://irc-orcasa.eu/) to federate scientists and stakeholders on soil C into an International Research Consortium on Soil Organic C (https://irc-orcasa.eu/join-the-soil-carbon-irc/).

This survey is being conducted at international level, and the results will be forwarded to the funding agencies participating in the International Research Consortium on Soil C. Calls for proposal will be jointly released by funding agencies in different countries on certain priorities that we will send them and that they will have selected.

YOUR PROFILE	
	In which country do you mainly work?
	What is your job? (choose among the items of the list)
	Which land use do you work on the most? (choose among the items of the list)
YOUR PRIORITIES for SOIL C research: For the land use in which you have the most expertise, list up to three important research needs relating to soil organic C (or economics and social sciences	
	What is your 1st priority? (eg provide a research question)
	Could you specify which topic it falls into?
	Explain why this is a priority :
If you wish, you can state two other priorities.	
	What is your 2nd priority?
	Could you specify which topic it falls into?
	Explain why this is a priority :
	What is your 3rd priority?
	Could you specify which topic it falls into?
	Explain why this is a priority :

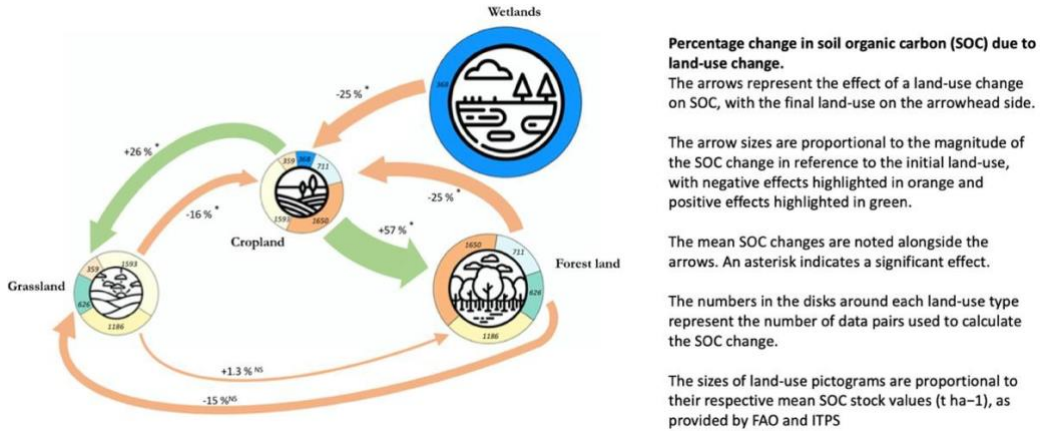
We now invite you to discover a new web knowledge platform called 'Impact4Soil', which brings together global data on soil carbon and maps (https://www.impact4soil.com/), and to complete a questionnaire to identify what you consider to be the priorities for soil organic C research in the coming years (see below + **excel file for answers**).

The Impact4Soil knowledge platform: visit the Impact4Soil knowledge platform, discover the resources it offers and answer a few questions.

Impact of climate change and land-use change on changes in C stocks

Impact4Soil platform allows you to explore the resources used in the meta-analysis by Beillouin et al 2023 on soil C stocks on a global scale (https://doi.org/10.1038/s41558-023-01810-5)

Results from Beillouin et al. 2023 about land-use changes and soil C stocks.



Results from Beillouin et al. 2023 about climate changes and soil C stocks.

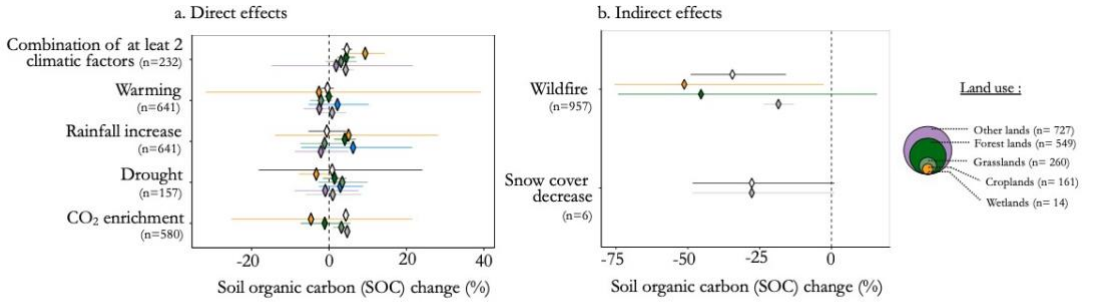


Fig. 4 | Percentage change in soil organic carbon (SOC) due climate change. Results are detailed for direct (**a**) and indirect factors (**b**) of climate change. Diamonds and lines represent the estimated mean effect sizes and the 95% confidence intervals (CIs), respectively. The number of paired data (n) for each category of land-use type is shown in the bubbles on the right side of the plot. Details of the information used to make this graph as well as details by sub-category of climate change factor are available at https://rpubs.com/dbeillouin/Figure4.

Please visit https://www.impact4soil.com/scientific-evidence/ to explore it for the impact of land-use change and climate change in your own country.

What change in land use or climate would have a strong impact on the change in SOC in your region and would appear to be a major priority for research? (This factor may or may not be included in the Beillouin et al. study*).* => *answer in Excel file*

Please justify why it is necessary to carry out research on this subject (e.g. great potential for eliminating CO_2, large surface areas, adaptation to CC, growing population, preservation of biodiversity, etc.). => *answer in Excel file*

Impact of management practices on soil C stocks

The meta-analysis by Beillouin et al. also examined the impact of management practices on the change in soil C stocks. This can also be explored for your own country using Impact4Soil.

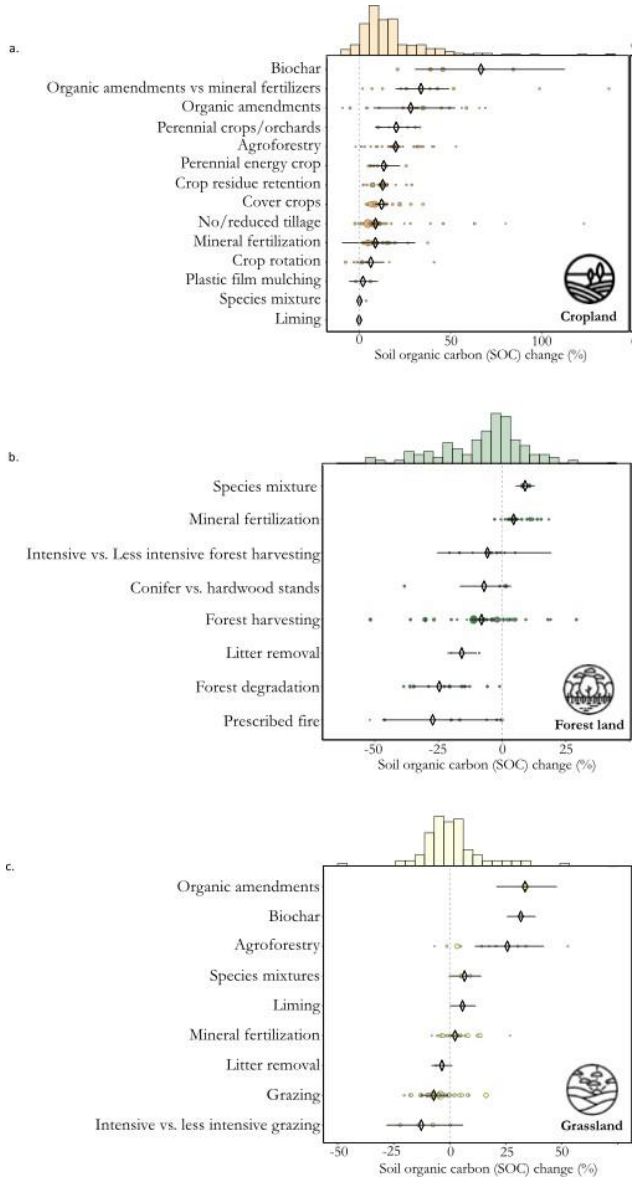


Fig. 3 | Percentage change in soil organic carbon (SOC) due to land management practices. Results are detailed for croplands (a) forest lands (b) and grasslands (c) Diamonds and lines of the main plots represent the mean effect sizes and 95% confidence intervals (CIs), respectively. The dot sizes are proportional to the number of paired data analyzed. The histograms above each plot represent the probability distribution of effects for all practices combined

For the land use on which you are the most expert, what would be the most important research need, either among the management practices highlighted by the meta-analysis, or among practices missing from the list?).=> answer in Excel file

Please justify why this is a priority for research and innovation (e.g. high CO2 elimination potential, large surface areas, adaptation to CC, growing population, preservation of biodiversity, etc.). => answer in Excel file

7.9 Workshop and survey supporting documents: economic and social sciences

Concerning economic and social sciences (ESS) issues, the existing agendas and roadmaps we collected and analyzed tend to mix actions to be undertaken and challenges to be met with (a few) research gaps. We listed all these elements, tentatively grouped by broad topics in Table 7.

As mentioned in the introduction, the ORCaSa strategic research and innovation agenda will be used by funding agencies to select relevant research topics for national or regional calls for projects. It can also be used by ministries to direct funding for research and/or for studies to provide the data necessary for policy design. And, finally, it can be used by companies and private funders either to direct their funding on more applied research, studies or dedicated consulting.

This is why it is important to identify and separate “theoretical and applied research items” (i.e. the research questions that have never been dealt with or not in the particular case of soil carbon, or the items for which we lack specific information for this region and/or land use) from “action items” (i.e. we know what needs to be done and have all the necessary information). Only challenges and “theoretical and applied research” items shall remain in the extended SRIA, along with a justification on why they are relevant in this region or for this land use type.

Given that the ESS section is often rough or lacking in existing agendas, we designed the ESS workshop and survey a bit differently to complete and update the research needs in economics and social sciences on the soil carbon issue. So, for each broad topic in the list (see 1st column of Table 7), participants are asked i) if there is (still) a need for research or further investigation, and of which type (research gap vs. more information); and ii) to make explicit the needs in the form of a research question and the associated methodology, as far as possible (examples are provided in the 2nd column of Table 7).

Table 7: The list of challenges to be met to improve the adoption of practices that have a positive impact on SOC storage, collected from existing agendas (1st column). Examples of associated research questions and approaches to address them provided by French economists (2nd column).

Topic	**Research questions and methodology** (examples from the first ESS workshop)
Capacity building • Tailored guidance and advice for farmers on how to increase soil organic carbon • Strengthen farm advisory services and knowledge exchange (e.g., workshops, demonstrations) • Networking • Education to incentives • Entrepreneurship promotion	
Decision support and MRV • Science-based information to policymakers on where and how to target SOC sequestration policy • Science-based indicators and tools for farmers and policymakers to measure progress in improving carbon storage in soils • Cost-benefit analysis of « positive » practices • Cost-effective system to implement C sequestration and financing: baseline quantification, cost-uncertainty and cost-accuracy trade-offs of MRV framework, baseline quantification vs. uncertainty to ensure additionality • Tracking development of science outputs and climate-related claims	Cost-benefit analysis including the co-benefits–synergies and trade-offs– of "positive" practices in terms of, e.g., land quality/fertility, land value/rent, biodiversity, resilience. Cost-Benefit analysis under uncertainty w.r.t. policy-driven benefits
Types of incentives/ instruments to be enforced • Mandatory targets and regulatory requirements for SOC sequestration • Payments for ecosystem services (result/practice-based, hybrid) • Financial engineering to frontload investments • Carbon certification schemes (and product labels) • Compulsory standards set by food companies • Development of carbon credit schemes • Include SOC in emission trading schemes • Improve infrastructures to access inputs and technologies	Comparison of the cost-effectiveness of various instruments–including 2nd best instruments–using economic modelling and "field experiments" approaches Assessment of the impacts of existing policy instruments–not necessarily climate-related, e.g. EU Common Agricultural Policy payments– on soil carbon sequestration, by modelling the removal of existing instruments Optimal design of threshold-based payment schemes for ecosystem / environmental services How is the economic surplus shared between farmers and operators/intermediaries within carbon farming projects?
Carbon credit schemes and Financing	

Topic	Research questions and methodology (examples from the first ESS workshop)
• Credit schemes dealing with the impermanence of C storage (issue of continuous engagement of stakeholders): carbon contract duration, discount buffer... • Financing of preservation of existing C stocks • Public-private funding of carbon finance (avoid direct competition between both; public funding better supplements the shortcomings of the market; offsetting/insetting) • Refine carbon market design to ensure that costs, benefits, and (environmental and financial) risks are fairly distributed among participants • Incentive model for both land managers and landowners • Clarity on MRV implementation: avoid double counting and financing, clarity on third-party verification, carbon removal certification framework regulation for all land uses	Measuring the impacts of large-scale implementation of such schemes on prices and food security, using economic modelling. Economic analysis of the role of (private/public) debt burden as a limitation to finance mitigation schemes. Need for reliable public data on individual carbon credit projects and carbon credit transactions (including selling price) along the value chain, to help characterize the demand and willingness to pay for such credits depending on their quality. Need for ex-post impact evaluation in relation with MRV
Policy issues and Governance • Policy coherence at different scales and across sectors (e.g., regional/national/supranational stakeholders or various environmental/agricultural/energy policies) • Account for the indirect effect of land-use change or practices induced by a policy (e.g., C leakage across countries or world regions) • Build a narrative on C sequestration and co-benefits: guiding principles to adhere • Provide a trajectory and transition pathway toward the narrative • Governance structure with a clear mandate and clear vision • Decreasing transaction costs: e.g., coordinating stakeholders within the region (time and cost effectiveness, operability), reducing administrative burden. • Improved awareness among the public	Analysis of carbon policy building at international scale, using game theory Foresight analysis (incl. economic modelling) integrating medium-term scenarios of bio-based energy demand How should it be coordinated with carbon markets in other sectors (e.g., sectoral quotas), and on what scale?

This structure has been used for workshops in form of a Klaxoon on economics and social sciences (https://app.klaxoon.com/participate/board/TJ5T77Y), a survey (https://ec.europa.eu/eusurvey/runner/SRIA_Survey_Long_Version), and a PowerPoint (in French for the CASA network or in English).