

# Coordination of International Research Cooperation on soil Carbon Sequestration in Agriculture (CIRCASA)

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# 1. Identifying the challenges around soil organic carbon sequestration in agriculture

## 1.1. Introduction

Soils sit at the interface of the geosphere, atmosphere and biosphere underpinning almost all terrestrial ecosystems. At the global scale, soils act as a store, filter and reactor for energy, water and nutrients. Of Earth's 4 main carbon pools, soil is the most concentrated and the second largest store of organic carbon (Keil and Mayer, 2014). Since the advent of agriculture (~12,000 years ago) soils have lost 116 Gt C (Sanderman et al., 2017, 2018). This suggests that there is potential for some of this loss to be restored to agricultural soils through changing agricultural practice, providing a sink for atmospheric carbon which has increased since the industrial revolution (Keeling and Keeling, 2017; MacFarling Meure et al., 2006).

## 1.2. Soils as a sink and source of carbon.

Due to the size of the soil carbon reservoir, small changes in the balance between soil carbon storage and release processes have a significant impact on atmospheric CO<sub>2</sub>, potentially exacerbating or mitigating the consequences of anthropogenic climate change (Kirschbaum, 2000). Carbon storage in soils occurs when plant- and microbially-derived carbon is stabilized as soil organic matter. Soil organic matter is a complex mixture of carbon moieties across a continuum of decomposition states, in a variety of chemical and physical forms (Totsche et al., 2010) which is stabilised through a combination of biotic and abiotic processes leading to long term carbon stabilisation. (Lehmann and Kleber, 2015; Liang et al., 2017; Schimel et al., 2007; Six et al., 2000, 2002a, 2002b). Both short- and long-term carbon release from soils occurs as carbon is microbially degraded and eventually released as CO<sub>2</sub>. It is now generally considered that carbon decomposition can be controlled more by biotic and environmental factors than the inherent molecular structure of carbon inputs (Schmidt et al., 2011). In particular, microbial community composition and structure influence the processes of carbon decomposition, while (largely through their effect on microbial activity) soil moisture and temperature exert a strong control over the rates of carbon decomposition (Stockmann et al., 2013).

## 1.3. Agriculture, driving soil organic carbon change.

Under native unmanaged vegetation, soil organic carbon (SOC) eventually reaches equilibrium at maximum stable levels. Since the dawn of agriculture, this equilibrium has been disturbed by the introduction of systems which, in comparison, provide fewer organic inputs to the soil and, through disturbance, increase decomposition and therefore SOC losses to the atmosphere. Native forests and grasslands systems tend to allocate more biomass belowground, above ground necromass is returned to the soils and soils tend to remain undisturbed (Paustian et al., 2016). All of this is conducive to the build-up of SOC. Conversely, in agricultural systems many annual crops can have shallow rooting systems, having been bred for above ground harvestable biomass, above ground biomass is removed from the system and soils are deliberately disturbed during tillage. This does however mean that agricultural soils have a higher potential for SOC increase, presenting a large opportunity for climate change mitigation through judicious agricultural management. It is these ideas which drive the 4 per 1000 initiative launched at the COP21, Paris 2015 (Chambers et al., 2016; Lal, 2016; Minasny et al., 2017; Rumpel et al., 2019; Soussana et al., 2019). The 4 per 1000 initiative aims to increase global soil carbon stocks to offset anthropogenic greenhouse gases, minimising rising global temperatures.



## 1.4. Soil organic carbon as an agricultural resource

In addition to offsetting anthropogenic greenhouse gas emissions, stabilising organic carbon in soils benefits a wide range of soil functions (Banwart et al., 2015, 2019; Milne et al., 2015; Wiesmeier et al., 2019), underpinning ecosystem services (Jónsson and Davíðsdóttir, 2016; MEA, 2005), and enabling progress towards the UN sustainable development goals (SDGs) (Bouma, 2018; Keesstra et al., 2016). Improved soil organic carbon has large benefits for food security by increasing crop yields and yield stability for soils initially low in SOC (Soussana et al., 2019). It has been estimated by economic modelling that improved soil carbon could reduce calorie loss per capita associated with the potential rise in food prices under strong global and regional agricultural mitigation measures by 65%, saving 60–225 million people from undernourishment compared to a baseline agricultural mitigation scenario without improvement of SOC (Frank et al., 2017).

Soil organic carbon is vital for the formation of macro- and microaggregates in soils, maintaining soil structure (Panakouli et al., 2017), and aiding the movement and filtration of water. Soil organic carbon within organic matter is also an energy and nutrient source for microbial communities (Mummey et al., 2006; Wiesmeier et al., 2019), underpinning the soil food web (Jackson et al., 2017), and retaining a reservoir of N, P and other nutrients for plant productivity. Increasing soil organic carbon content and the formation of aggregates, also makes soils more resistant to erosional losses by wind and water (Lal, 2003, 2005). The role of soil organic carbon in this range of soil functions highlights its importance and high value as a component soils.

## 1.5. Challenges to soil carbon sequestration in agriculture

Increasing soil organic carbon is not trivial. We can consider the challenges to fall into 3 main themes: (1) understanding soil processes; (2) managing and monitoring soil; and (3) adoption of best land management practices. Within these 3 themes several specific challenges limit our ability to predict soil carbon changes, and prescribe best land management practice, and promote adoption of those practices (Fig. 1).

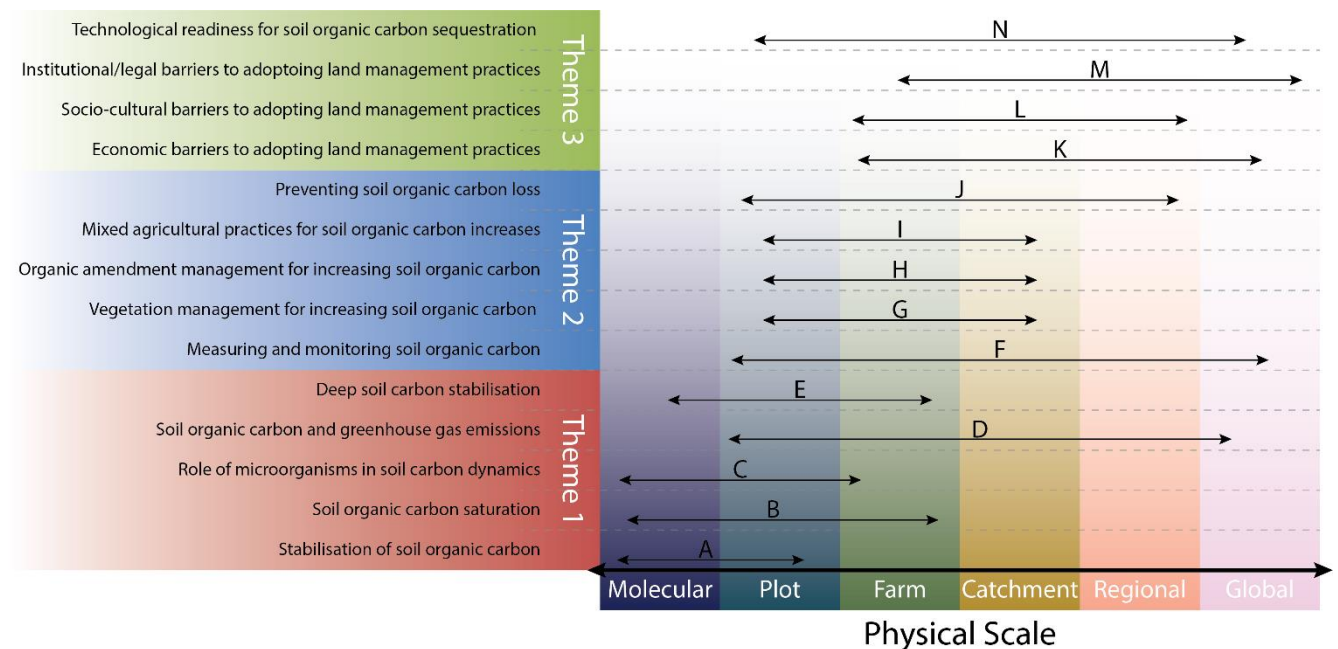


Figure 1. Challenges to soil carbon sequestration in agriculture divided into three themes and presented as a function of physical scale.

## 2. Questionnaire

We took the 14 challenges identified from the literature within the 3 themes and designed a questionnaire with the aim of prioritising these for future research. The questionnaire was distributed to researchers and was open for responses for 10 weeks from November 22<sup>nd</sup> 2018 through to January 31<sup>st</sup> 2019. Respondents were presented each challenge and asked to rate their interpretation of our community's understanding from 0 (no understanding) to 10 (complete understanding). Respondents were then asked to rank the challenges in each theme in order of importance.

### 2.1 Respondent Demographics

A total of 211 researchers responded to the questionnaire during the 10 weeks it was open, the timing of responses was linked to publicity efforts. The plot (1 – 100 m) and farm (0.1 – 10 km) scales were the most common scales of expertise for respondents, whose expertise covered a wide range of topics, but the most dominant were responses for Agricultural Practice and Soil Management (Fig. 2.1). Researchers from Social Science disciplines were poorly represented. The responding researchers were based around the world (Fig.2.1D) with the most responses from South America (30%) and Europe (29%). However, this translated to a more balanced distribution of regional knowledge across the globe.

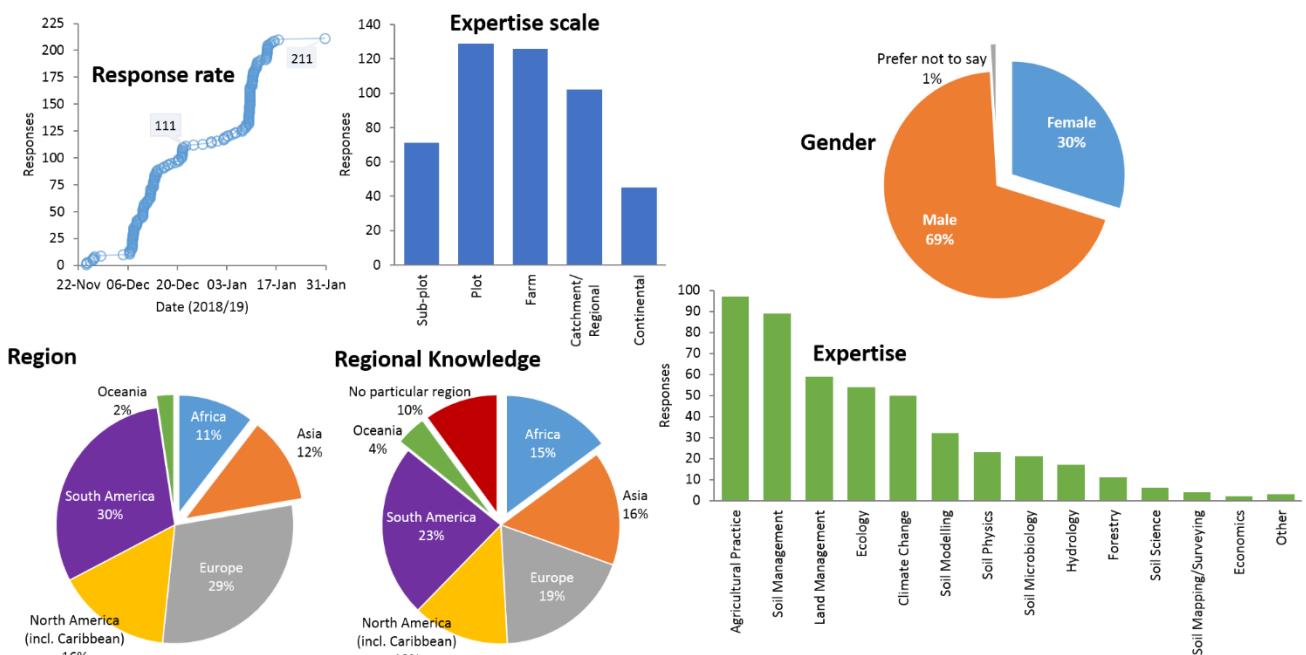


Figure 2. Clockwise from top left: Questionnaire responses as a function of time. Respondents' scale of expertise: Sub-plot, < 1 m; Plot, 1 – 100 m; Farm, 0.1 – 10 km; Catchment/Regional, 10 – 100 km; Continental/Global. Respondents' gender. Respondent's expertise topic. Region of knowledge/expertise. Region of residence.





Figure 3. Compilation of knowledge ratings frequency plots of each challenge. The vertical axes are the frequency of counts, the horizontal axis is the measure of the scientific community's understanding: 0 = no understanding of topic, 10 = complete understanding. The inset tables contain some basic statistical parameters for each challenge dataset.

## 2.2 Perceived knowledge

The ratings of each of the challenges can be seen in Fig. 3 with some basic statistical indicators. Most challenges have a normal/bi-modal distribution ( $n = 6$ ) or are skewed towards a greater understanding ( $n = 7$ ). Only one challenge skewed towards a poor understanding, deep soil carbon stabilisation and cycling. Of note, challenge A received the highest average rating of all topics (6.86), with challenge E receiving the lowest average (4.83). Challenge F, measuring and monitoring soil organic carbon, received the most 1<sup>st</sup> and 5<sup>th</sup> importance rankings within theme 2 (Fig. 4), i.e. respondents view this area as either the most important or least important for agricultural soil carbon sequestration. The challenges within theme 3, adoption of best land management practices, have a strong normal distribution around modal responses of 5, 6, or 7. Respondents were instructed to select '5' if they did not feel equipped to judge the knowledge of a topic. This may be representative of the small number of respondents who would identify within the social sciences ( $< 5$ ). However, challenges K and L on the economic and socio-cultural barriers to adopting land management practices were ranked within the top 3 most important overall.

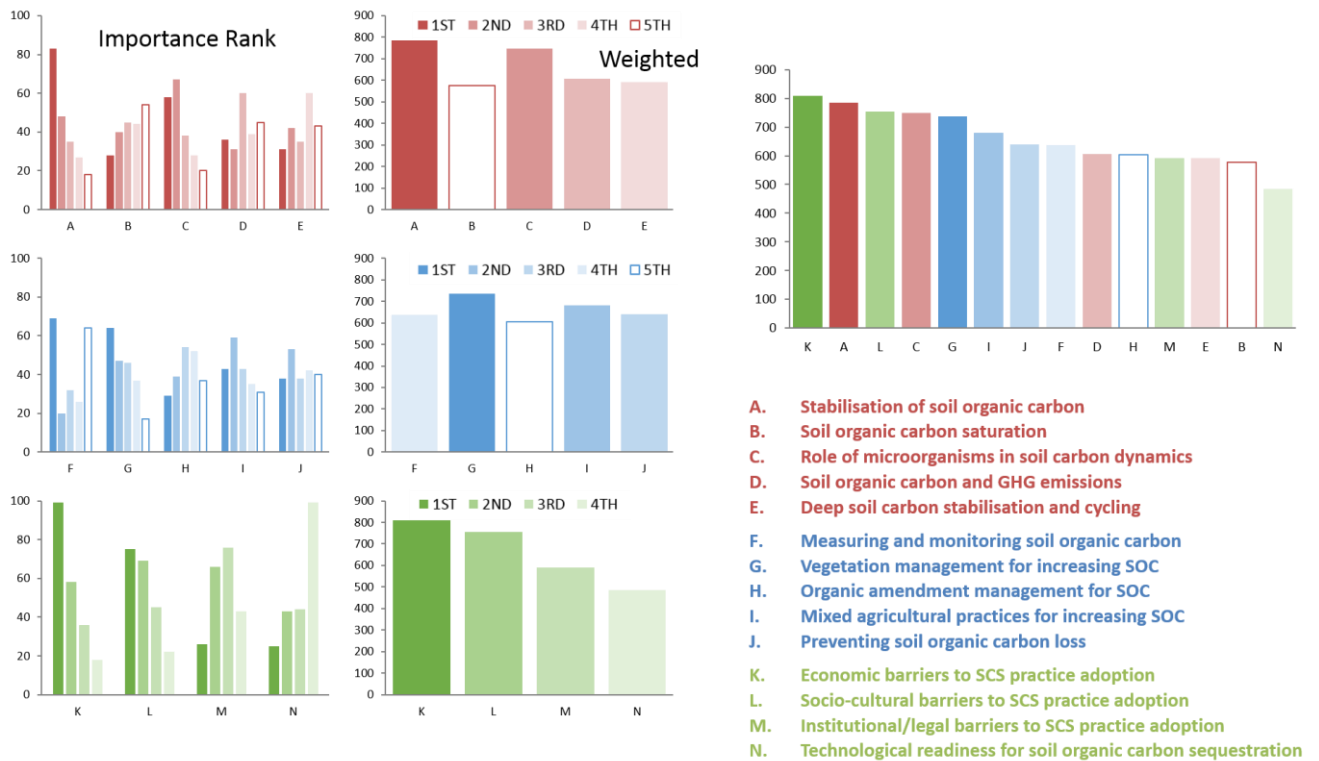


Figure 4. Challenge topics in each theme ranked in order of importance (left). The weighted rankings for each theme are also presented (centre), and overall ranking across themes (right).

### 2.3. Questionnaire perspectives

The responses from this questionnaire provide valuable information on soil researchers' perception of our community's level of knowledge with respect to some key challenges facing soil organic carbon sequestration. However, much more work is needed to attempt to understand the relationships between demographics and questionnaire responses.

There appears to be no relationship between perceived knowledge of each topic and the importance (Fig. 5i). However, conflicting trends appear if topics are grouped by the distribution of their knowledge ratings, normal/bimodal distribution, positive skew (more knowledge on a topic), and negative skew (less knowledge on topic). Challenges with positively skewed knowledge ratings are ranked more important the more we know about them (Fig. 5ii). Conversely, topics with a normal or bimodal distribution appear to be less important the more we know about them (Fig. 5iii). One challenge, deep soil organic carbon had a negative skew, and this was the lowest rated for knowledge, and ranked the 3rd least important. These trends may be the result of bias from the respondents' areas of expertise. They may also be a symptom of past funding directions, leading to the question of whether we can confidently identify the important areas for future research and, as a community, have we been funding and researching the wrong avenues? Additionally, these trends may be the result of poor cross-discipline communication, limiting our understanding of the relative importance of topics as a whole community.



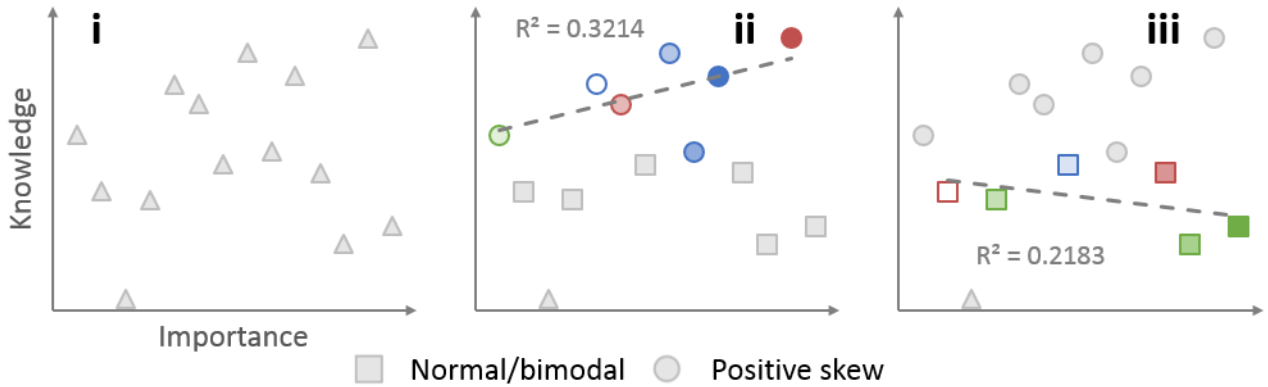


Figure 5. Knowledge and importance of challenge topics viewed as (i) a whole, (ii) with positive skew, (iii) with normal/bimodal distribution.

The over and under representation of disciplines across respondents, and the associated bias, make this data very difficult to interpret. These deficiencies mean it may be problematic to use the ranking of topics presented in Fig.4 to justify prioritisation of future research. All 14 challenge topics identified from the literature are legitimate and useful directions for future research into agricultural soil carbon sequestration.

### 3. Twelve Testable Hypotheses for Soil Organic Carbon Sequestration in Agriculture.

To address the challenges identified from the literature and evaluated through the questionnaire to researchers, we have devised a series of 12 testable hypotheses to address these intellectual, logistical, and technical challenges to implementing the best land management practices for soil carbon sequestration in agriculture. These hypotheses and innovative solutions span both the physical scales and disciplines of the challenges considered in the questionnaire (Fig. 6).

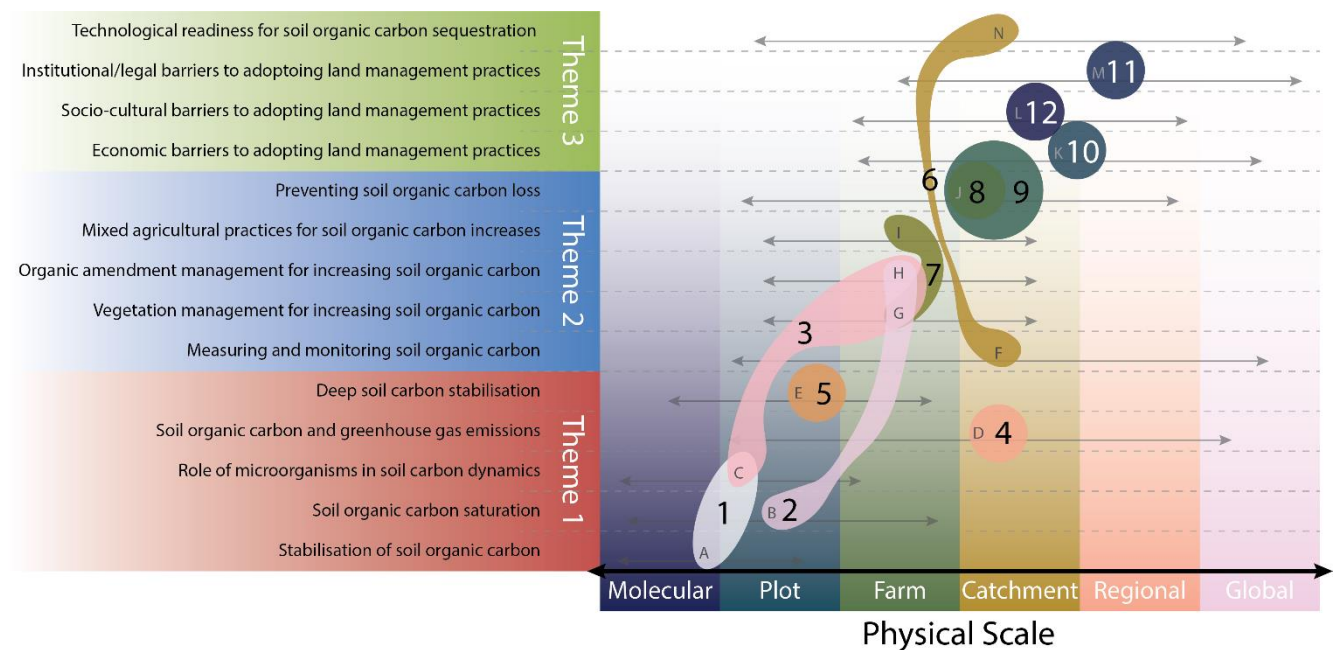


Figure 6. The 12 Testable Hypotheses mapped onto the challenges identified from literature.

### *3.1. Hypothesis 1: Organic carbon preservation is the result of the interplay between mineralogical and microbiological processes.*

Organic carbon has inherent reactivity which renders some molecules more susceptible to preservation processes. Minerals actively preserve organic carbon through physical and chemical protection imparting chemical stability, decreasing organic carbon decomposition susceptibility by microorganisms. Organic carbon processed by soil microorganisms is more persistent in soils. This may be because microorganism digested organic carbon is more chemically stable, or more chemically reactive towards minerals and thus more amenable to mineralogical preservation processes. Therefore the input of carbon adjacent to reactive surfaces (e.g., through roots or leaching) results in greater carbon storage than input onto the top of the soil (e.g., leaf litter or manure).

### *3.2. Hypothesis 2: For a given soil type, there exists a finite amount of carbon that can be stabilised through organo-mineral interactions.*

Stable carbon pools are thought to be protected from decomposition by binding to mineral surfaces and the maximum a specific soil can stabilise has been termed “carbon capacity or saturation”. Carbon saturation is posited to be fixed for a specific soil, because it is limited by the number of available binding sites. However, due to climatic factors, many soils are unable to attain levels of soil organic carbon predicted from organo-mineral associations. An important research focus is to determine whether a given soil or set of soils is near to its saturation point. Soils reach a carbon equilibrium point (steady state) for specified land uses or management practices, but this could be below carbon saturation point. Being able to determine how close a soil at steady state is to the saturation point allows identification of soils where, at national or regional scales, additional long-term carbon storage might exist, but will likely require a new balance of carbon inputs. Furthermore, reactive surfaces in a topsoil and so saturation level might be considered fixed, alterations of these surface areas might be possible.

### *3.3. Hypothesis 3: Living soils have a net positive impact on soil organic carbon persistence.*

There is specific microbiological functionality that governs organic carbon cycling in soils. Functionally diverse soil microbiological communities are needed to drive soil ecosystems to stabilise persistent organic carbon. Macroorganisms, underpinned by a functionally diverse microbiome, are key to the processing and distribution of organic carbon through the soil profile.

### *3.4. Hypothesis 4: Calculating the ratio of soil carbon sequestration to nitrogen release will enable the realisation of agricultural greenhouse gas budgets.*

The dynamics and interactions of soil organic carbon and greenhouse gas (primarily CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub>) emissions is different in different ecosystems. For national inventories, GHG emissions are often estimated by using the IPCC Tier approaches which do not account for the complex dynamics underpinning soil organic matter turnover in soils. It can be hypothesised that a) N<sub>2</sub>O emissions can be estimated from N inputs with low C:N ratio, b) carbon input to soil can be estimated from NPP and the fraction of this returning to soils and c) under given climate and soil physicochemical conditions, the mean residence time of C in SOM could vary, through increased turnover (the priming effect) whenever the balance of C to N inputs to soils is high.



### *3.5. Hypothesis 5: The persistence of deep soil organic carbon is governed by soil microbial activity.*

Organic carbon in subsurface soil layers contributes to about half of the total soil organic carbon stocks. The mean residence time of this form of carbon is often larger than that of the organic carbon in the surface soil layer, and the proportion of older organic carbon increases with depth. It can be hypothesised that deep soil organic carbon is stabilised via the same processes at play in topsoils, and that deep soil organic carbon is not more chemically resistant to decomposition than topsoil organic carbon. Rather, that organic carbon persistence in deep soils is the result of separation from microbes, substrate, and the atmosphere. And therefore deep soil environments are ideal for soil organic carbon storage.

### *3.6. Hypothesis 6: Changes in soil organic carbon stocks can be measured accurately with design-based sampling and a standardised methodology.*

Soil organic carbon sampling and measurement requires standardisation. Citizen Science can help to integrate soil organic carbon measurements across scales. Design-based approaches for monitoring regional and global topsoil organic carbon stock changes is feasible and cost efficient. Yet model-data platforms are required for quantifying and forecasting carbon storage in soils.

### *3.7. Hypothesis 7: Combining crop, livestock, and tree production in mixed agroforestry systems stabilises more soil organic carbon than when separate in production.*

It can be hypothesised that one hectare of agroforestry (mixed trees and crops) results in a greater net soil organic carbon increase than the same area of separate crops and forest, without substantially affecting agricultural yields. By estimating a Carbon Equivalent Ratio (CER) we would be able to assess the relevance (in terms of C) of mixing trees, crops, and livestock rather than keeping them separate.

### *3.8. Hypothesis 8: Sustainable intensification using agroecological approaches can reduce soil organic carbon (SOC) loss and restore SOC in depleted soils.*

While there is considerable emphasis on determining techniques for increasing soil carbon stock, avoiding or reducing losses can also contribute to a net benefit to carbon dioxide concentrations in the atmosphere. Agroecological approaches to soil management increase soil biodiversity and restore soil functions and if integrated into farming systems at the moment of conversion they can reduce soil degradation and loss of organic matter. Organic soils in particular are subject to high losses of organic matter when drained and cultivated. Paludiculture, producing crops, fibre and bioenergy feedstocks under high water table conditions may offer some opportunities for halting carbon losses in organic soils.

### *3.9. Hypothesis 9: Agricultural soil carbon erosion can be minimised, while maintaining connected environments.*

One of the ways soil organic carbon is displaced from a given point through erosion. These erosional detachment, transport, and deposition processes could be carbon sinks, or sources of greenhouse gas emissions. The key questions are: where does the carbon go? How much of the carbon is lost in transport? How much carbon is deposited elsewhere? There is little understanding in the processes acting at the small scale. However, viewing at the landscape scale is essential to answering these questions. The ‘connectivity’ principles identify key linkages at a range of scales across the landscape that impact carbon cycling. By understanding these connections, we can aid the development of management strategies and interventions that



will increase in carbon storage within the landscape without incurring degradation elsewhere. Studying the connectivity of carbon cycle dynamics at the landscape scale will improve the understanding of the mitigation potential of agricultural carbon loss to erosion, without detrimental changes to connected environments.

### *3.10. Hypothesis 10: Soil organic carbon has inherent value through regulation of ecosystems services.*

Changing land management practices often have set up costs, lags in investment returns, and require long term implementation. Many farm based economic decisions cannot adequately include the value of soil organic carbon. There is an inherent value to soil organic carbon through its control on many ecosystem services. However, soil organic carbon has no economic market. Two future directions in addressing the economic challenges around agricultural soil organic carbon sequestration may lie in: (i) determining an accurate value for soil organic carbon and the role it plays in regulating soil functions and ecosystem services; and (ii) focusing widespread soil organic carbon sequestration projects at large-scale farms in areas with soils where practice change leads to the greatest increases in soil organic carbon for the lowest cost.

### *3.11. Hypothesis 11: The lack of soil governance will limit agricultural soil carbon sequestration.*

Current research shows that soil is one of the last environmental issues to be addressed beyond the national level. In recent years there has been an increase in international soil governance activities. Yet, at the international level there is no general consensus that soil is an issue or medium that calls for or requires international policy and governance efforts.

Future research should explore how to overcome states' reluctance to accept that soil is an issue that can, and should, be addressed internationally and by regional bodies such as the EU. One approach could be to combine a general (legal) principle of soil protection with more specific guidance that builds on existing political agreements and leaves sufficient flexibility. The general principle could build on existing concepts such as “common concern of humankind” (Ginzky, 2018), which are used and promoted in international law in order to establish that an issue is not solely the domain of national sovereignty. Research indicates that soil has implications that go beyond national borders. Climate change is one key area given the importance of SOC storage in reducing atmospheric GHG levels, migration and security are another.

### *3.12. Hypothesis 12: Stakeholder engagement, knowledge exchange and learning can help to overcome socio-cultural barriers to increase soil organic carbon.*

Socio-cultural barriers to soil management practices that can increase soil organic carbon are poorly understood but harnessing local knowledge offers many opportunities to upscale sustainable soil management practices. Emerging research suggests that increasing coordination and collaboration between stakeholders (including project funders, farmers and government agencies) could support learning and knowledge exchange, allowing partnerships and networks to be built, field experiences to be shared, and multi-stakeholder learning to take place.



## 4. Key research and innovation advances

Through testing these hypotheses and addressing these challenges we expect that agricultural soils will offset a significant quantity of greenhouse gas emission annually, build resilience of agricultural production, and take steps towards a number of the UN Sustainable Development Goals.

### *4.1. Offsetting greenhouse gas emissions*

Increasing soil carbon content draws carbon from the atmosphere. The extent to which this can or will contribute to climate mitigation is unclear. However, the co-benefits of increasing soil organic carbon and improving soils have additional climate mitigation advantages. Soils with more organic carbon regulate water and nutrient cycling better, minimising the energy needed to produce inorganic fertilisers and distribute water through irrigation systems. Many climate smart agriculture/conservation agriculture approaches are less intensive than conventional farming, reducing emissions from farm equipment, and we will be more able to monitor and estimate net greenhouse gas production from agriculture.

### *4.2. Agricultural production*

Better regulation of soil nutrients and water through increasing organic carbon content should also build resilience to agricultural production, maintaining agricultural production while adapting to changing climatic conditions. As a community we will be more able to model, monitor, and manage soils across the globe to increase/preserve soil organic carbon. This will help us to optimise our recommendations for best agricultural practice for individual farmers/land managers.

### *4.3. Tackling the UN Sustainable Development Goals.*

Soils are inherently involved in at least 5 of the 17 UN SDGs. Through testing these hypotheses we will better understand soil processes and our impact on them. This will aid us in abolishing hunger (goal 2), ensuring good health and well-being (goal 3), providing clean water and sanitation (goal 6), taking climate action (goal 13), and protecting and preserving life on land (goal 15).





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