
# EIP-AGRI Focus Group – Grazing for carbon
# Mini-paper – *Monitoring*

## Authors

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## Introduction

Soil organic carbon (SOC) is the carbon (C) in the organic fraction of the soil (soil organic matter - SOM). The SOM consists of C-based molecules that have a wide range of chemical and physical properties. Approximately 58% of SOM is carbon with some variation in some soils (Pribyl, 2010). **The origin of the vast majority of C in soil is the $CO_2$ fixed by plants by photosynthesis** (Figure 1). Some of this C enters the soil directly in crop residues such as dead stems, leaves and roots, and some indirectly e.g. in the excreta that results from animals eating plant products. Not all organic matter (and consequently carbon) is the same, and in different regions of the world having higher overall SOC concentrations may not indicate any particular consequence for grasslands.

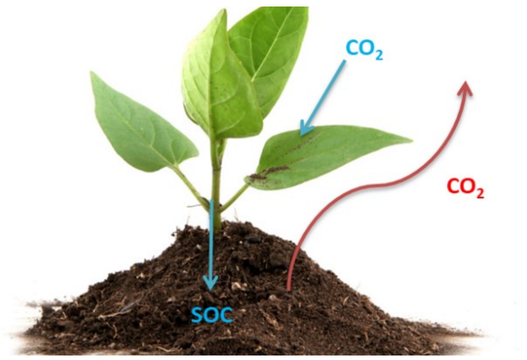



*Figure 1 – Schematic depiction of the process of soil organic carbon (SOC) accumulation.*

The **SOM is a food source for the wide range of microorganisms that live in the soil**. In the process of extracting nutrients and energy from SOM, the microorganisms break down the complex compounds that form SOM. The microorganisms use some of the C in the decomposed material for growth and excrete some in waste products; the remainder is mineralised and emitted to the atmosphere as $CO_2$. The waste products are less easily decomposed than plant or microorganism residues, especially if they bind to soil minerals. Processes within animal digestive systems and manure management systems also lead to the mineralisation of plant C, with an emission of $CO_2$ and methane ($CH_4$) and the formation of new C compounds that vary in their resistance to decomposition in the soil.
It is convenient to **group the complex mixture of different compounds into a limited number of pools or fractions that are typically classified according to their turnover speed, i.e. how "stable" or how slowly they decompose**, depending on the proportion of the different organic types of materials. According to Cordovil (2004), the fast or "labile" readily mineralizable fractions are fast to decompose and mineralize almost immediately once moisture conditions in the soil exist through microbial action. The slow

or “recalcitrant” fractions of organic compounds are typically the most stable and are responsible for the persistence of C stored in soils as SOM. For grassland yield maximization, turnover speed (i.e. the ratio at which SOC is mineralized and replaced in soils by new organic matter) is useful as fast mineralization provides more nutrient availability for grass growth, namely of nitrogen. **In carbon sequestration studies, however, it is recalcitrant SOC that is believed to matter the most** in terms of SOM buildup, as it is resistant to mineralization and can be stored for longer periods in soils. The mineralisation of the compounds in these pools can typically be described using a first-order decay function, which leads to an exponential reduction in the mass over time. In addition to the physical and chemical characteristics, the mineralisation rate also depends on the environmental conditions in the soil, being greatest when it is warm but not too hot, and moist but not waterlogged. **The amount of C sequestered as SOC at any time is therefore determined by the quantity and quality of C inputs, and mineralisation rate**, stretching back over long periods. Agricultural practices, including the grazing of pasture by livestock, affect the quantity and quality of the C input to the soil, and the rate at which it is subsequently decomposed and mineralised. There may thus be a trade-off between agronomic usefulness and maximization of carbon storage (Lehmann and Kleber, 2015). Fast turnover of labile C could be a results of high biomass production, i.e. high above ground biomass production leads to high soil respiration (loss of C) (Koncz et al., 2015) but at the same time it is important that it is not “recalcitrant” C that is lost. SOC is a factor of resilience to drought (Bot and Benites, 2005), while also being lost under drought in dry grasslands (Nagy et al., 2007) that are in danger of losing C through heterotrophic respiration during drought (Balogh et al., 2016) largely from the recalcitrant C pool. The motivation for considering the effect of grazing on the C sequestered in the soil is that society has an interest in this increasing. **For the period that C is sequestered in soil, it is removed from the atmosphere and will not contribute to global warming**. Maintaining or increasing C sequestered in the soil is also important for climate regulation, as the consequent increase in SOM increases soil water holding capacity and nutrient retention, and improves drainage. This maintains or increases productivity, especially in arid and semi-arid regions, and reduces surface runoff of water, hydric soil erosion and sediment loss (Bot and Benites, 2005). The diverse benefit of SOM and SOC means that **many stakeholders with different goals are involved and interested in monitoring different SOC pools**. Farmers commonly use SOM analysis as a basis for fertilizer recommendations; policy-makers are interested in SOM/SOC as results indicators for agricultural agri-environmental policy; with the rise of carbon markets, both voluntary and within the scope of the Kyoto Protocol, carbon sequestered in soils become important as a new commodity; businesses support carbon sequestration as a mitigation or compensation measure to the impacts of products in greenhouse gas emissions (this issue is discussed in the Incentives mini-paper). Each of these goals may require an approach to monitoring that is more or less intensive, and may focus on particular aspects of SOC in ecosystems. Monitoring changes in the C sequestered in soil to assess its contribution to decreasing or increasing global warming is particularly problematic, since the half-life of the more stable or recalcitrant SOC may be decades or centuries. This means **direct measurements using soil sampling and analysis or indirect measurements using remote sensing, have to be made over long periods if the change in C sequestered over time is to be described accurately**. Relying on long-term measurements alone for guiding land management is impractical for farmers and policymakers. For this reason, a mixture of measurement and modelling may be required.

The **goals of this mini-paper** are:

1. To **survey the methods for monitoring SOC**, highlighting their strengths and limitations and providing examples of their application;
2. To **identify the main motivations and reasons for measuring SOC**, stakeholders involved and the main results expected from each method;
3. To **identify the main bottlenecks and barriers to the implementation** of each monitoring scheme, depending on their goals;
4. To **recommend future research lines** that can overcome the limitations identified;

5. To **suggest ideas for operational groups** involving SOC monitoring.

## Motivations for monitoring

**Motivations to measure SOC depend on the type and number of different stakeholders involved** and on whether the reasons are voluntary or due to compliance obligations (Table 1).

*Table 1 – Stakeholders involved in monitoring SOC and possible reasons.*

| Stakeholder | Main reasons for monitoring carbon |
|---|---|
| **Farmers** | Fertilization and production<br>Yield<br>Resilience and adaptability related to soil quality<br>Participation in incentives schemes |
| **Advisors** | Recommendations for management |
| **Policy-makers** | Results of agri-environmental policy<br>Climate mitigation projects |
| **Private decision-makers** | Private mitigation projects<br>Corporate supply chain sustainability |
| **Consumers** | Sustainability claims and product labelling |
| **Researchers** | Understanding soil processes and dynamics<br>Understanding the role of SOC in ecosystems |

First, **farmers/producers use soil monitoring, including SOC, to assess the fertility level of soils**. Based on data on the fertility level of soils, farmers make choices for fertilization, often unaware of the fact that by improving SOC (and thus SOM), soil fertility improves and hence fertilization needed decreases, namely concerning nitrogen. SOC is also a factor of resilience to drought as well as to excessive precipitation, thus reducing nutrients losses, namely nitrate leaching. Thus it can be used as an indicator for grass production potential in unfavourable meteorological years.

**Farm advisors may be interested in using the results from SOC monitoring to better advise farmers on SOM and carbon sequestration management**. The relationship between SOC, fertility and yield requires knowledge of soil state and also outcome of management procedures. In the case of sown pastures, baseline SOC is important to recommend seed mixes, fertilization and correctives such as application of lime.

**Policy-makers are interested in SOC as an indicator of the outcome of agri-environmental policies.** The rise of climate mitigation schemes using carbon sequestration, such as the Portuguese Carbon Fund project, the Emissions Reduction Fund in Australia also require monitoring of SOC. Other projects must arise to interlink the fertility of pastures and other crops regarding the integration of SOC/SOM and nutrients management.

**Private decision-makers**, such as companies that source animal products produced in grasslands, **care about SOC due to private-sector projects for carbon mitigation** that are reported in Environmental Product Declarations or Sustainability Reports, **or as part of supply chain sustainability assessments** such as calculation of indicators for environmental labelling of products.

**Consumers, as the end users of this information, are also interested in SOC data associated with products** to ensure correct claims of sustainability and to avoid fraud. The EC is promoting product labelling, as part of the Integrated Product Policy. A pilot project is currently underway to develop and test sectorial adaptations of the Product Environmental Footprint guidelines, which establish a method for calculating and


reporting product sustainability using LCA. As SOC is the recommended indicator for land use impacts, this is an indicator of growing importance in product sustainability.
Finally, **researchers on agronomy, soil science or environmental science use SOC due to its importance to understand soil processes and nutrients and elements dynamics and also the effects of SOC dynamics on ecosystems**.

## Methods for monitoring of soil carbon and examples of projects

The methods for monitoring SOC depend on the objective of the sampling and degree of accuracy of the equipment, the spatial and temporal coverage of the data, the effort involved and frequency in sampling. Here we adapted and extended a recent capacity building framework in biodiversity monitoring (Schmeller et al., 2017) to describe the possible monitoring options for SOC. **There are three main approaches to monitoring**: (1) **direct measurement** with varying degrees of geospatial and/or temporal coverage (extrapolation, extensive, intensive), and accuracy, (2) **indirect measurement** using proximity sensors or remote sensing, and (3) **bottom-up or top-down modelling** (Table 1).

### Direct sampling and measurement

Monitoring schemes involving **direct sampling and measurement** are based on the principle that **at least some part of the area of interest for monitoring should be analysed**, and vary in regards to geographical and temporal coverage. It is good practice to measure SOC yearly using standardized methods (Stolbovoy et al., 2007) to obtain enough data to observe trends. However, SOC could change over a few years (1-3) only if there is a dramatic management change. Due to the relatively little added soil C input per year to the large soil C pool it usually takes 5 or more years to be able to detect SOC changes (Schrumpf et al., 2011, Smith, 2004). In order to observe SOC changes less than 5 years after management change, the carbon inputs to the soil should increase over 20% and the sampling method should have a minimum of 3% detectable difference over the background SOC, besides requiring a large number of samples (Smith, 2014).

#### *Extrapolation*

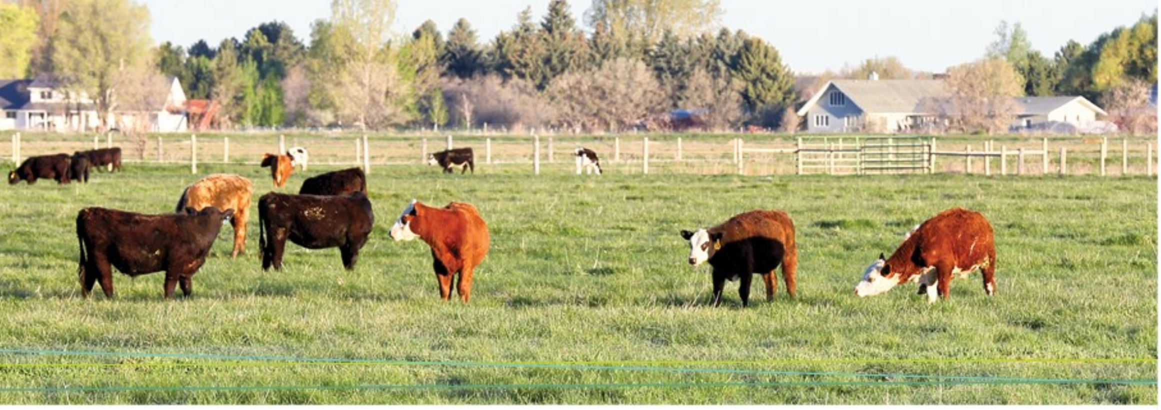
First, **it is possible to sample a very reduced fraction of the area of interest**, collecting soil samples and conducting laboratorial measurement of SOC at a given time interval, and then **consider those measurements valid for the entire region** as long as it fits the soil, climate and management profile of the subarea sampled. The underlying idea is to **concentrate an intensive sampling effort on a limited area and temporal window**.
For example, in Portugal, this strategy was adopted in the Portuguese Carbon Fund (PCF) project (Teixeira et al., 2015). Eight farms in a similar pedoclimatic region were surveyed during five years and SOC was measured to determine a carbon sequestration factor for sown biodiverse pastures in those farms (Teixeira et al., 2011). The management operations in these farms were similar, and served as a blueprint for the rules applied to a larger area of 1000 other farms and 50,000 hectares. This method proved to be the most feasible due to the costs involved in monitoring the entire area. Those farms were then only checked for conformity in management, and as long **as the farms complied with the management rules the carbon sequestration factor was assumed to be valid**.


*Table 2 – Types of approaches to monitoring soil organic carbon (SOC), their advantages and disadvantages, and examples of application.*

| | Direct sampling and measurement | | | Indirect measurement | | | Modelling | |
|---|---|---|---|---|---|---|---|---|
| | **Extrapolation** | **Extensive** | **Intensive** | **Proximity sensors** | **Remote sensing** | **Eddy covariance** | **Bottom-up models** | **Top-down models** |
| **Description** | SOC is sampled and measured in a controlled and limited number of sites, and measurements are then extrapolated for larger areas | A territory is divided into sub-regions and at each region SOC is monitored (sampled, measured) sparsely or only at distanced temporal moments | Full monitoring of a given region including SOC sampling and analysis with high geographical and temporal coverage | Proximity spectroscopy sensors are used to replace laboratorial analysis | Satellite or drone-based data is used and only calibrated to SCO data at field-level | The eddy covariance (EC) method provides information about the net $CO_2$ flux (net ecosystem exchange) between the atmosphere and ecosystems | Statistical models that use already available data to relate SOC levels and their change to management practices | Process-based or mass balance models that use indirect measurements of soil and climate variables to estimate SOC |
| **Advantages** | Limited effort for soil collection and analysis<br>Works well over relatively homogeneous landscapes | Medium effort for soil collection and analysis<br>Works well over relatively homogeneous landscapes | Detailed geo-temporal variability assessment<br>Capable of tracking changes through seasons and changes in management | Only requires calibration, reducing the effort for soil analysis | Only requires calibration, reducing the effort for soil analysis<br>Enables detailed geospatial coverage over large regions | If there is a correlation between soil C sequestration and net $CO_2$ uptake of the ecosystem, than EC method could be a proxy for soil C sequestration | Feeds on available data and studies to infer larger connections to SOC<br>Reduces or eliminates the need for data collection (sampling and analysis)<br>Enables the assessment of counterfactuals | Feeds on available data and physical laws to infer larger connections to SOC<br>Reduces or eliminates the need for data collection (sampling and analysis)<br>Enables the assessment of counterfactuals |

| | Direct sampling and measurement | | | Indirect measurement | | | Modelling | |
|---|---|---|---|---|---|---|---|---|
| | **Extrapolation** | **Extensive** | **Intensive** | **Proximity sensors** | **Remote sensing** | **Eddy covariance** | **Bottom-up models** | **Top-down models** |
| **Disadvantages** | No spatial or temporal differentiation between specific cases<br>All fields comparable to the pre-established average are assumed to be the same | Some spatial or temporal differentiation insufficient to fully depict all possible management options | High effort and cost to thoroughly assess a single region<br>Large data processing requirements for usability | Although analysis costs are reduced, sampling costs remain high | Difficult data collection due to meteorological conditions (e.g. clouds)<br>Depends on good correlation between SOC and remote sensed data | These methods are expensive and require experts in meteorology<br>Also, research is needed to establish a reliable correlation between soil C sequestration and net C uptake | Critically dependent on data quality<br>Statistical analysis explains mostly average effects but may lose part of the variability and fringe cases | Critically dependent on an accurate parameterization ("garbage in-garbage out")<br>May depart from data in situations for which the model was not duly tested |
| **Examples** | Portuguese Carbon Fund project for sown biodiverse pastures | The LUCAS soil project<br>USDA soil map[1]<br>FAO SCO mapping[2] | The Czech "ÚKZÚZ" data; Farmer soil samples; Scientific studies (see - effects and trade-off mini papar); National inventories; SOM content map of Hungary (Agrotopo[3]); Portuguese EDP project | The LUCAS soil project<br>DIGISOIL[4] | Shepherd et al. (2002)<br>Gomez et al (2008) | CarboEurope project[5]; ICOS project[6] | Life Cycle Assessment impact indicator for land use;<br>Simple soil models[7];<br>IPCC Tier 3, RothC[8] model | Scientific literature;<br>Process-based mechanistic grassland models (e.g. PaSIM) |

[1] https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/
[2] http://www.fao.org/3/a-bs901e.pdf
[3] http://dosoremi.hu/szervesanyag.html
[4] http://cordis.europa.eu/result/rcn/196165_en.html
[5] http://www.carboeurope.org/
[6] https://www.icos-ri.eu/
[7] https://cran.r-project.org/web/packages/SoilR/SoilR.pdf
[8] https://www.rothamsted.ac.uk/sites/default/files/RothC_guide_DOS.pdf





*Extensive monitoring*

A different option is to **extensively monitor a region**. In these **schemes the entire area of interest is monitored, but only at scant spatial and temporal intervals**. The underlying idea is to ensure that the variability found in reality is reflected on the results, but maintaining the sampling and analysis effort relatively low. Typically the sampling units are chosen at random, from regular grids or from a pre-division in homogeneous regions (e.g. Taghizadeh-Toosi et al, 2014). In the Land Use and land Cover Survey (LUCAS) of the European Commission (EC), SOC and a variety of other parameters were measured in 2009 in approximately 19,000 locations along the 4.5 million square kilometres of the European Union (EU-28) (Tóth et al., 2013). Only approximately 4,500 of those samples were grasslands.

*Intensive monitoring*

**Intensive monitoring respects to covering regions of interest in full detail** regarding geospatial or temporal variability, i.e. on a farm-by-farm or plot level, and/or using intra-annual or annual sampling. These schemes involve a significant effort due to the time and resources needed for sample collection and analysis. In the Czech Republic the Central Institute for Supervising and Testing in Agriculture (ÚKZÚZ) established by the Ministry of Agriculture is testing soils throughout the country (**http://eagri.cz/public/web/en/ukzuz/portal/fertilisers-and-soil/**). Every 6 years soil samples are collected and analysed for soil quality, nutrient contents etc. This procedure, paid for by the Czech government, is performed only on arable land, not on grasslands. However, due to a long time series dating back to the communist era, when there were extensive cropping projects throughout the country, grassland farmers can have access to the history of their land and historical SOC contents. The data, which includes SOC data, can be accessed by the farmers for free after the 6-years monitoring period.
Another example of **intensive monitoring was the Portuguese Energias de Portugal (EDP) project**, which preceded the PCF project mentioned above. EDP, the main Portuguese electrical company, decided in 2006 to sponsor a project aimed at demonstrating how land use activities could help Portugal comply with its Kyoto Protocol target (Teixeira et al., 2010). The project financed the sequestration of 7 kt $CO_2$ per year in more than 1,500 ha. Land uses included in this project were afforestation, forest management, the agricultural practice of no-tillage, and as the centrepiece of the project the installation and management of sown biodiverse pastures. The project helped to establish accounting methods for sequestration factors, including detailed monitoring through collection of soil samples to obtain a data set for SOC from 2006 to 2012. For EDP this project was a strategic move. It contributed to foster innovation in society and position the company itself as a precursor of the widespread incentives provided by the PCF later on.
**The sampling and analysis effort may, however, be distributed**. **Farmers frequently collect soil samples and have them analysed by a laboratory to depict the status of soils** and obtain fertilization recommendations. Although there is no European-wide known database compiling these data, as it is proprietary to each farmer, these data exist and if compiled would be equivalent to an intensive sampling resource (see "Recommendations for further development" below). In the Netherlands such a database is available at national level (Reijneveld et al., 2014), and all farm analyses are used by the Dutch laboratoy *Eurofins* for recommendations and scientific purposes. In Hungary, the national soil mapping survey was based on field and laboratory soil analyses, and it now provides chemical and physical data of the soil (including SOM content) on an online, digital map (Digital Kreybig Soil Information System, AGROTOPO, **http://maps.rissac.hu/agrotopo/**).

## Indirect measurement

What the previous three approaches have in common is that they require soil collection and laboratorial analysis. **Laboratorial analysis of SOC may be replaced by emerging indirect measurement procedures using proximity sensors, remote sensing and eddy covariance techniques.**


### *Proximity sensors and remote sensing*

Hyperspectral data from proximal analysis or remote sensing indices using visible (400-700 nm) and near infrared (700-2500 nm) reflectance (vis-NIR) are found to highly correlated with SOC (Islam et al., 2003). Proximal analysis involves using field sensors that measure reflectance of soils, and then **correlates spectral bands with SOC measured conventionally to calibrate a correlation curve** (for example, Cambou et al., 2016; Gomez et al., 2008). This correlation can then be used for different regions. In the LUCAS project, an application of vis-NIR spectroscopy was performed (Stevens et al., 2013). This was the first spectral library established at continental scale. Remote sensing, using satellite data or data acquired using drone flights, works similarly but is capable of surveying larger areas. Additionally, **distant sensing does requires soil sampling only for calibration and validation**.
At the moment, this is a very active area of research (Jaber et al., 2011; Mondal et al., 2017; Peng et al., 2015) and it is developing fast, but to our knowledge there are no large scale applications of this concept in SOC monitoring projects outside of scientific research.

### *Eddy covariance*

Another option for **indirect measurement could be the use of eddy covariance methods**. This would be an indirect procedure because SOC change would be inferred from measured net ecosystem $CO_2$ flux exchange (NEE) between the atmosphere and ecosystems. Correlation between NEE and SOC change could be used for extrapolation to larger scale (i.e. where SOC is not measured but NEE).**More research would still be needed to establish a reliable correlation between soil C sequestration and net C uptake**. Data of CarboEurope or the International Carbon Observation System (ICOS) can be used for further analysis if SOC is measured parallel with NEE.

## Modelling

SOC could additionally be determined by modelling **to supress data gaps and/or reduce the data collection effort**, provided that input data are available.

### *Bottom-up modelling*

In **bottom-up models,** starting from available datasets, **statistical interpretation is made to extend measurements to larger regions**. For example, the LUCAS project also provided a statistical interpretation of point data collected in the form of a continuous map depicting SOC stocks over the entire EU territory (de Brogniez et al., 2014). In Life Cycle Assessment (LCA), the impacts of land use are often depicted using SOC change due to land use (Legaz et al., 2017), which is the indicator recommended by the EC (EC-JRC, 2011). Although broad categories are used (e.g. grasslands are usually a single land class), the LCA impact assessment models typically resort to pre-existing SOC maps and assign changes in SOC stocks to each occupation and transformation of land within each geoclimatic region (Brandão & Milà i Canals, 2013; Morais et al., 2016). These "characterization factors" (i.e. factors depicting SOC change during land occupation and transformation with a given land class/management) are presented as continuous maps and can therefore be used for large-scale monitoring.

### *Top-down modelling*

An alternative monitoring procedure is top-down or process-based modelling. **Process-based soil models integrate complex biogeochemical processes formulated on mathematical-ecological theory** and take into account climatic variations, agricultural management practices and soil conditions as input data (Cuddington et al., 2013). Using theory and data on related variables, they are capable of estimating SOC stocks and variations under different management regimes and in different regions of the World. There are many soil models and applications of soil models in the scientific literature applied to grasslands. Some examples (Byrne et al., 2005, Ponce-Hernandez et al., 2004, Smith et al., 1997) are DNDC (the Denitrification

Decomposition model), PaSim (Pasture simulation model), RothC (Rothamstead Carbon model) and the CENTURY/DAYCENT model.

### The optimal monitoring scheme

Reducing the requirements for sampling, through **extrapolation of extensive monitoring, improves usability but reduces accuracy and the ability to grasp all natural variability**. The finer assessment of management influence in SOC may be lost in the process. Indirect measurement using vis-NIR has the potential to combine both aspects – reducing costs for surveying large areas in detail. However, there are still many open research questions regarding the accuracy of these methods and how much natural variability can be assessed using proximity analysis or remote sensing. Modelling can also fill out data gaps and help assess SOC both in real and counterfactual settings, reducing the need for field SOC data. However, these models are critically dependent of assumptions and other types of data.

In general, **a monitoring scheme should be** (1) **accurate**, to the extent required by the commissioner of the study; (2) **cost-effective**, so that the price and resources required are not prohibitive; (3) **systematic**, so it can be applied in different regions and situations; and (4) **scalable**, so that it can be applied to farms or whole regions (possible as a combination of two or more approaches). As all methods have advantages and disadvantages and some score better than others in each of these criteria, the selection of the method for monitoring should be guided towards the reason for monitoring. The next section assesses the possible motivations for monitoring SOC.

## Match between monitoring needs and methods

Given the reasons each stakeholder has for monitoring SOC presented in Table 1, it is possible to estimate which are the most likely monitoring methods, out of the approaches in Table 2, to address the needs of each type of stakeholder (Table 3).

**Farmers may require specific data about their farms**, and even particular parcels, in an annual/biannual basis for reasons unrelated with carbon (e.g. fertilization recommendations) but that can provide carbon data (e.g. measurements commissioned by farmers). Therefore, **intensive monitoring is required, or at least extensive monitoring with sampling points carefully chosen** to capture the spatial variability within the farm. vis-NIR spectroscopy analysis can potentially replace field surveys, but only if offered as a service to farmers (due to the expertise and equipment needed).

**Advisors** can use data from basically all types of monitoring approaches, but they **require** (1) **field-level measurements** to better advise the specific case of a particular farmer, and (2) **context information** at least at regional level. **Researchers can also develop methods and draw conclusions from any form of monitoring**.

**Policy-makers are not necessarily interested in individual, farm-by-farm data but more on the overall results of policies.** Although detailed data is also useful, accurate large scale results from indirect measurements or modelling are sufficient.

**Private decision-makers can also use virtually all data available**, but restrictions regarding **data quality in sustainability claims require some level of field validation**. Intensive monitoring is therefore more appropriate for their requirements. For the same reason, consumers are also interested in detail and accuracy.

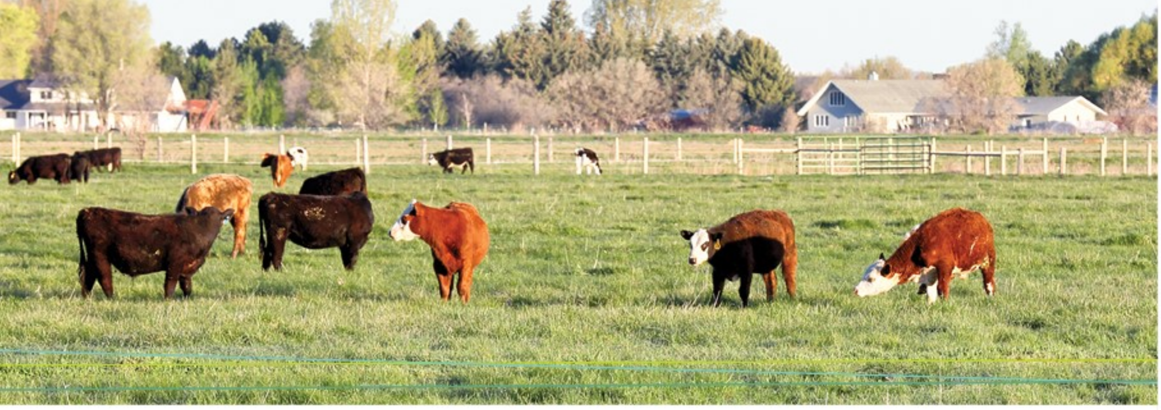


*Table 3 – Potential match between monitoring approaches and stakeholders given reasons for measuring carbon, at the current level of development of each approach. ✗ – not likely to be useful; ✓ – relatively useful; ✓✓– very useful.*

| | Direct measurement | | | Indirect measurement | | | Modelling | |
|---|---|---|---|---|---|---|---|---|
| **Stakeholder** | **Extrapolation** | **Extensive** | **Intensive** | **Proximity sensors** | **Remote sensing** | **Eddy covariance** | **Bottom-up models** | **Top-down models** |
| **Farmers** | ✗ | ✓✓ | ✓✓ | ✓ | ✗ | ✗ | ✗ | ✗ |
| **Advisors** | ✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓ | ✓ |
| **Policy-makers** | ✓ | ✓ | ✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ |
| **Private decision-makers** | ✓ | ✓ | ✓✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Researchers** | ✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ |
| **Consumers** | ✓ | ✓ | ✓✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

## Proposal for potential operational groups

Potential ideas for operational groups are presented next. They address the proposals for research needs from practice and the recommendations for further development.

### The role of management in carbon sequestration

The role of grassland management in carbon storage is still largely unknown and very likely to be site-specific. An operational group could be established to **improve management-specific monitoring systems** and collect data on the **direct correlation between the quantity of carbon sequestered and the practices used**. There are multiple variables affecting this relation such as climate, type and conditions of soils, orography, etc., and also stocking rates, grazing duration or animal type. The nature of Operational Groups enables the promotion of multiple national groups all over Europe, presenting an opportunity to assess the impact of those practices in the carbon storage in manifold territories with different conditions, and therefore, to **improve the monitoring systems through empirical testing**. The operational group should consist of farmers and researchers. More details on the topics that should be tackled by this group can be found on the mini-paper on grassland management and soil carbon.

Research needs addressed: "Connection to management practices"
Further developments addressed: "Multifunctional ecosystems"

### Devising better indirect indicators of carbon sequestration

One operational group can be established **to test and transfer knowledge regarding the use of remote sensing-derived indices** as indicators for soil carbon. This group should include research institutions to apply best practices and methods, labs conducting conventional soil analyses to ensure calibration, and also farmers to test applicability. An assessment of the technologies involved in indirect measurement in terms of accuracy and cost-effectiveness should be included in this analysis.

Research needs addressed: "Connection to management practices"
Further developments addressed: "Multifunctional ecosystems"

## Establishing good, long-lasting databases of soil carbon

Determining carbon sequestration from multiple practices in many regions depends crucially on data availability. While in some case it is necessary to collect more data, in many cases the issue is those **data are scattered among many institutions and stakeholders and are inaccessible for farmers or even researchers**. An operational group could be established **to set up a centralized system where SOC data could be stored and curated**, including an option to upload data as it becomes available. This system could be used as a reference by farmers or as a source by researchers to address many of the pressing issues regarding carbon sequestration and grasslands. This would certainly require researchers to set up the system, but the involvement of institutions (e.g. governments) that possess or can negotiate obtaining the many data sources would be required, as well as farmers, who are the most likely to possess intensive monitoring data. The main goal of the operational group would be to ensure that a procedure is set up that ensures that in the future the centralization of data collected is automatic and to discover how these data can be made widely available.

Further developments addressed: "Stability and persistence", "Harmonizing soil sampling methods", "Connecting data and curating databases"

## Comparing the costs of different monitoring methods

As described, the best monitoring scheme may depend on the stakeholders involved and their motivations for measuring. A trade-off between costs and accuracy has to be determined for each monitoring project, but data on costs is too scarce to enable effective comparisons. This group would **look into the actual cost of each method presented earlier and produce a decision tree for each stakeholder to see which methods are the most appropriate to their purposes**. It would need to include many of stakeholders presented in Table 1.

Research needs addressed: "Assessing the costs of monitoring"

## Simplifying and standardizing monitoring

Besides costs, **it is also crucial to compare the accuracy, effectiveness and labour work of different methods estimating SOC**. An additional Operational Group could be established as a result of the previous ones to simplify monitoring practices. The main task of this group would be to evaluate the outcomes of prior projects and monitoring initiatives and provide recommendations for the level of detail that was needed to identify C sequestration in grasslands. Questions to be answered, for example, would be (for different cases of farm size, structure, etc.) the geospatial coverage needed, the time between samples (e.g. annual, once each 5-years), etc. The group could **devise standards or rulebooks for each appropriate case**, taking also into consideration costs. Researchers from agronomy and environmental science, as well as farmers and other stakeholders should integrate this group.

Further developments addressed: "Harmonizing soil sampling methods"

## Communication and valorisation of C sequestration

The establishment of a reliable and cost-efficient monitoring system could support credible mechanisms for the valorisation of products based on grazing management practices that favour carbon sequestration. The **credibility of C sequestration measurement may play a role in the credibility of the claims of sustainability of these products**. Along these lines, various operational groups could be set up involving diverse actors from the value chain to test the viability of products (beef, milk, butter, etc.) based on these practices, and the response of consumers to different quality distinctions (brand, label, etc.). This group

could also assess the effectiveness of different communication schemes (e.g. labels, targeted marketing tools) and how information should be relayed to stakeholders, particularly consumers.

Further developments addressed: "Connection to incentives schemes"

### Assessing C sequestration along supply chains

An Operational Group could be established to broaden the scope of C sequestration monitoring systems, avoiding shifting of burden. **C sequestration in farms should not take place at the expense of C depletion elsewhere** (e.g. more C sequestration at the cost of yield loss, and supplementation of animal feed using SOC-depleting crop products from elsewhere). A group consisting of farmers, their suppliers and customers (consumers, secondary producers) could work on establishing mechanisms to look at C sequestration not in an isolated farm-by-farm approach but rather in a mosaic interlinked by supply chains, and produce standards for joint monitoring of C sequestration and emissions at every level.

Further developments addressed: "Agriforestry/silvopastoral", "Whole carbon (and nitrogen) cycle assessment", "Conservation farming and carbon sequestration"

### Assessing C sequestration in multifunctional frameworks

**C sequestration should be understood in the context of provision of multiple ecosystem services besides climate regulation and adaptation** – services such as soil stabilization and improved water management are as important particularly in Southern European countries. When determining monitoring schemes, it would be useful to join researchers interested in C sequestration with other experts on other ecosystem services (soil scientists, biologists, ecologists, etc.), as well as farmers who are the ultimate providers of these services, and expand on the monitoring systems proposed here to **devise integrated monitoring systems of a multitude of ecosystem services, thus saving time and effort in data collection and providing a wider picture of the effects of grazing**.

Research needs addressed: "Understanding links between C sequestration and other ecosystem services"
Further developments addressed: "Agriforestry/silvopastoral", "Whole carbon (and nitrogen) cycle assessment", "Conservation farming and carbon sequestration"

## Proposals for (research) needs from practice

Below we identify some proposals for overcoming research needs. These proposals can be advanced through the establishment of operational groups or other instruments.

### Assessing the costs of monitoring

**Direct collection of soil samples and laboratorial analysis is more likely to have lower uncertainty** as it assesses geospatial and temporal variability. However, **there are questions regarding the cost-effectiveness of intensive monitoring** due to the time and resources required. Analysis through conventional laboratorial analysis can become burdensome if the surveying required is too intensive. One option would be to **use more extensive surveying**. For example, one may take only composite samples representative of a certain area of a farm (e.g. one composite sample per hectare) and abstain from repeating the measurement every year (e.g. use a 5-year window, which is sufficient enough to detect SOC changes for most cases as shown by Schrumpf et al., 2011) particularly when the system is slow to react. Nevertheless, it remains uncertain who should conduct this procedure. **Research projects are usually carried out in 3-5 year cycles, which may be insufficient to fully depict the results of some**

**practices**, and for incentive schemes even very extensive measurements may be too burdensome if it rests on the farmers (as reference, analysing one soil sample for SOC may cost between 10-15 €).

In the examples of projects presented earlier, there were three main cases mentioned of intensive monitoring. Two of them (Czech Republic, Hungary) were publicly funded, and spatially intensive monitoring was made possible due to the fact that sampling was temporally distributed along longer time periods (e.g. once every 5-6 years). In the third one, the Portuguese EDP-funded project, monitoring was spatially and temporally intensive (samples collected every year), which in this case was possible because of private funding.

These examples suggest that **intensive sampling is only possible in cases where (1) temporally intensive sampling is not needed** (e.g. no land use change or other alterations in management where there may be significant annual changes in SOC), **and/or (2) there is alternative sources for funding that do not burden the farmer**. In the PCF project, for example, monitoring costs were considered and intensive sampling was discarded due to the exceptionally high costs to survey the 50,000 hectares for 5 years. Annual payments to farmers meant that the scheme could not work unless intensive annual monitoring was conducted. An alternative is the use of indirect surveying and compliance verification, as described for the project with sown biodiverse pastures in Portugal. In the PCF project, the only viable option was an extrapolation method where a carbon sequestration factor contingent on management was established, and then only management practices were monitored. This method was successful not only because it was a low cost option but also because it translated increased carbon sequestration into an operational procedure for farmers. There was knowledge transfer for farmers regarding best management practices which made it easier to ensure success in pasture output.

It should nevertheless be noted that **indirect monitoring and modelling options are not free of costs either**. Indirect monitoring methods are labour-intensive and in many cases require expensive equipment (vis-NIR sensors, flux measurement towers). It is unknown at the moment what the costs of using indirect monitoring would be, for example, as a replacement for laboratorial analysis. At the moment, there are no major service providers that could fulfil the role of carbon sequestration analysers for farmers or in incentives projects. Modelling is also labour-intensive, requiring experts who can use the models, plus data collection of auxiliary variables necessary for estimating carbon sequestration. Ultimately the costs of these new monitoring options should be researched as better methods are developed.

## Connection to management practices

Many monitoring methods assess SOC on a simple land use class basis. The **relationship between SOC accumulation and grazing management is complex and location-specific, depending also on the system of pastures**. The results for SOC increase or decrease of using different stocking methods (e.g. rotational stocking) and grazing pressure (i.e. stocking rate) are debatable. The role of fertilization and irrigation is highly sensitive to region and production system, affecting also SOC persistence. There is also some idea of the factors driving C inputs from the aboveground biomass into the soil, but there is still uncertainty about the response to management of belowground dry matter in pastures, namely root production and turnover. This knowledge is essential for farmers and advisors, as well as policy-makers when devising policy rules. Ideally, this should lead to farmer-oriented tools and decision support systems that enable context-dependent management optimization of SOC.

Further developments should explicitly include **differentiated monitoring for each type of management practice and relate the outcomes with a region-specific context**. As explained previously, the cost of different methods to monitor SOC are mostly unknown and can vary significantly depending on the goal. For this reason, the costs of methods selected for dealing with SOC and management should be explicitly compared.

### Better indirect monitoring systems

Today **the most reliable and accurate methods to determine soil carbon stock changes are direct measurements**. More research is needed to validate the remote sensing/modelling methods since it is currently impractical to use them at the moment other than for research. **Although remote sensing (vis-NIR) methods are promising for indirect, simplified measurement of SOC, they are still a relatively new technology and the methods are still insufficiently stable for large scale applicability in monitoring**. Fundamental research is necessary to establish and curate good spectral libraries, and relate them with SOC in large databases through the inclusion of location-specific variables that also influence this correlation.

The correlation between net ecosystem carbon exchange (NEE) and soil C stock change should be investigated. ICOS sites (where NEE is measured) could provide a framework for this research. NEE could potentially in the future be used as a proxy for soil C stock change, provided that there is a good correlation between NEE and soil C stock change, and this method proves to be cost-efficient. Similarly, correlation between remote sensed vegetation indices such as the normalized difference vegetation index (NDVI) and soil C stock change could be used as a proxy to determinate soil C stock change provided that there is a strong correlation.

Modelling needs detailed input data (e.g. soil properties, daily weather and management data which may not be easy to obtain), and experts to perform modelling. There has been great progress to provide user-friendly models recently (Hidy et al., 2016), but farmers would still require assistance to handle these models. It is therefore also crucial to assess the cost-effectiveness of this approach.

Further developments in this area should work towards overcoming these limitations and establishing new technologies and advisory systems that can put remote sensing and big data tools at the service of farmers.

### Understanding links between C sequestration and other ecosystem services

**C sequestration plays a role on several ecosystem services provided by grasslands**, such as climate regulation, climate change mitigation or biotic production potential. Different grazing practices may have different outcomes in how strongly they promote these and other services. At the moment, the assessment of co-effects of practices that promote C sequestration is relatively unclear. **To avoid undesired effects or avoidable environmental trade-offs, there is a need to perform integrated analysis of the most important ecosystem services provided by each practice, and how they are reinforced of antagonized by C sequestration**. Particularly important indicators in this analysis are soil/water quality and the state of biodiversity. One important limitation is that these ecosystem services are often measured separately. Understanding the relationship between these amenities requires establishing joint monitoring systems that approach the problem of assessing the effects of grazing systemically.

## Recommendations for further development

Below we identify the main topics for future development, listing them and briefly explaining each one. These topics range between applicability barriers and fundamental research needs. We (1) outline the issues, (2) describe which motivations and stakeholders they involve, and (3) provide suggestions for further development.

### Stability and persistence of SOC

**SOC monitoring always implies a definition of SOC** that is not frequently discussed outside from the specialized literature, but is crucial to determine the outcomes of management practices. Labile organic matter and key C fractions (such as coarse-particulate C and easily oxidizable C) should be investigated as these could be proxies for C accumulation/decomposition and thus for C sequestration. As noted in the Introduction, the **methods for measurement and analysis of SOC target different "labile" and/or**

**“recalcitrant” SOC pools**. When soils are analysed for total SOC without separation between the reactivity of SOC, there may be insufficient information: (1) for farmers and advisors, about the mineralizable fraction that can provide solubilized nutrients in the short-term; (2) for all decision-makers and researchers, about the expected persistence of carbon stored in the soils. Both concerns can be addressed simultaneously – in which case it is important to have high SOC stocks and also to ensure continuously high C fluxes into the soil (Lehmann and Kleber, 2015).
Monitoring this aspect also requires some **knowledge about the time period relevant for monitoring**. **In case persistence is the goal, monitoring should take place over a longer period and long lasting projects are required**. Longer periods of research and **a post-project analysis of incentive schemes are also important to establish the long lasting effects of carbon sequestration**.
Further developments should focus on harmonized methods for soil analysis that unify indicators and clearly report to farmers and advisors the interpretation of a stratified understanding of SOC.

## Agriforestry/silvopastoral

**Grasslands are not always an isolated land use system**. Iberian *Montado/Dehesa* ecosystems are an example of an important low density agro-forest landscape where grasslands coexist with trees. In these cases, the main ecosystem product may not even be an animal product, but a forestry product (such as timber or, more commonly, cork from cork oak). **The role of trees in grassland SOC monitoring is mainly twofold**. First, **deep-rooted trees** (or even superficially rooted trees like cork oak) **affect the carbon balance of grasslands by introducing larger carbon inputs into soils**. These inputs can have a significantly different chemical composition than grassland litter, and consequently contribute to more recalcitrant SOC pools. Second, **grasslands themselves affect trees through nutrient recycling**. However, the tree strata of multifunctional grasslands adds further complexity to grazing management and SOC accumulation. It also makes measurement much more complex. **SOC may vary more within a single plot depending on the distance from the range of influence of trees** (immediate vicinity, beneath canopy/shadow, open ground). **Stocking may be unequal between these zones**, and different grasses and legumes may also have different affinity to these zones. For farmers, micro-managing these ecosystems for SOC accumulation may be important. For other stakeholders more interested in average effects, the average sampling of these heterogeneous environments may be sufficient.
Further developments should **incorporate multifunctionality as an explicit variable in monitoring**. Multifunctional areas may need more intensive monitoring. Additionally, some monitoring approaches may be impossible or hard to apply accurately in such regions – for example, remote sensing may be difficult due to the role of tree canopy.

## Harmonizing soil sampling methods

**Soil sampling methods should be harmonized** for comparability sake. Some key parameters when setting up monitoring schemes are still highly variable. **Depth of sampling varies**: in the Portuguese Carbon Fund projects, only 10 cm was used (depth of rooting for most plants in the seed mix); the LUCAS project used 20 cm; the Intergovernmental Panel on Climate Change (IPCC) recommends 30 cm. **Collecting soil samples is still a highly manual procedure that introduces uncertainty** into measurement due to mistakes made during sampling. The **method of collection can also vary** – samples can be collected at random within a farm, according to a structured regular grid, or from representative, homogeneous plots. When collecting each sample, sometimes a single sample is collected, while other times several samples are collected (e.g. in a circle around the selected sampling point; or several collection points in a given homogenous parcel) and then mixed so that a single composite sample is analysed. As farmers often collect samples themselves, clarity on procedures would help ensure that results obtained independently could be included in a single database and used for research, policy-making and advisory services.
For extrapolations and indirect measurement/modelling, the issue is slightly different. **The need for sampling points and data for model calibration and validation**, for example, **requires knowledge**


**on how the data was obtained**. It is **important for the data to be collected systematically**. One important issue is whether data collected from small scale test sites is representative of real farm processes even when the test sites replicate real management.
An additional issue has to do with the conversion of SOC concentration to SOC stock. Laboratorial results are usually provided as g SOC. g$^{-1}$ soil. The conversion to t SOC. ha$^{-1}$ requires knowing the soil bulk density and, if present, removal of rocks and other materials.
Further developments should include methodological clarity, in particular to assist farmers when collecting samples and the interpretation of analysis results.

## Connecting data and curating databases

There are large SOC databases worldwide that have been compiled and are available in the form of continuous maps or tables. However, **many data sets are still scattered, available only in the native language of the curator, or in the hands of farmers and farmer association** (e.g. results of individual soil samples). These data would be very important for researchers conducting modelling exercises, for policy-makers and also businesses and consumers, as it could provide better characterization models that feed the calculation of environmental indicators.
This exercise should also consider future expansions. In possession of a bird's eye view of available data, it may be possible to better inform future monitorization efforts. For example, at the moment it is an open question how to improve extensive direct monitoring. To amplify the sampling effort in the LUCAS project, should analyses be repeated more often (higher temporal intensity of sampling)? Or should more sites be sampled (higher geospatial coverage)? Or would it be better to shift the sampling to include different managing practices (non-random selection)? These questions can be better answer with contributions from relevant stakeholders, once all available resources are compiled.
Further developments in this area should **make an effort to compile and curate aggregated databases that report transparently, and as completely as possible, SOC measurements performed in as many regions as possible by as many stakeholders as available**. These data would help monitoring schemes, for example, if applied to modelling – e.g. in parameterization or validation.
It is also crucial to continue/start long-term soil C monitoring studies and national surveys. Long time series are missing, in part because of the short temporal cycle of scientific projects and the discontinuity between research activities. Projects that follow up other projects that ended are usually shunned for innovative projects, which make it harder to compile long-term data. Besides raising awareness with funding bodies to the importance of long-term projects, diversifying the sources of funding for research may also be one of the solutions. Complementary funds (e.g. private funds) can and should be used to ensure that long-term experiments are continuously funded.

## Whole carbon (and nitrogen) cycle assessment

Discussions about grazing and carbon are mostly centred on SOC and carbon sequestration. Monitoring schemes are, consequently, also focused on measuring carbon in soils. However, for reasons noted previously, **being aware of carbon flows can be as important as knowing carbon stocks in grasslands**. This knowledge of the carbon cycle would be an important asset for all stakeholders. Understanding the entire grazing system as an interconnected network of causes and effects and their feedbacks can help understand how farmer activities ultimately affect greenhouse gas emissions and C sequestration. Knowing how carbon flows through grassland ecosystems, including grazing animals, could identify hotspots or important areas where management should act to maximize accumulation and ensure a functional system that maximizes ecosystem service production. The carbon and nitrogen cycles are related, and nitrogen is particularly important in grassland production.
Including a coupled carbon-nitrogen cycle approach when understanding SOC accumulation, and monitoring both together, could therefore be important not only for farmers but also to assess the full greenhouse gas balance of farms to ensure that even if carbon is being sequestered, that sequestration does not come at


the cost of increased emissions of other greenhouse gases or from other sources. Establishing monitoring systems towards this end would also match the needs of researchers interested in the role of C sequestration for whole-systems dynamics.

### Conservation farming and carbon sequestration

There is a recent growing interest in conservation agriculture (CA) as opposed to the conventional agriculture, as an efficient C sequestration tool. **CA is an approach where soil quality is at the centre of all the management options** in the farm, including the concerns for C sequestration via SOM improvement to fight soil quality depletion namely desertification. This way of managing the ago-ecosystems aims at improved and sustained productivity, increased profit while preserving and improving natural resources and the environment. The three main principles of CA rely on minimum or zero tillage, on a permanent cover of the soil with organic materials, and on the use of multicropping as opposite to monocropping. This is a long term C sequestration technique with the advantage of producing results within the first 1 or 2 years after implementation. SOM is clearly increased after a few years, as well as soil structure improved thus promoting better nutrients management (namely N and P) and plant production.

### Connection to incentives schemes

A **consistent and reliable monitoring system is of main interest for the development of instruments to promote grazing managing practices for carbon sequestration**. Further, a reliable and cost-efficient monitoring system would ensure the confidence of consumers and transforming industries towards differentiated products that favour the sequestration of carbon, with the consequent opportunity for added value grazing productions. The exact **choice of monitoring is specific to the incentive scheme** (e.g. conformity with policy instruments, carbon markets), but the connection is thus far unclear as this match between best practices for monitoring and the ultimate goal has mostly not been done.

## Conclusions

The goal of the focus group "Grazing for Carbon" is to understand to what extent grazed grassland can contribute to carbon sequestration and thus mitigate greenhouse gas emissions. Part of this goal is fulfilled through improved knowledge of practices related to grazing that can help sequester the most carbon and how these can be supported, but another crucial part is how that carbon sequestration can be measured, documented, validated and/or verified through monitoring.

**This mini-paper discusses the options for documenting the provision of carbon sequestration services by farmers/land managers** for multiple reasons such as participation in public or private incentive schemes. We discussed direct and indirect methods of accounting for carbon sequestration. Given the lack of examples of projects for some methods and the research needs still faced by some of the options, **we concluded that there are two main viable ways to do this**:

1. **Measure the carbon content of the soil directly** over time and use these data to estimate the change in carbon storage.
2. **Register farming activities or indirect indicators of farm activities, calculate their** potential for increasing carbon storage, **and monitor only those activities**.

**The two options are not mutually exclusive** (i.e. one can do a mixture of the two). Although in general the role of management in carbon sequestration is still unknown, it can be established for the particular monitored case and then only practices are monitored. The example of the PCF carbon sequestration project in Portugal shows how direct measurement can be used to establish the results from certain practices, and then register only the compliance with those practices.

**Measuring the carbon content over time is at the moment the gold standard but it may be expensive for some incentives schemes**, **and only gives a sensible result if continued for some**

**time** – which might not be synched with the typical time frame for research projects or policies. **The second method is cheaper and can be used over much shorter time periods** but relies either on prior data or on modelling to identify relevant farming practices and quantify their effect. Ultimately **the best monitoring system must respond to the reasons for measuring carbon and the stakeholders involved**.

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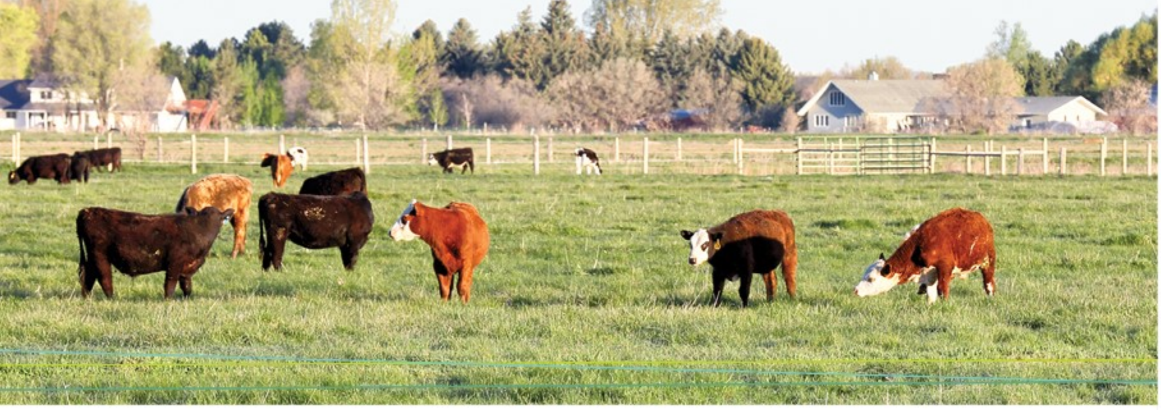

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