Measuring and monitoring soil carbon sequestration

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Key words: MRV; SOC sequestration; soil measurements; SOC modelling

Abstract

The monitoring, reporting and verification (MRV) of soil organic carbon (SOC) sequestration following management changes is complex due to the multitude of influencing factors related to ecosystem processes but also due to (socio-)economic or legal requirements. Several protocols for MRV applications have been published. In this chapter we will provide an overview about available systems and their advantages and limitations. There is a wide range of options to quantify SOC changes, but most of these options have limitations. Field measurements, including periodic on site measurements, short-term experiments and long-term monitoring are time consuming, cost and labour intensive. On the other hand modelling, and/or remote sensing approaches are associated with uncertainty, and/or data demand. Therefore,

an effective MRV application should be a combination of different approaches. This chapter will discuss the different aspects, which will be picked up in the other chapters of this section that will present more details on quantification options.

1 Introduction

Soils have recently received attention in the context of climate change, because they are the largest terrestrial carbon pool (Batjes, 1996, Lal, 2004) and small changes of this large reservoir may affect atmospheric CO_2 concentrations. To preserve current atmospheric CO_2 levels and to limit climate change impacts it is thus important to protect the carbon stored in soils and prevent its release to the atmosphere. Carbon may be stored in soils at long timescales and soil carbon sequestration may therefore have a large potential as negative emission technology (Paustian et al., 2016, Minasny et al., 2017, Paustian et al., 2019). Such technologies need to be employed to meet the climate targets of the Paris Agreement or the different national net zero targets (Climate Ambition Alliance: Net Zero 2050). Increasing soil organic carbon (SOC) sequestration will remove atmospheric carbon and store it in the soil. This process can have a range of positive side effects (Smith, Pete et al., 2021). Rumpel et al. (2018) describes eight steps to make soil more resilient, more productive and improve the storage of carbon. One central part for awarding land managers for improving soils and for the application of SOC storage as a large-scale climate mitigation strategy, is the availability of a system for measuring, reporting and verification (MRV) of the effect of land management practice. This includes the quantification of SOC changes over time. However, SOC sequestration is a complex and slow process affected by a wide range of factors (see Chapters 3, 4, 5). This makes the measurement and monitoring of SOC challenging. While point measurements are associated with errors and uncertainties, large-scale quantification presents even more challenges, as it requires either large amounts of samples, which is costly and labour intensive, or upscaling methods based on assumptions.

Soils are used for different purposes and often managed by a variety of users with their own interests. Activities to increase SOC are not necessarily the main interest of the users and/or landowners. Farmers, for example need to rely on constant harvest to provide food and make a living. Incentives or legal obligations are required to introduce changes to maintain and/or increase SOC (see Chapters 26, 27 and 29), and their implementation depends on a functional monitoring system. This system will be based on available and future development of tools and approaches to quantify SOC changes (measurements, modelling, etc.). Available tools show a wide range of complexity and accuracy, with a general trend towards application of of simpler options with easy, cheap and rapid methods.

To account for varying complexity of methodologies, the IPCC introduced a three-step tier-system, with Tier 1 indicating a basic method with an equation and default emission factors, Tier 2 using the same equation but country / region-specific emission factors and Tier 3 any more complex method, ranging from alternative equations to process-based models.. The equation and default factor for Tier 1 describe a linear relation between an activity (e.g. fertilizer application on the field) and the related estimated GHG emissions. Scientific data build the basis for this relation, which is a simplified, but effective and standardised approach to estimate GHG emissions. While the used values in Tier 1 are more generic (based on global data), the Tier 2 approach is similar to Tier 1, but uses country specific values that provide a more accurate estimate for the target country. Available emission factors are summarised in the emission factor database (EFDB; https://www.ipcc-nggip.iges.or.jp/EFDB/main.php).

There is an increasing interest in the economics of carbon sequestration. While there is already an interest in an investment in more sustainable companies (Kareiva et al., 2015), carbon accounting and trading of carbon units generated by SOC sequestration has started already. However, all of these different interests rely on a functional and applicable MRV system. Recent research focussed focused on MRV applications and has developed suitable frameworks (Paustian et al., 2019, Smith et al., 2020, FAO, 2020). In this chapter we will present available systems and discuss their advantages and limitations

2 Measurement/monitoring, reporting and verification (MRV)

In this chapter we distinguish MRV frameworks from MRV applications. While a framework provides a more theoretical description of an optimum MRV system, the application describes an applied MRV system, using protocols that include concrete definitions of used models, measurement approaches and other required details (e.g.

responsibilities for the different actions). Smith *et al*. (2020) outlined a generic concept for an MRV framework as a combination of different approaches to quantify SOC change over time. Generally, management changes are applied on a field or farm level. The farm level is the scale for the beneficiaries of subsidies or carbon trading. Therefore, field and farm scale are most relevant to an MRV scheme. A central part of quantifying SOC changes on this scale are field measurements, but these are costly and labour intensive. Additionally, MRV protocols often lack clear measurement standards (Bispo et al., 2017). While some aspects are clarified (depth of the top 30 cm, 1 m if possible (FAO, 2020)), other specifications are missing (number of samples, date of sampling relative to the management practices, spatial distribution of sampling, etc.). Therefore, alternative approaches to measurements need to be considered. Modelling is a very attractive alternative, as all problems and limitations of the measurements are resolved by using a model. But the quality of the simulation result needs to be considered, especially in comparison to measurements. Models include errors and uncertainty based on the assumptions used and the underlying concepts and they require data for calibration and validation, in addition to those needed for running the models. MRV frameworks as outlined by the FAO (2020) and Smith et al. (2020) specify that only calibrated models can contribute to SOC quantification, but further specification of the models is not provided. A combination of both (measurement and modelling) will compensate the disadvantages of each other and improve the result (Smith et al., 2020). Overall, a combination of different approaches secures the optimum quantification of SOC changes over time. Smith *et al*. (2020) list seven components of an MRV framework: long-term experimental sites, field experiments (short-term), field specific modelling, spatial data analysis combined with modelling, collection and aggregation of activity data (e.g. conventional and intervention management), remote sensing and spatial re-sampling. The different components complement each other to allow an optimum framework for measuring and verifying SOC changes over time. There are advantages and disadvantages of all different components and all show some limitations. Only a combination of all, or at least several of these methods, will provide good MRV outcomes.

2.1 Measurements

Direct measurements of SOC content involves quantifying the fine earth and coarse earth fraction, the organic carbon concentration and soil bulk density or fine earth mass (FAO, 2019). Estimating the rock content of sample soils can be a challenge but will significantly affect soil bulk density (Poeplau et al., 2017, Throop et al., 2012). Another challenge is that a change in management (whole practice as well as depth at which that practice is applied), will not only impact on the bulk density of the soil but also on the amount of soil in a soil sample at a certain depth (Haynes, 1998). Therefore, corrections and use of the equivalent mass approach may be necessary (Chapter 11). As soils are characterised by a high spatial variability, direct measurements rely on appropriate study designs and sampling protocols (Minasny et al., 2017, Chapter 11). At the field scale, large number of soil samples is usually required to give reliable SOC stock estimates with an acceptable error margin (Garten & Wullschleger, 1999, Vanguelova et al., 2016).

IPCC recommends a sample depth of 30 cm, but several methods for increasing SOC content require deeper sampling for confirming the expected effect (Smith et al. 2020). For example, the effect of a no tillage practice on the SOC content may be overestimated if the measuring depth is insufficient (Angers & Eriksen-Hamel, 2008, Blanco-Canqui, Lal, 2008).

A change in SOC stocks can also be estimated through indirect measurements and by presenting the full carbon budget. This approach uses the net balance of carbon fluxes measured through chamber measurements or the eddy covariance (EC) method (Baldocchi, 2003). From the carbon fluxes, the initial uptake of carbon through photosynthesis and its subsequent partial loss through respiration (from soil, plant and litter) are estimated to give net ecosystem exchange or net ecosystem production and further C inputs (organic fertilization) and outputs (harvest) to and from the system (Smith et al., 2010, Soussana et al., , 2010). Through this complied carbon budget, a change in SOC can be estimated. This approach indirectly measures the change in SOC for larger landscapes but can only be used under horizontal homogeneity of the footprint area and under sufficient air turbulences (Aubinet et al., 1999). The maintenance of most measurement systems is costly and time consuming. The post processing of the measured data is also needs time and expert knowledge about flux corrections for density and gap filling (Falge et al., 2001, Reichstein et al., 2005). In an MRV application EC provides landscape specific data, which can be used as baseline data or for model optimisation purposes (calibration and validation).

Long-term study sites are crucial for the implementation of MRV framework (Smith et al., 2020). Study sites for different management combinations allow a long-term observation and quantification of all relevant parameters and variables that affect the SOC sequestration. 'Long-term' is relative and not defined as a fixed duration. The IPCC suggests 20 years as the default period to observe SOC changes, because SOC sequestration rates are fast at the beginning, but slow down over time until they approach zero (Sommer & Bossio, 2014). Measurements are impractical for a generic implementation of an MRV process (too costly and labour intensive) and other solutions that replace or at least reduce the sampling intensity in the field are required. Besides modelling and remote sensing, long-term study sites in combination with short-term field experiments can complement field measurements. These study sites provide data for re-assessment of potential impacts, reference for expected changes or baseline for a particular management practice. Additionally, these data will be the basis for development, calibration and validation of models and remote sensing approaches. Ideally, land cover, soil, climate, management and environmental conditions are represented by available study sites or at least a reasonable number of combinations (good representation of all climate zones, soil types, crop species, etc.). A standard protocol for the acquisition of these data would be beneficial, because differences in the set-up of the measurement approaches could introduce uncertainty. Organizing and providing these data on accessible platforms is the best way for an open and tranparent handling of the data. Two platforms for long-term experimental sites were initiated by the SOMNET (Smith et al., 2002) and the EuroSOMNET (https://www.ufz.de/somnet/,(Franko et al., 2002)) platforms. The SOMNET platform evolved later to an online, real-time inventory project including a webpage with Long - Term Soil - Ecosystems Experiments. The database contains meta-data of more than 200 long-term experiments and is hosted by the International Soil Carbon Network (http://iscn.fluxdata.org/network/partner-networks/ltse/). More than 80 % of the long-term experimental sites concern agricultural systems (Smith et al., 2012). However, the majority of the sites are in the temperate climate zone with focus on Europe and North America, under-representing tropical and sub-tropical regions and the Southern hemisphere (Smith et al., 2012). For good coverage of the variability of global agricultural systems, more long-term sites in other parts of the world need to be established. The better the representation of different management options, soil and climate zones by experimental sites, the better the data basis for MRV application. This requires immediate action, as study sites that are established today, will be able to be used to assess long-term effects on SOC in 20 years (Smith et al., 2012). Special funding is required to initiate long-term monitoring sites, as project funding for 3 to 5 years duration is insufficient.

2.2 Remote sensing

Beside *in-situ* measurements, remote sensing can support the monitoring of SOC changes and/or provide data for the verification of measured SOC changes. This technology allows non-invasive measurements, including at large scale. Remote sensing can be applied in the lab or on the field by handheld or transportable systems, or by airborne or satellite device devices (Chabrillat et al., 2019). As part of an MRV application the latter two options are more useful, as these systems allow a wider coverage and delivery of large-scale data globally. Considering the wide application and availability of the data, this would reduce costs for monitoring SOC changes (Nocita et al., 2015), once the approach is established. There are different approaches used for SOC estimation and two of them are highlighted below.

One established remote sensing approach is the reflectance spectroscopy. It uses characteristic spectra that are reflected from the soil surface for quantitative and quantitative analysis of soil properties. The recommended wavelength range for these measurements is the visible near infrared–shortwave infrared (700-2500nm), as it shows a good signal to noise ratio and is a cost and time effective option for spectroscopy (Mohamed et al., 2018). The characteristic spectra are reflected by the bonds in the SOC molecules (O-H, N-H, C-H), which allow a qualitative and quantitative analysis of SOC. This method provides soil-type-specific quantitative SOC estimates (Grinand et al., 2012). To secure a wider application without site specific measurements, spectral libraries are required that contain several thousand soil types with varying soil properties, as a reference. This is a cost- and time-effective alternative to other traditional measurement options in the laboratory, such as wet digestion or dry combustion (Nayak et al., 2019).

The introduced high spectroscopy measures for fixed wavelength using multispectral sensors, which is associated with some limitations, especially for quantitative measurements on SOC (Ben-Dor et al., 2018). Therefore, recent developments on hyperspectral sensors show an improved approach with higher capability for quantitative data over large areas. Hyperspectral remote sensing (also called image spectroscopy) provides a continuous spectrum for each pixel, using 100 or more contiguous spectral bands. However, Ben-Dor et al. (2018) also list a wide range of drawbacks with the signal to noise ratio as a major problem (caused e.g. by non-transparent atmosphere, problems with sensor calibration) and more problems with changing conditions (e.g. changes in soil particle size). Further developments are required to improve the approach. For large scale application, there is again a demand for developing new libraries for the new approach.

The advantage of large scale remote sensing using airborne devices and/or satellites is that it can provide additional information, e.g. land use change (Winkler et al., 2021), primary production (Zhao et al., 2005) or different soil properties (Viscarra Rossel et al., 2006). Nevertheless, remote sensing has limitations. The availability of images is affected by cloud cover, measurements are affected by plant cover on the ground and only the top centimetre can be measured (Smith et al., 2020). Despite good results in different studies and the availability of spectral libraries, the measurement is still uncertain, which renders remote sensing as the sole MRV method unsuitable. In contrast, it is an excellent additional approach to complement other methods, and should therefore be used only in combination.

The latest developments in multi-spectral systems to quantify SOC have shown great progress (Aldana-Jague et al., 2016). These kind of measurements have the potential to reduce uncertainty (Chabrillat et al., 2019), new libraries have to be built for the new approach. Chabrillat et al. (2019) refers also to studies using hyperspectral systems (Gomez et al., 2008, Lu et al., 2013), but rates the performance as moderate. Similar to the other approaches, remote sensing shows a good potential to complement measurements and reduced costs but is not able to replace field measurements completely.

2.3 Modelling

As there are limitations to field measurements and remote sensing,,modelling becomes the most prominent supplement to provide data for MRV application. Models can contribute in different ways to MRV: 1) provide baseline information, 2) interpolate measurements (temporally and spatially), 3) extrapolate measurements for projections or for an ex-ante assessment, 4) estimate SOC changes, and 5) provide information for an optimised measurement plan. Different models with different complexity and accuracy can be used in MRV application. However, there are no standards defining the quality of a model used in an MRV application. Choosing the right model depends on the objective, data availability and modelling skills of the user (Table 1), as different models vary in their characteristics, complexity and accuracy (Table 1).

Table 1: Specifications for different model categories. The category emission factors also include simple empirical equations (Tier 2 approaches). The categories SOC and biogeochemical models (Tier 3 approaches) are separated to indicate if a model only includes SOC dynamics or also addresses processes (e.g. N cycle, plant growth). The category decision support includes tools that are designed to provide information on GHG emissions, SOC changes or both (these tools use mainly Tier 1 and Tier 2 approaches but can also include Tier 3 routines).

	Emission factors	Decision support tools	SOC models	Biogeochemical models (Tier 3)
Data requirement	low	high (farm specific data)	high (environmental data)	high (environmental data)
Calibration requirement	low	low	high	high
Required expertise	low	medium	high	high

Management options	medium (categories)	medium-high	no-high	high
Targeted scale	country and larger	field -farm	point/site	point/site
Uncertainty/expected error for field scale	high	medium-high	low	low
Example models	UNFCCC models, Tier 1, Tier 2	Cool Farm Tool, Comet Farm Tool	RothC	EPIC, DAYCENT, DNDC

Biogeochemical models seem to be most suitable for MRV approaches, as they are able to simulate SOC with the highest accuracy and provide additionally information about impacts on yield and GHG emissions (Camino-Serrano et al., 2018, Campbell and Paustian, 2015). However, these models are sometimes impractical, as they require a large amount of data and expert knowledge to use them. Emission factors and simple equations are often used by carbon trading platforms, but these models are developed for large scale (country scale) application and might show large errors on the field scale. Most suitable seems to be decision support tools for carbon accounting, like the Cool Farm Tool (https://coolfarmtool.org/, (Hillier et al., 2011)) or COMET-Farm (http://comet-farm.com/, (Paustian et al., 2017)), as they address or show the potential to address the aforementioned problems of the emission factors and process based models (Whittaker et al., 2013). These tools use different routines of different complexities (Tier 1 to Tier 3, depending on the tool). Unfortunately, the most popular options also show limitations, as the SOC component of the Cool Farm Tool (CFT) uses the Tier 1 approach of the IPCC 2006 guidelines (although this is under review in the moment) and the COMET-Farm Tool uses a Tier 3 approach in combination with a data base that only covers the USA. Further developments of both tools are ongoing, and in the future, these may be reasonable options. Both tools are developed for stakeholders with an easy-to-use interface. The CFT was developed with an interface usable by farmers and the input information they have at hand. The CFT calculates the GHG emissions on a farm level for a specific site and specific management. The methods used within CFT range from emission factors to a model approach considering region specific parameters and farm level data (e.g. management, soil, climate) on an annual basis. Therefore, the CFT can be seen as a Tier2 or simple Tier 3 model. COMET-Farm calculates the carbon footprint of a farm. The tool provides the opportunity to test different management interventions and explore their mitigation potential, i.e. the potential reduction of GHG emissions. GHG estimates for crops are calculated using the DayCent dynamic model (Del Grosso et al., 2010, Parton et al., 1998)– a process-based model - and follows the official USDA GHG inventory guidelines for entity-scale reporting (Eve et al., 2014). Both tools consider soil carbon sequestration and calculate the SOC change for a land use change or change in soil management.

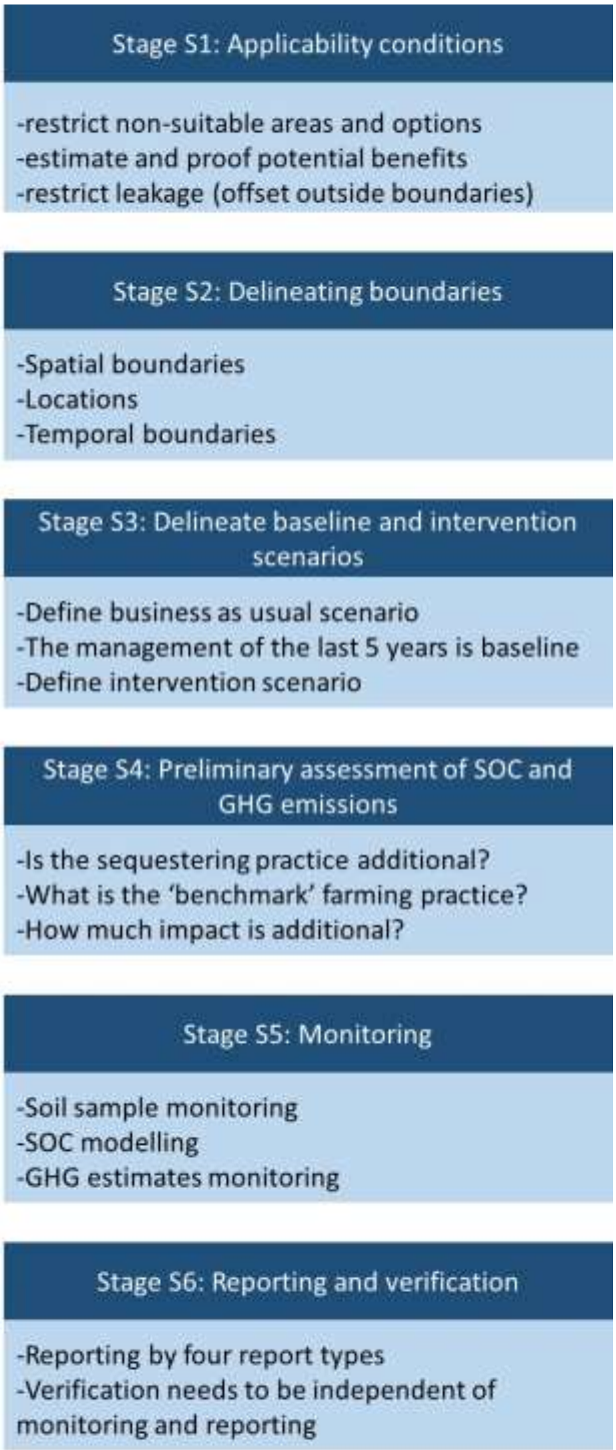

Figure 1: The MRV framework of (FAO, 2020) follows a 6-stage approach to set up a MRV protocol.

3 Existing MRV protocols

FAO (2020) published a protocol that provides concrete guidelines about the structure and steps to apply an MRV application (Figure 1). The FAO protocol differentiates reporting into four different categories: 1) pre-implementation report, 2) initial report, 3) biannual report and 4) final report. These reports describe the different stages of MRV frameworks as outlined in Figure 1. The protocol also provides suggestions and guidelines for the responsibilities for MRV framework. It is suggested that the reporting can be organised by the farmer but needs to be done in consultation with a relevant expert. An independent person or entity must verify the reports. The monitoring and verification require expert knowledge, which can be secured by accreditation of independent experts specialised in these activities and by external expert reviews, respectively. The accreditation and certification can be organised by governmental institutions (e.g. for subsidies), other large organisations (e.g. FAO or entities). Certain specifications are not included (e.g. measurements approaches, suitable models) as the protocol is a blueprint for a global use and might require local adaptation.

In addition to FAO's standardised framework, two other examples of MRV protocols in Alberta, Canada and Australia are already in place. The Government of Alberta published an MRV protocol to quantify impacts of tillage management on GHG emissions and SOC. It differs from the FAO protocol by specifying the target area and the management to be applied, which allows some aspects to be considered in more detail. For example, some reversal events are allowed for natural farms. Conventional tillage is allowed in less than 10% of the farm area for weed control. Another protocol has been published by the Australian Government (Australian Government., 2018), which includes bare land and pastures alongside croplands for baseline conditions. This protocol has a similar structure and content as the FAO framework, but it is more specific on defining in some detail the management options that are allowed but differs in some other details (e.g. review every 5 years).

Carbon accounting platforms have also started to trade carbon based on SOC gains. The good standards of the protocols are undermined by their implementation. One example for the actual protocols is the Verified Carbon Standard (Shoch, Swails et al. 2020). Measurements are very limited (one measurement suggested), SOC changes are quantified by Tier 1 models and the project time is restricted to a short period (e.g. 10 years). The implementation of a simple MRV application by businesses is economically motivated. Even though, there is a demand for cost reduction, the methods applied need to be improved, to provide an adequate data for carbon trading. Nevertheless, improvements in this sector would provide a business solution that will improve mitigation actions once a functional system is established.

4 Outlook of the use of MRV applications

MRV applications are essential to the implementation of strategies to mitigate climate change (Smith, Pete, Soussana et al. 2020). It is also a requirement for subsidies from governmental institutions, carbon trading or for the initiatives of companies with net zero targets (FAO 2020, Kareiva, McNally et al. 2015, Paustian, Collier et al. 2019). In contrast to MRV applications for other processes or variables, monitoring of SOC stock changes has additional challenges; (1) the slow rate of change in soil carbon against the large background stock, (2) the heterogeneous distribution in space and depth, (3) the complexity of measurements and the reversibility of the gains, which make the requirements of MRV complex. MRV protocols overcome these problems by applying a combination of different methods, to compensate for limitations of individual quantification methods. The implementation of MRV applications require an integrated approach but barriers exist. The combined approach can be costly, labour intensive and/or requires a wider skill set (or even expert knowledge). In summary, current MRV methods are often impractical for stakeholders.

In the near future, the challenge for science is to reduce complexity and to remove these barriers in order to provide practical solutions. One relatively easy target could be the development or improvement of models, that are easily applicable by stakeholders, but that provide robust results at the field and farm scale. More challenging and more time intensive will be the further development of remote sensing approaches. Remote sensing will never be able to replace the field measurements, but it will improve the quality of the measurements and might allow for a reduction of the number of samples to save labour time and lower costs.

Other approaches like digital mapping will also contribute to an improved understanding and to quantification of SOC changes. Such developments have the potential to improve the measurements in MRV applications.

The following chapters will further detail some aspects of MRV approaches. Chapter 11 will give an overview on methods for quantifying SOC stocks and characterising its turnover times at the profile scale. Chapter 12 will introduce the digital soil mapping as an additional option to quantify SOC on a farm level (De Gruijter et al., 2015). The chapter will indicate the advantages and limitations of this approach, including the measurement demand and the associated uncertainty. Chapter 13 will give a detailed overview on SOC modelling approaches with special focus on its permanency. Finally, Chapter 14 will outline digital stock taking, with the focus on the field scale. This will include an analysis of knowledge gaps in field-specific digital stock taking and new approaches, such as application of smartphones to quantify SOC stocks. These methods will be discussed in the context of an application in MRV applications, which would bring down measurement costs and potentially improve accuracy.

5 Summary

Sequestering atmospheric carbon through increases SOC stocks requires a functional MRV application to monitor impacts of management practices on the soil. A single quantification approach is not sufficient; instead a combination of different methods is necessary to monitor SOC changes over time and to provide appropriate verification methods. For simplified MRV applications, there is a risk for errors and uncertainty. Developments of the available tools do not all meet the demands for an MRV applications applied for different purposes. There is an imbalance between complexity and accuracy (for modelling) as well as in costs and accuracy (measurements). The chapters in this section describe currently available approaches and future developments that might provide effective solutions to be applied in MRV applications. The approaches presented do not target the implementation in MRV applications, but they are measurement tools, which can be used in MRV applications.

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