DRAFT for Comments: Synthesis Paper on

Holistic Climate Soil Carbon Monitoring Approaches and Potentials

Content

1 Global Frame....1
2 Approaches, challenges and requirements....3
2.1 SOC measurement/ monitoring approaches....4
2.2 Key challenges....5
2.3 Requirements....5
2.3.1 Reliability and scale....5
2.3.2 Practicability....5
2.3.3 Connectability....6
2.3.4 Capacity development....6
3 Key actors working on SOC monitoring....6
4 Case studies....12
5 List of abbreviations....15
6 References....15

This synthesis paper considers the role and importance of soil organic carbon (SOC) monitoring systems in global development agendas, climate finance and voluntary carbon markets. It provides an overview of the different SOC measurement and monitoring approaches, challenges and requirements to consider in the development of sustainable land management actions for SOC protection and sequestration.

1 Global Frame

As the global population continues to grow, so the demand for food production also increases. The interaction between food production (agriculture), climate change and land degradation is getting increasing attention due to the shared challenges and potential solutions to address multiple global priorities. Both climate change and ongoing land degradation limit global food production through rising temperatures, changes in precipitation patterns, extreme climatic events, and decreased productivity of agricultural soils due to land degradation (IPCC, 2019). These challenges especially affect many smallholder farmers in seasonally dry and tropical developing countries who produce a large share of the world's food (FAO, 2020; Thompson and Cohen, 2012). With nearly 1/4 of the world's landscapes already degraded, the ability of soils to provide ecosystem services such as providing the largest terrestrial carbon sink is severely limited (Chotte et al., 2019).

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It has been widely recognized that through sustainable land management (SLM), carbon protection and sequestration in soils can contribute to climate change mitigation through negative and prevented emissions (IPCC, 2014), as well as adaptation by impeding land degradation and providing multiple co-benefits for food security and biodiversity by improving soil health and fertility (FAO, 2020; IPBES, 2018; Sykes et al., 2019).

The Agriculture, Forestry and Other Land Use (AFOLU) sector is one of the biggest emitters of greenhouse gases (GHGs) (Figure 1). Unsustainable land uses contribute 10-12 GtCO2e[1] per year, or nearly 25% of global emissions. About half of this is due to agriculture, which is also the most vulnerable sector to climate change (IPCC, 2019). Yet, the land sector, holds a large mitigation potential (Griscom et al., 2020). The global soil carbon mitigation potential from agricultural soil is estimated to be 2-5 GtCO2eq per year (Fuss et al., 2018; Smith et al., 2019), with sequestration rates due to management practices in agricultural lands estimated in the range of 0.7-2.9 tCO2e per ha per year (FAO, 2020). A large proportion of this SOC sequestration potential lies in developing countries, with the specific magnitude and rate of SOC sequestration per country depending on land use, management practices, soil characteristics, vegetation, topography, climate, historical carbon loss, and more (FAO, 2020; Sanderman et al., 2018; Wiesmeier et al., 2019; Zomer et al., 2017).

During the past five years there has been an increase in the development of an enabling political-instrumental environment that would support the adoption of SLM practices that support SOC protection and sequestration. From a climate change perspective, this is illustrated through the Paris Agreement (United Nations, 2015), the Koronivia Joint Work on Agriculture (UNFCCC, 2018), and the Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate and Land (IPCC, 2019) under the UNFCCC[2]. In terms of land degradation, the UNCCD[3] has set Land Degradation Neutrality (LDN) by 2030 as its main target. LDN is also the goal of Sustainable Development Goal (SDG) 15.3 with its indicator 15.3.1 ("proportion of land that is degraded over total land area") which consists of three sub-indicators and metrics[4] that includes SOC (Orr et al., 2017).

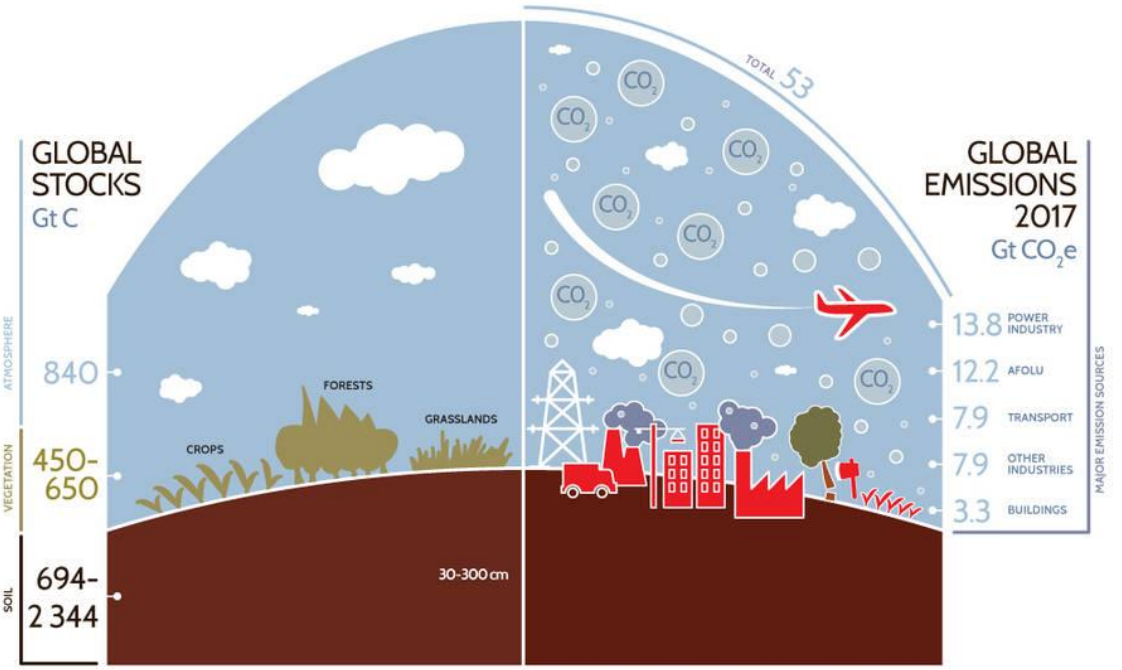

Figure 1. Global carbon stocks and global emissions. Gt = gigatonne = 1015 g C = 1 petagram = billion tonnes. 1 Gt = 3.664 Gt CO2
Source: (FAO, 2019)

[1] 1 GtCO2e = 1 000 000 000 tCO2e (metric tons carbon dioxide equivalent)

[2] UNFCCC = United Nations Framework Convention on Climate Change

[3] United Nations Convention to Combat Desertification

[4] The three sub-indicators (and associated metrics) for SDG indicator 15.3.1 are: land cover (land cover change), land productivity

Through these global conventions and mechanisms, countries have set national targets to prevent or reduce GHG emissions (through Nationally Determined Contributions to the Paris Agreement) and reduce land degradation by implementing SLM and enhancing SOC sequestration (through national LDN target setting). For example, SOC protecting or sequestering activities, policies and targets related to agriculture were included in 28 first Nationally Determined Contributions (NDCs). Three of these 28 NDCs include quantified targets specifically for SOC (Wiese-Rozanova et al., 2020). As a result, countries are required to monitor and report on SOC stocks and stock changes to track and report on progress in achieving their set targets.

The [4 per 1000 Initiative](), founded alongside the Paris Agreement in 2015, aims to increase SOC sequestration through the implementation of agricultural practices adapted to local environmental, social and economic conditions. Specifically, the initiative focuses on encouraging the transition towards agriculture that is productive, highly resilient, based on appropriate land and soil management, creating jobs and income, and therefore supporting sustainable development.

International interest in improved monitoring and reporting of SOC stocks and stock changes has been growing in relation to improved land management to increase SOC content to enhance climate change resilience and underpin food security (Smith et al., 2020). This growing interest has also increased the urgency for credible and reliable SOC monitoring systems (FAO, 2020; Smith et al., 2020) for purposes such as national reporting, to visualize the development of land degradation and evaluate the efficiency of SLM actions, and reduce the risk of investments through climate finance which can be used to overcome investment barriers in SLM (Chotte et al., 2019; FAO, 2020; Smith et al., 2020; Vågen et al., 2018). Climate finance, in the form of funds or through carbon markets, must be justified by demonstrated effects on GHG emissions and/or adaptation to climate change, benefit-sharing with communities, as well as various co-benefits related to biodiversity and more (Unger and Emmer, 2018).

Thus, comprehensive SOC monitoring systems are crucial to track worldwide SOC protection and sequestration in relation to climate change resilience and food security. However, efficient SOC monitoring systems are complex and a diversity of approaches exist.

(land productivity dynamics), and carbon stocks (soil organic carbon stocks)

In the following sections, this paper provides further information on the requirements of climate soil carbon

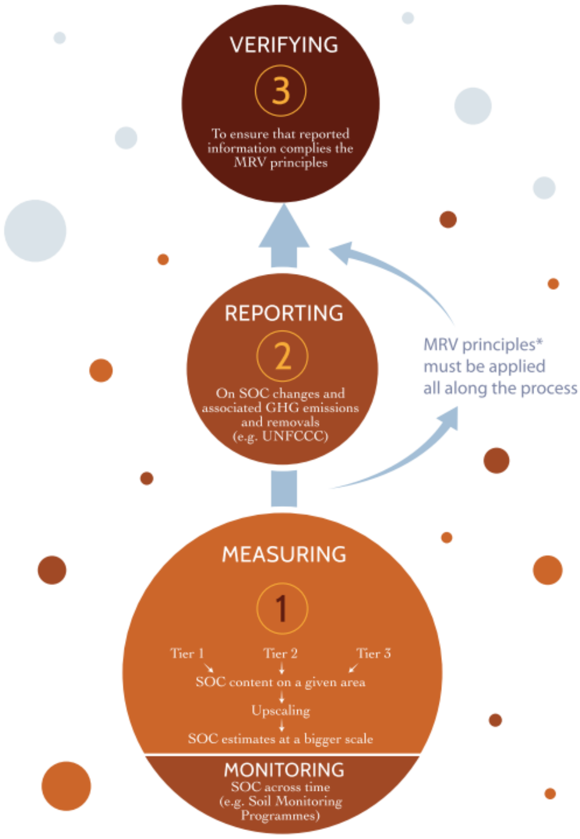

Figure 2. Summary of the SOC Measurement, Reporting and Verification (MRV) Framework. Source: (FAO, 2017)

monitoring, along with insights into existing monitoring approaches, links to more detailed information, and selected case studies.

2 Approaches, challenges and requirements

Under the UNFCCC, countries are required to monitor and report data on emissions, mitigation commitments and related actions and to do so using a measurement, reporting and verification (MRV) framework. Essentially, MRV refers to processes whereby information is provided, examined and assessed to see whether parties meet their obligations. The process includes direct measurement or estimated calculations (M) of emissions and emission reductions, reporting (R) the measurement results through relevant documentation, and verifying (V) the quality of the data and estimates through specific procedures or expert reviews (Figure 2) (MRV Platform for Agriculture, 2020; UNFCCC, 2014). Countries may also develop or have national MRV systems in place to support national tracking of progress towards climate-resilient and lower-carbon economies. With increased opportunity to include SOC in voluntary carbon markets (VCM), MRV has become a critical tool to assess and verify changes in SOC resulting from project implementation, and efforts to curb the barriers to their adoption are underway.

Monitoring and Evaluation (M&E) systems are used by governments, international organizations, NGOs and other project implementing agencies for their own tracking and policy purposes. These M&E systems include project-based M&E systems, as well as sectoral M&E systems that government agencies use to track the progress and outcomes of national plans and programs, including national land management, agriculture and other plans that promote SLM. As highlighted through recent developments by FAO (FAO, 2020) including SOC MRV in SLM projects is essential as a tool to support adaptive management, build confidence for investments in activities that improve soil health, as well as track and account for impacts resulting from such activities that would drive subsequent investment to enhance the further adoption of SLM practices.

Together with national statistical systems, sectoral M&E systems often provide the data and assessments used to measure and report progress on mitigation and adaptation at national and international levels. International, domestic and project monitoring, evaluation and reporting processes are distinct but closely related and should ideally be integrated to ensure the all levels benefits from data generation.

The following sections provide a synopsis of the main SOC monitoring approaches, as well as important requirements for effective SOC monitoring.

2.1 SOC measurement/ monitoring approaches

Various tools and methodologies for GHG assessments exist, but in the past, many of them excluded SOC stocks and land use change (Colomb et al., 2013). Traditional measurement of SOC content can be expensive and labour intensive, which presents a key barrier to implementing programs to increase SOC at large scale and track the impact of implementation on SOC stocks (Smith et al., 2020). Due to the high cost of direct SOC measurement and the complex nature of SOC stock changes resulting from specific management practices such as SLM, there is still a critical need for standardized, robust, reliable, cost-effective and easily applicable MRV platforms applicable to different agricultural systems to assess SOC stocks and stock changes (FAO, 2020).

Credible and reliable SOC MRV platforms are required for national monitoring and reporting, as well as for emissions trading to reduce the risk of investments related to SOC (Smith et al., 2020), however few governments or projects have adopted their use. From a climate finance and VCM perspective, donors and buyers of carbon credits require reliable proof that the required amount of carbon offsets have occurred (CFI, 2020). Such proof is essential to minimize investment risk, as well as reputational risk through the ability to show a carbon footprint with quality offsets and avoiding external criticism and concern about activities they are involved in while delivering the required amount of offset.

For SOC monitoring results to be reliable, it needs to effectively demonstrate that the adopted management practices in a specific area or project are resulting in the preservation of SOC stocks or SOC sequestration over the medium term as compared to an initial or baseline scenario. This requires the accurate and repeated measurement of SOC stock to determine the baseline content and track stock changes over time (FAO, 2020).

SOC measurement can be done directly by taking and analyzing representative soil samples, or indirectly using activity-based models or remote-sensing based models. (FAO, 2020; Smith et al., 2020). However, indirect approaches still require direct SOC measurement to calibrate and determine the accuracy of the respective methods. Table 1 summarizes the main characteristics, advantages and challenges associated with approaches using direct measurement, activity-based models, and remote-sensing based models. Table 2 highlights some examples of these approaches and their key characteristics.

More information

More detailed information on MRV for SOC change to realize SOC sequestration potential is available in a recent review by Smith et al. (2020). The review includes information on a wider set of models available, as well as on novel indirect methods of measuring changes in SOC not discussed in this paper. The novel methods involve inferring SOC stock changes from flux measurements, as well as spectral methods for measuring SOC stocks in the field and in the laboratory.

Chotte et al. (2019) provide a comparison of six tools for SOC assessment and monitoring.

For detailed reviews of remote sensing techniques for SOC estimation, refer to Angelopoulou et al. (2019) and Croft et al. (2012).

2.2 Key challenges

The design and implementation of SOC monitoring systems is complex and pose several scientific, technical and operational challenges at various levels (Smith et al., 2020; Wiese-Rozanova et al., 2020) as follows:

- Potentially high initialization costs associated with the development and implementation of integrated SOC monitoring systems and associated networks
- Insufficient access to appropriate measuring and monitoring technologies
- High costs of direct SOC measurement and insufficient activity data to apply accurate modelling of SOC stocks
- Insufficient accuracy, affordability and data availability for MRV and monitoring changes in SOC, especially at smallholder farmer level
- Difficulty to infer changes in SOC stocks based on the implementation of management practices
- Practices that are good for SOC sequestration may not be considered economically viable by land users, leading to low adoption
- Insufficient ability to track implementation of specific SLM practices and changes in those practices
- Increases in SOC are slow and potentially small compared to the baseline which makes it difficult to detect changes in SOC stocks
- Insufficient capacities to collect relevant data and monitor country- or project-specific emission factors and SOC changes
- The more complex the monitoring system, the more capacity development is required to apply it efficiently

2.3 Requirements

Considering the challenges associated with SOC monitoring, several requirements need to be considered when selecting, developing, or customizing an appropriate SOC monitoring system.

2.3.1 Reliability and scale

SOC stocks at any given time is influenced by a number of factors including land use and management activities, soil characteristics, climate, topography, vegetation, and other soil forming factors and processes. Increases in SOC generally occur over many years, and it is often difficult to identify small changes in SOC stocks. Therefore, a larger change in total SOC stock, which may take several years or longer to occur, is required before a significant change could be measured with any degree of confidence (FAO, 2020; Smith et al., 2020). To be reliable, SOC monitoring protocols therefore need to be designed to detect changes in SOC over relevant spatial and temporal scales, with adequate precision and statistical power (Smith et al., 2020).

Related to reliability of SOC monitoring is the required spatial scale at which SOC monitoring takes place (i.e. national, regional, local, or field scale), which impacts the data required to accurately quantify SOC stocks and stock changes. As a result, the SOC monitoring approach would differ when applied for national inventories compared to project monitoring, for example. Particularly at field-to-local scale there are significant challenges related to the potentially high variability in SOC stocks within a field which requires intensive sampling for accurate assessment. At regional or national level, the approach tends to be more aggregated based on potentially larger datasets which improves confidence in SOC estimates (Smith et al., 2020).

2.3.2 Practicability

A particular SOC monitoring approach must be feasible to apply in practice which requires (Mäkipää et al., 2012; Smith et al., 2020):

- **Suitability**: A particular SOC monitoring system should be suitable for the particular purpose and scale at which it is to be applied in order to capture the complexity in SOC stocks and stock changes at relevant scales. In other words, it needs to account for the factors affecting SOC and changes in SOC stocks in the particular context. In order to optimize SOC monitoring for a specific purpose (i.e. a SOC project), a combination of approaches may be considered and combined to yield optimal information and results.
- **Data/information availability:** The required data and input information for a specific approach should be available, substitutable using default values or estimates from literature, or possible to generate as part of the SOC monitoring process. Where feasible, the collection of data as part of the SOC monitoring process would be ideal to support the development of robust models or improve the robustness and accuracy of existing models. Furthermore, making

newly collected data openly available (open source) would improve the availability of common variables measured for cross-site comparisons and global analysis (see also Section 2.3.3 Connectability).

- **Cost efficiency:** The costs associated with collecting, processing and storing soil samples, as well as analysing relevant soil properties such as C content, bulk density and stone content is generally considered labour- and cost-intensive, and should be factored into the sampling design (Smith et al., 2020). Direct SOC measurement should therefore be used strategically whenever possible to determine a quality baseline and provide local data to calibrate any indirect approaches used.

2.3.3 Connectability

It is important for a SOC monitoring system process to link with other available institutional data collections and platforms. This is important to share data across locations and practices, enable the use of data for reporting at different scales and purposes, and to improve provide additional data for the continuous improvement of calculations and models at various scales.

2.3.4 Capacity development

Sufficient national and local capacities will be required to select, design, or modify and implement a SOC monitoring system. Available capacities need to be considered and relevant capacity development included in the implementation process to support efficient SOC monitoring.

3 Key actors working on SOC monitoring

With the high global interest and demand for reliable, practical and cost-effective SOC monitoring systems, the various actors working on the development and improvement of such monitoring systems are too many to mention. Some of the key global actors involved in driving the development of SOC monitoring systems are highlighted here.

The United Nations Framework Convention on Climate Change **(UNFCCC)** is providing ongoing transparency-related technical support to developing countries through its Consultative Group of Experts. Information on the arrangements for transparency of climate action is provided in a series of videos and training reference materials:

- Series of four informative videos explaining how countries can transparently communicate climate actions
- Technical handbook for developing country Parties on Preparing for implementation of the enhanced transparency framework under the Paris Agreement
- Handbook on institutional arrangements to support MRV/transparency of climate action and support
- Handbook on Measurement, reporting and verification for developing country Parties

The Food and Agriculture Organization of the United Nations **(FAO)** developed the Ex-Ante Carbon-balance Tool (EX-ACT) as an appraisal system providing estimates of the impact of agriculture and forestry development projects, programs and policies on the carbon-balance. Under the FAO, the Global Soil Partnership (**GSP**) launched its RECSOIL – Recarbonization of Global Soils initiative. RECSOIL provides a set of tools to offset GHG emissions to decarbonize the economy based on the implementation of SOC-centered sustainable soil (land) management practices on a large scale. The GSOC MRV Protocol was released in September 2020 as part of the RECSOIL toolbox to provide a framework for SOC MRV. Through its Global Soil Laboratory Network, the GSP has launched an initiative on soil spectroscopy to address constraints that prevent the wider uptake of spectral technology in soil analysis, mapping and monitoring.

The CGIAR Research Program on Climate Change, Agriculture and Food Security (**CCAFS**) Low Emissions Development Flagship aims to reduce GHG emissions and increase carbon sequestration in the agriculture sector. Research focuses on:

  - Quantifying GHG emissions from smallholder systems
  - Identifying priorities and options for low-emissions development
  - Policy, incentives and finance for scaling up low emissions practices

Table 1. Summary of SOC measurement approaches, advantages and disadvantages (Angelopoulou et al., 2019; Croft et al., 2012; Mäkipää et al., 2012; Smith et al., 2020)).

	Direct measurement	Activity-based models	Remote sensing (RS) based models
Description	• Physical soil sampling for laboratory analysis • Essential analyses: organic carbon (using dry combustion or Walkley-Black methods), bulk density, stone content • Useful analyses: soil texture, inorganic carbon • Need robust study design and clear sampling protocols that account for spatial variability in SOC • Requires resampling to track changes in SOC stocks	• SOC is represented using 2-5 carbon pools that differ in carbon residence time • Residence times are controlled by decay rate of carbon in the different pools • Data used: field areas, crops grown, crop yields of last agricultural season, types of SALM practices implemented, quantity of agricultural inputs by type, crop productivity, amount of crop residues and residue management, soil texture and clay percentage, information on livestock to calculate manure input (number of cattle, sheep, etc.), depending on the specific model. • Mathematical formulations are applied to model SOC based on the input data	• Remote sensing data generated from satellites, aircraft, or Unmanned Aerial Systems • Soil spectral signatures are defined by the reflectance of electromagnetic radiation by chemical substances as a function of wavelength • Soil reflectance varies according to chemical factors, such as soil mineralogy, soil organic matter content and soil moisture, and physical structure, such as surface roughness and particle size • Requires field data with geo-referenced soil samples to build robust models with remote sensing data to generate predictive maps • Machine learning applied to predict soil properties from spectral data, libraries, and laboratory measurements based on collected data
Advantages	• Relative accuracy • Direct measurement of SOC - no proxies needed • Provides calibration data for indirect measurement approaches • Sampling design and soil measurements can be coordinated with national inventories • Existing well-established statistical procedures to estimate uncertainties • Trend estimates can be verified with model-based estimates • Other soil properties can also be determined from collected samples	• Makes use of measurements taken elsewhere • Increased measurements and further development continuously improve the system • Application in one country benefits from all previous system developments in other countries • Possibility to improve the model using direct measurements • Less expensive than soil sampling and remote sensing • Allows a tiered approach if limited data is available	• Non-destructive method to collect information about soil properties • Provided data covers large geographical areas and multiple scales • Can provide information in otherwise inaccessible areas • Help to reduce the need for direct soil sampling, though models are based on field data • SOC predictions can be continuously improved by using ancillary data, scale-specific methods, improved development of spectral libraries and better integration of RS technologies into empirical and simulation SOC models, etc. • Can use a variety of RS data to monitor spatio-temporal SOC dynamics

<table>
<tr><td></td><td></td><td></td><td>• Can apply direct measurement of SOC using reflectance from the bare soil surface, or indirectly by linking RS images with field data (requires large datasets)</td></tr>
<tr><td>Disadvantages</td><td>• Measurements are often conducted in top 30cm to save cost and labour, but SOC sequestration often occurs deeper
• Laborious and expensive to collect, process, store and analyze soil samples
• Requires repeated sampling and repeated costs
• Destructive sampling method
• Usually requires high number of samples to account for spatial variability at local scale, especially if a direct measurement approach is applied alone
• Resulting information is not spatially continuous and requires interpolation</td><td>• Activity-based data still missing or insufficient
• Data is needed to calibrate estimates across different landscapes
• Soil processes are not linear and often go beyond project duration which limits reliability of estimates
• Many models calibrated for temperate ecosystems and not as robust for tropical ecosystems with weathered soils
• Lack of long-term datasets to text model performance
• Estimation of plant input based on allometric relationships leads to large uncertainties
•</td><td>• Restricted sensing in wet tropical areas due to high cloud coverage
• RS techniques have low signal to noise ratio, low spectral resolution, and are subject to geometric and atmospheric distortions
• RS using direct measurement of SOC from bare soil is limited to the first few centimeters of topsoil
• Ongoing research is addressing modeling approaches that consider the partly complex data processing steps from RS spectrometric data and proximal soil sensing data with the influence of in situ disturbance variables
• SOC signal can be masked by other biochemical components e.g. iron and manganese, increasing the need for large datasets</td></tr>
<tr><td rowspan="2">Considerations</td><td>• Evaluate direct measurement costs against the value of SOC sequestered and search for trade-offs and alternative SOC estimation methods</td><td>• Information on land use history can improve estimates
• Need to measure the amounts of biomass entering and getting off the field to improve SOC estimates</td><td>• Data that can be generated includes cover crop presence and patterns, tillage, residue coverage, crop type, flooding, etc. which could eventually provide additional information to feed into activity-based models</td></tr>
<tr><td colspan="3">• Use a combination of direct measurements (at the plot scale), activity tracking, modeling and remote sensing (at larger spatial scales) for the most cost-effective and reliable estimates.</td></tr>
</table>

Table 2. Examples of approaches to monitor SOC and their main characteristics

Example	Description	Data and specificity
	Activity-based models	
Ex-Ante Carbon-balance Tool (EX-ACT)	• Free appraisal system developed by FAO providing estimates of the impact of agriculture and forestry development projects, programs and policies on the carbon-balance • Land-based accounting system – relates activity data to estimated values of the five carbon pools, including SOC • **Ex ante model** that **predicts future C stock changes** based on planned management activities • Estimates C stock changes (i.e. emissions or sinks of CO_2) as well as GHG emissions per unit of land, expressed in tCO2eq/ha/yr • Helps project designers to estimate and prioritize project activities with high benefits in economic and climate change mitigation terms • Provides eight modules (Microsoft Excel sheets) for different AFOLU activity areas • Modules for SLM: Crop production and management, Grassland and livestock • Information is entered based on changes occurring *With Project vis a vis Without Project* situation – i.e. compares impacts of a planned intervention to the business-as-usual scenario • Can accommodate two levels of data specificity using a tiered approach	**Tier 1 data**: – uses IPCC recognized default values for emission factors and carbon values – includes data on wide range of land-use change activities and agricultural management practices with relatively few geographical, climatic and agro-ecological variables – **low specificity** – easiest to procure for project managers as part of standard information available in project appraisal documents **Tier 2 data:** – more complex than Tier 1 – allows for location-specific variables that provide specific carbon content and stock changes for all five carbon pools and emission factors for selected practices – example variables: SOC content, rates of SOC sequestration per land use, crop residue management, N2O and CH4 emissions from manure management, etc. – data can be difficult and expensive to collect, so it is strongly advised for core project components providing stronger GHG sources or sinks – **higher specificity** that Tier 1 with increase in location-specific data
Rothamstead carbon model (RothC)	• The only SOC monitoring system applicable in the Voluntary Carbon Standard for Sustainable Agricultural Land Management (SALM) Carbon Accounting Methodology • Freely available model developed by Rothamstead Research • Models medium to long-term turnover of organic carbon in non-waterlogged topsoil, allowing for effects of soil type, temperature, moisture content, and plant cover • Uses monthly time step to calculate total organic carbon (t/ha), microbial biomass carbon (t/ha) and changes in ^{14}C on a years to centuries timescale	**Required data:** – Monthly rainfall (mm) – Monthly open pan evaporation (mm) – Average monthly mean air temperature (^{o}C) – Clay content of the soil (as a %) – Estimate of decomposability of incoming plant material (DMP/RPM ratio) – Soil cover – is the soil bare or vegetated in a particular month? – Monthly input of plant residues (tC/ha) – Monthly input from farmyard manure (FYM) (tC/ha) if any

	• Runs in two models: "forward" using known inputs to calculate changes in SOM and "inverse" which calculated inputs from known changes in SOM • **Ex-post model** that **models C stocks after implementation** of management activities	– Depth of soil layer sampled (cm) **Higher specificity** based on localized data **Specificity may be affected** if some parameters need to be substituted from external sources e.g.: – If soil clay content is derived from literature rather than direct measurement or site-specific data – Substituting monthly open pan evaporation with potential evaporation values from literature
Combination of direct measurement and activity-based model		
GSOC MRV Protocol	• Develop by FAO to provide a framework and standard methodologies for the measuring, monitoring, reporting and verification of changes in SOC stocks and GHG emission removals • Mainly designed for application in agricultural projects that implement sustainable soil (land) management practices at the farm level • Places farmers at the center of the process as key actors for SOC sequestration and GHG mitigation • Applicable to different agricultural lands, including annual and perennial crops (food, fiber, forage and bioenergy crops), paddy rice, grazing lands with livestock including pastures, grasslands, rangelands, shrublands, silvopasture and agroforestry. • Protocol consists of a series of six (step-by-step) stages and sub-protocols • Soil sampling, SOC modeling and GHG emission estimations conducted in year 0 and then bi-annually over an 8-year period • Protocol includes the periodic soil monitoring of labile particulate organic carbon (POC) with higher turnover rates and higher sensitivity to management practices than total SOC	**Soil sampling:** – Mandatory for baseline: complete sampling round (0-10 cm and 10-30 cm depths, optative up to 1 m depth) for SOC, bulk density – Optative every two years: (0-10 cm) for POC – Mandatory every four years: complete sampling round as for baseline – Soil sampling sub-protocol provided **Laboratory determinations:** – Protocol applies for SOC determined using Dumas dry combustion method (preferred option when possible) or Walkley and Black method – POM determination adapted from Cambardella and Elliot (1993) – Spectroscopic techniques for SOC determination may be used when technical capacities for adequate chemometric calibration are available **SOC modeling monitoring** – Model simulations of SOC stocks for a 20-year period performed for baseline and every two years – Protocol does not prescribe a specific SOC model to be applied, but requires the same model to be used for all stages of the MRV protocol – Sub-protocol for RothC model provided as an example – Model simulation results used to estimate relative SOC sequestration rates per unit area for each intervention area **GHG emissions estimation monitoring** – Annual agricultural key GHG emissions estimated for a 20-year period for baseline and every two years

		– Every four years: Current and projected total GHG emissions for BAU and IS – Sub-protocol for GHG emissions estimation tools provided
Remote-sensing based model		

Land Degradation Surveillance Framework (LDSF)	• Developed by World Agroforestry Centre (ICRAF) to assess soil and land health using indicators and field protocols
	• Indicators: vegetation cover and structure; tree, shrub and grass species diversity; current and historic land use; infiltration capacity; soil characteristics; land degradation status
	• Able to monitor SOC changes over a time
	• Data collected at multiple spatial scales to understand indicator variation across landscapes:
	  – Random sites (10 x 10 km) across region/ watershed/ project area
	    - Random clusters 16 (1 km^2) per site
	      - 10 plots (1000 m^2) per cluster
	        - 4 sub-plots (100 m^2) per plot
	• Indicators within the framework are mapped independently, but are related and relations can be modelled
	• Evidence is generated through systematic on the ground data collection, citizen science to crowd source data from apps and models to produce data and maps
	• Uses Open Data Kit for GPS field data collection
	• LDSF forms part of Ecosystem Health Surveillance System (EcoHSS) which uses open source tools to apply statistical modeling and machine learning to assess processes of land degradation, soil functional properties, vegetation cover and biodiversity based on earth observation data and remote sensing
	• Sensors are available at 10 m (Sentinel 2) and 30 m (Landsat) spatial resolution, making it suitable for a smallholder farming context
	• Outputs mapped at fine resolution (5–10 m), high resolution (20-30 m) and moderate resolution (250-500 m)
		Plot-level data collection:
		– Basic site characteristics described and recorded (altitude, slope, landform, presence/absence of soil and water conservation structures, vegetation cover and strata, land use, etc.)
		– Minimum 3 soil infiltration measurements per cluster
		Sub-plot-level data collection:
		– Soil surface characterization:
		  o signs of visible erosion recorded and classified; percentage rock/stone/gravel cover on soil surface recorded)
		– Vegetation measurements:
		  o (woody- and herbaceous cover ratings; woody plants, shrubs and trees counted, tree and shrub distance-based measurements taken)
		– Soil sampling:
		  o Top- and subsoil samples collected at 0-20 cm and 20-50 cm using soil auger
		  o Samples pooled into 1 sample per layer per plot
		  o Auger depth restrictions (cm) recorded at each sub-plot if present
		  o Cumulative soil mass samples collected at each center subplot (0-20, 20-50, 50-80, 80-110 cm) for soil mass and SOC stock calculations
		Earth observation data:
		– Obtained from Copernicus and NASA
		– Sensors include Sentinels 1 and 2, Landsat and MODIS

4 Case studies

Farmer-based monitoring systems in the Kenya Agricultural Carbon Project

The Kenya Agricultural Carbon Project (KACP) (Vi Agroforestry, 2020, 2019) was initiated in 2008, and in 2009 became the first project to receive carbon credits issued under the sustainable agricultural land management (SALM) carbon accounting methodology, certified under the Verified Carbon Standard (VCS). Vi Agroforestry, a non-governmental organization, implemented the project with ca. 30,000 smallholder farmers organized in 1,700 registered farmer groups[5] on 22,000 ha. Based on the evaluated project successes, Vi Agroforestry scaled the project and included a dairy component with private investors. KACP provided advisory services to support farmers to adopt SLM practices, market crop produce, and manage savings and loan schemes, and also provides additional capacity building on family planning, HIV prevention, child nutrition, and other issues. SLM practices promoted by KACP included manure management, use of cover crops, composting and agroforestry. Carbon payments were one innovative element of the project. In the first ten years of the project, the average farmer sequestered about a total of 3 tCO_2 per hectare per year in the form of SOC and tree biomass. The carbon revenues were shared among farmer groups (60%) and used for advisory services provided by Vi Agroforestry (35%). 5% of the revenues were used for administrative cost selling the credits. Carbon credit revenues covered only ca. 20% of the project costs. The monitoring costs were US$1.4/ha/year. However, the most important benefit for farmers was the increase in crop yields due to the combination of project interventions. Average maize yields more than tripled from 1500 kg/ha in 2009 to more than 7,400 kg/ha in 2017. Progress in the adoption of SLM measures and the resulting GHG emission reductions were tracked through an activity-based monitoring system. KACP monitored adoption of SLM practices, and a science based biophysical (activity-based) model (RothC) was used to estimate the effects of SLM practices on SOC stocks and GHG emissions. Supported by farmer group leaders, farmers self-reported using a simple template for their agricultural crops and activities, along with land area, yield and specific SLM practices implemented. Farmer group leaders collated the data from their members and produced a group summary that was sent to the project team via SMS. This provided the input data for estimation of carbon benefits, as well as data on adoption rates and proxy indicators of food security and other socio-economic benefits. The monitoring system was also used by farmer groups to identify training needs and priorities for advisory support. Activity monitoring engaged farmers, provided crucial information to improve extension and supported self-learning by farmer groups, strengthening the commitment of farmers to the adoption of SLM activities and farmer groups' capacities. Several indicators monitored in the KACP are relevant to adaptation and food security outcomes, such as numbers of beneficiaries (by gender) and crop yields. However, since funding for the KACP did not explicitly target adaptation finance, the project had no separate adaptation reporting. During the scaling up of the KACP by Vi Agroforestry in another location, a tool based on the Revised Universal Soil Loss Equation was specially designed to use the activity data collected to estimate the benefits of SLM practices for soil and water conservation.

Spatial assessments of soil organic carbon for stakeholder decision-making- a case study from Kenya

(Vågen et al., 2018)

This case study shows the incorporation of a soil organic carbon (SOC) spatial assessment and socioeconomic data to develop an online platform, the Resilience and Diagnostic and Decision Support Tool (RDDST), which facilitates evidence-based decision making in Turkana County, Kenya. Importantly, this study points to the usefulness of SOC spatial assessments in monitoring the status of land degradation neutrality (LDN) compliance and examining how SOC dynamics can be included in decision-making.

Land degradation in Kenya costs approximately USD 1.5 Billion annually, which is close to 5% of its GDP (Munoz, 2016). Turkana County is located within the Arid and Semi-Arid Lands (ASALS) of Kenya, inhabited by about 1 million people, mostly pastoralists, and receives 250 mm of precipitation annually. Developing assessment tools for soil and land degradation is of critical importance, especially since Kenya is currently

[5] Project development was initially supported, and the carbon credits purchased by the World Bank BioCarbon Fund (BCF) and the Swedish International Development Agency (SIDA). The Livelihoods Funds and Brookside Dairy financed the scaling up.

debating baseline assessments and monitoring of the Sustainable Development Goal (SDG) 15.3 targets.

Using the Land Degradation Surveillance Framework (LDSF), key indicators of land degradation risk, including soil organic carbon (SOC), soil erosion and others were assessed based on data from several LDSF sites conducted in the tropics. The LDSF evaluates ecological indicators at four spatial scales ($100\ m^2$, $1000\ m^2$, $1\ km^2$ and $100\ km^2$) in parallel utilizing a stratified randomized sampling design. To examine SOC and other soil indicators, LDSF employs soil infrared (IR) spectroscopic analysis, which are budget-friendly and enable scaling up. Using 10 000 georeferenced archived LDSF plots and soil samples examined for SOC at the ICRAF Soil and Plant Diagnostics Lab in Nairobi, Kenya, the SOC spatial assessments were created. This assessment is used to detect temporal changes and setting up a land and soil health monitoring schemes, which enables proactive actions that can hinder land degradation or restore degraded ecosystems (Vågen et al., 2016; Winowiecki et al., 2018). Based on the data gathered and analytical framework, an online platform was created, using the Shiny web framework for R statistics, that generates interactive graphs and data management tools to engage with stakeholders and inform country-level and global decision-making processes.

Stakeholder engagement is a critical step towards effective and accelerated implementation of the 2030 agenda. As a response, a Stakeholder Approach to Risk Informed and Evidence Based Decision Making (SHARED) was developed to incorporate land assessments within the larger decision-making context in collaboration with stakeholders in Turkana County. Using evidence-based frameworks and scientific tools customized for decision needs enables a comprehensive inter-sectoral and inter-institutional approach that recognizes the complexity of decision-making processes.

The findings estimated Kenyan SOC stocks to be about 42 Mg Carbon (C) ha^{-1} stored in the upper 30 cm segment of soil. Arid and semi-arid areas, like Turkana County, had the lowest SOC stocks (an average of $<20\ Mg\ C\ ha^{-1}$), whereas higher amounts were found in the sub-humid and humid (see Figure 3). SOC concentration also followed similar trends with higher concentrations in humid and sub-humid areas as opposed to drylands. As would be expected, the

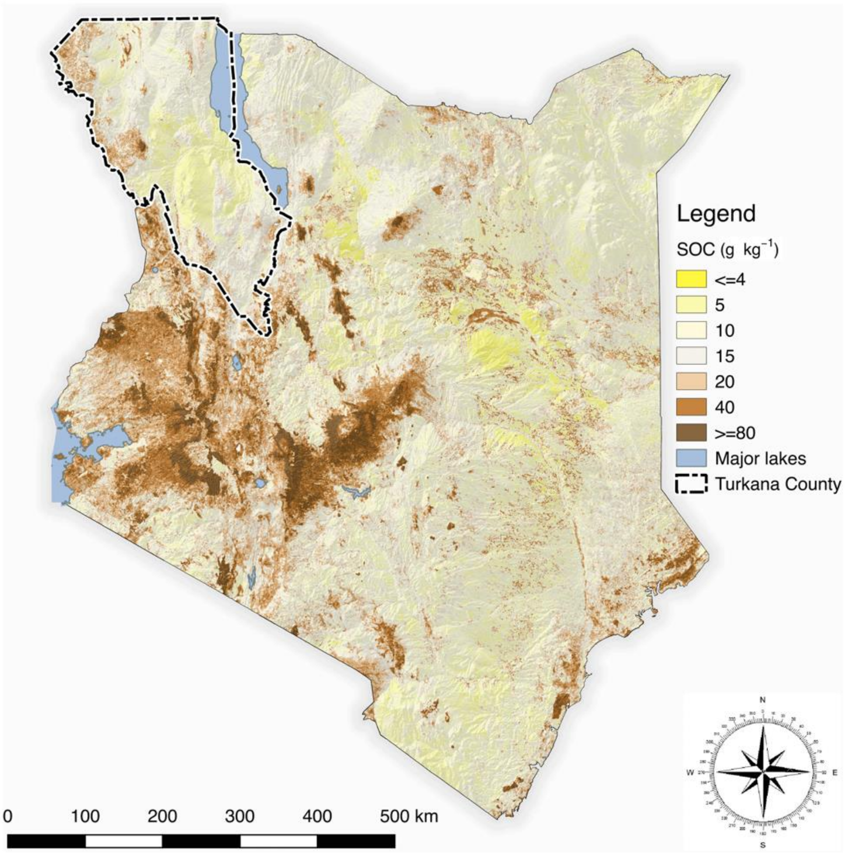

Figure 3: Soil Organic Carbon (SOC) map of Kenya with Turkana County outlined. (Vågen, T.-G., Winowiecki, L. A., Neely, C., Chesterman, S., & Bourne, M. (2018). Spatial assessments of soil organic carbon for stakeholder decision-making. A case study from Kenya. SOIL Discussions, (January), 1–14. https://www.soil-journal.net/4/259/2018/soil-4-259-2018.html)

highest SOC stocks exist in forest areas, such as around Mt. Kenya (>100 Mg C ha^{-1}) and others (the Aberdares, the Mau Forest Complex and Kakamega Forest). Although forest areas are only a small percentage of the total lands in Kenya, they are important carbon pools. Wetlands, such as Rift Valley lakes and lacustrine on the Kenyan coast, are another key carbon pool that store between 80 and 100 Mg C ha−1 at 0 to 30 cm depth, and offer other valuable ecosystems services critical for Kenyan land health and livelihoods (Minasny et al., 2017; Saunders et al., 2007; Zedler and Kercher, 2005).

However, despite drylands having low SOC stocks, pockets with high SOC are exist in some areas including the Matthews Range, Ndoto, Marsabit and Kulal mountain, and the Loima Hills in Turkana County (Figure 3**Error! Reference source not found.**). Thus, S OC pockets are critical resources for pastoralists, especially for grazing during dry seasons (Oba et al., 2000), in addition to being biodiversity hotspots.

The RDDST tool was generated during several workshops guided through the SHARED mechanism with the participation of representatives from Turkana County government, the United Nations, and non-government organizations (NGOs). To examine resilience within Turkana County, SOC maps were integrated in the RDDST tool using data from multiple sectors including education, health, security, and environment (Figure 4**Error! Reference source not found.**). Importantly, takeaways and recommendations from these workshops and the RDDST tool were used to the Turkana County Integrated Development Plan (CIDP) for the period 2018 to 2022. Furthermore, visualizing different land health indicators, such as vegetation cover an SOC stock, in parallel with other sectoral data resulted in a paradigm shift in decision-making that enabled identifying integrated county-integrated flagships that tackle land management and restoration while also addressing social and economic sectors.

As evident from this study, spatial assessments of SOC concentration and stocks, in addition to other land and soil health indicators, are integrated into interactive dashboards that allow diverse users to consider land health indicators when identifying interventions. This also helps bring the importance of robust monitoring tools, including assessments of SOC to the forefront of decision and policy makers. Additionally, the SHARED process underpinning the development of the RDDST was strengthened through organized stakeholder participation and shared learning and designing of the tools. Finally, this process proved instrumental in encouraging the uptake of land restoration interventions as well as those that increase SOC, all of

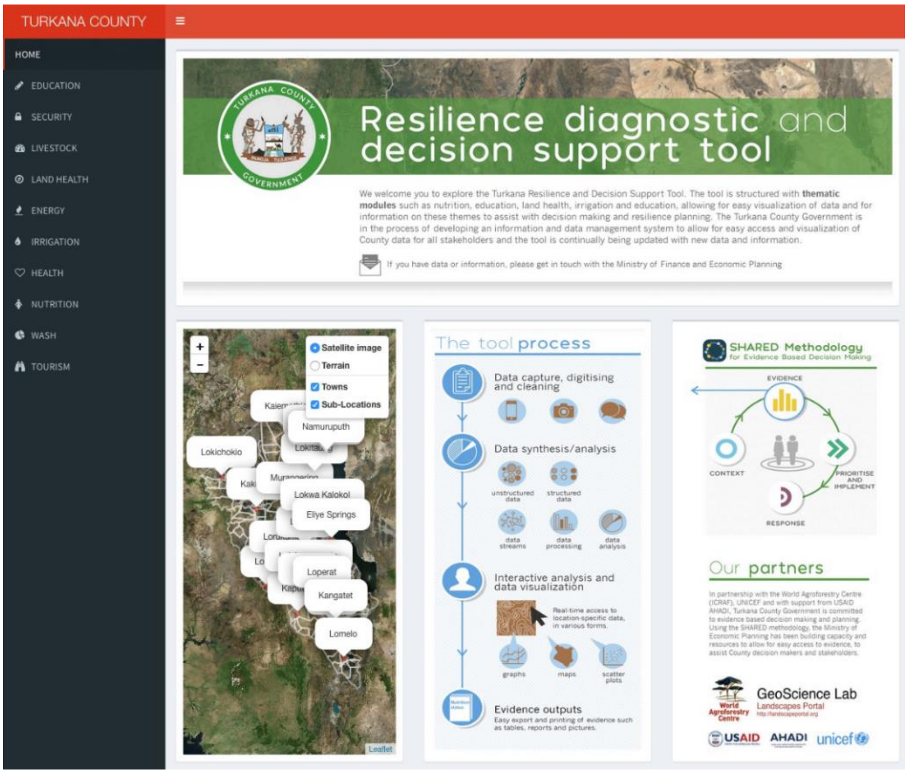

Figure 4. The main page of the Resilience Diagnostic and Decision Support Tool (RDDST) for Turkana County. (http://landscapeportal.org/sharedApp/)

which will contribute to achieving LDN and SDG 15 targets.

5 List of abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
CCAFS	Climate Change, Agriculture and Food Security
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gas
GSP	Global Soil Partnership
ICRAF	World Agroforestry Centre
IPCC	Intergovernmental Panel on Climate Change
KACP	Kenya Agricultural Carbon Project
LDN	Land Degradation Neutrality
LDSF	Land Degradation Surveillance Framework
MRV	Measurement, reporting and verification
M&E	Monitoring and evaluation
NDC	Nationally Determined Contribution
RDDST	Resilience and Diagnostic and Decision Support Tool
SALM	Sustainable agricultural land management
SDG	Sustainable Development Goal
SLM	Sustainable land management
SHARED	Stakeholder Approach to Risk Informed and Evidence Based Decision Making
SOC	Soil organic carbon
UNCCD	United Nations Convention to Combat Desertification
UNFCCC	United Nations Framework Convention on Climate Change
VCM	Voluntary carbon market
VCS	Verified Carbon Standard

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