Realising the Carbon Benefits of Sustainable Land Management Practices: Guidelines for Estimation of Soil Organic Carbon in the Context of Land Degradation Neutrality Planning and…

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A Report of the Science-Policy Interface

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A Report of the Science-Policy Interface

Realising the Carbon Benefits of Sustainable Land Management Practices

Guidelines for estimation of soil organic carbon in the context of land degradation neutrality planning and monitoring

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"Realising the Carbon Benefits of Sustainable Land Management Practices: Guidelines for Estimation of Soil Organic Carbon in the Context of Land Degradation Neutrality Planning and Monitoring" was prepared in accordance with the rules and procedures established by the United Nations Convention to Combat Desertification (UNCCD) Conference of the Parties (COP), by which any scientific output prepared under the supervision of the Science-Policy Interface (SPI) should undergo an international, independent review process (decision 19/COP.12).

The report was prepared by an author team of 2 lead authors and 10 contributing authors. A scoping meeting in October 2018 and writers meeting in February 2019 in Bonn, Germany was held, where SPI members, as well as external experts, participated in these meetings. The background paper was prepared by two expert consultants. Supplementary materials for more background information describing resource cards and inventory of soil organic carbon tools are available at: <http://www.unccd.int/spi2019-1>

The draft produced by the authors underwent a two-step peer review process, including an internal review and, an independent external scientific review. For the latter, seven external reviewers (individual experts) from the different UNCCD regions, and two representatives of international organisations, which are relevant to the UNCCD process on LDN were selected. The lead authors ensured that all peer review comments received appropriate consideration. A summary of the report was reviewed by the Bureau of the Conference of the Parties of the UNCCD.

Foreword

Today, nearly a quarter of our land has been degraded and it is estimated that by 2050, less than 10 per cent of the planet's surface will have escaped substantial human impact. Such dramatic change has a huge effect on the soil organic carbon created by decomposing natural materials, which supports all life on Earth; growing food, creating jobs, reducing poverty, maintaining biodiversity and, crucially, providing the second largest carbon sink after our oceans. That's why climate change and sustainable development can be significantly affected, for better or worse, by even the slightest change in the quantity and quality of soil organic carbon. It's also why this report offers countries practical guidance on better monitoring and managing those stocks to achieve land degradation neutrality.

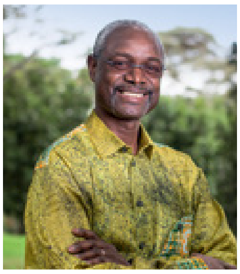
The clock is rapidly ticking down on the targets of the 2030 Agenda for Sustainable Development and a dangerous gap is growing between the Nationally Determined Contributions of the Paris Agreement and the emission levels actually needed to keep global warming below 1.5 °C. Achieving our targets for land degradation neutrality plays a key role in both, with soil organic carbon providing an ideal indicator and driver of progress, not only because it is responsive to land management practices, but because those practices can create much wider social, economic and environmental benefits.

However, you can't manage if you can't measure. Measuring and monitoring soil organic carbon is a challenge, while the volume and variability of techniques and data make it difficult to decide which interventions are the most cost-effective. For example, given the cost of measuring precise changes in soil organic carbon, it may be more efficient to embed it with a broader land health monitoring system. Likewise, practices that prove incredibly successful in one area may have limited value for national targets if they can't be verified or scaled up to match degradation elsewhere. For this reason, policy makers and land managers responsible for taking such difficult decisions and scaling up best practice need clear guidance and harmonized methods to estimate and optimize the stock of soil organic carbon. In response, the authors of this report have provided guidance to assist in identifying suitable locally-relevant sustainable land management practices and approaches to maintain or enhance soil organic carbon stocks, as well guidance to estimate and monitor soil organic carbon for land use planning and for monitoring LDN achievement.

This includes software reviews; decision trees to evaluate issues such as where to invest in monitoring or how to select sampling approaches; and policy-oriented proposals on sharing guidance, monitoring change, designing planning frameworks and addressing the significant, yet underestimated, role that gender inequality plays in land degradation.

The celebrations on agreeing the goals for sustainable development and climate change have long since been replaced by increasingly urgent calls for action. This report is a welcome policy tool for countries trying to answer those calls by better planning and tracking their land degradation neutrality measures, while both minimizing the costs and risks, and maximizing the spillover benefits for other goals. My thanks to everyone who has contributed and, in advance, to everyone who will ensure its swift application.

Ibrahim Thiaw
Executive Secretary
United Nations Convention
to Combat Desertification



Executive Summary

Land degradation is one of the threats to human and natural systems. Fortunately, over the past few decades awareness of this challenge has grown, and 122 countries have committed to setting land degradation neutrality (LDN) targets, of which 84 have officially validated their targets, and 51 have put their targets into legislation. In this concept, LDN is achieved if new degradation is balanced by reversal of degradation elsewhere in the same land type by restoration or rehabilitation. The primary instrument for achieving LDN is through the implementation of sustainable land management (SLM) practices.

Because of its multifunctional roles and its sensitivity to land management soil organic carbon (SOC) was selected as one of three indicators for LDN. Compared with the other global LDN indicators, that is, land cover change and land productivity dynamics (LPD) (measured as net primary productivity), SOC is challenging to manage and monitor at large scales. Moreover, SOC density in soils can vary greatly, even on the scale of meters, and fluctuates over time, for example between seasons. Comparative evaluation of SOC change between different SLM options (e.g. for land planning), tracking SOC dynamics through time (i.e. SOC monitoring) and effectively mapping SOC changes at large scales (e.g. for verifying LDN achievement) requires the combination of rigorous soil sampling schemes and the use of software tools/biophysical models for SOC assessment.

To provide practical guidance to support the deployment of SLM interventions to maintain or enhance SOC stocks, for LDN and for other objectives such as land-based climate change adaption and/or mitigation a series of decision trees was developed, based on the latest available knowledge. This report reviews and compares available tools and models for SOC estimation.

It presents practical guidance for land managers and puts forward policy-oriented proposals. Guidance for land managers emphasizes the selection of SLM practices to maintain or enhance soil organic carbon and achieve LDN. It addresses the choice of SLM practices suited to the local socio-economic and biophysical context; methods for measurement and monitoring of SOC; and the use of tools/models for SOC assessment to estimate SOC and map SOC, and how to choose an appropriate tool/model according to the purpose.

Policy-oriented options include to (i) share the guidance for land managers at the appropriate level; (ii) monitor SOC change as an indicator of SLM intervention to support assessment of LDN achievement in 2030; (iii) apply gender-responsive actions addressing gender-based differences and promote gender equality and women's empowerment; (iv) design a framework for LDN Planning and means to support it.

Land degradation neutrality (LDN) is achieved if new degradation is balanced by reversal of degradation elsewhere in the same land type by restoration or rehabilitation.

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Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
CBP	Carbon Benefits Project
CCAFS-MOT	Climate Change, Agriculture and Food Security Mitigation Options Tool
CFT	Cool Farm Tool
CH4	chemical formula for methane
DLDD	desertification, land degradations and drought
DNDC	DeNitrification and DeComposition
EX-ACT	EX-Ante Carbon balance Tool
FAO	Food and Agriculture Organization of the United Nations
GHG	greenhouse gas
GLADA	Global Land Degradation Assessment
GLADIS	Global Land Degradation Information System
GLOSIS	Global Soil Information System
GLOSOLAN	Global Soil Laboratory Network
GLTN	Global Land Tool Network
GRACEnet	Greenhouse gas Reduction through Agricultural Carbon Enhancement network
GSOC	Global Soil Organic Carbon
GSOCmap	Global Soil Organic Carbon map
GSP	Global Soil Partnership
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Reference and Information Centre
ITPS	Intergovernmental Technical Panel on Soils
LATSOLAN	Latin American Network of Soil Laboratories
LCC	land cover change
LDN	land degradation neutrality
LPD	land productivity dynamics
N2O	chemical formula for nitrous oxide
NAP	national action programme to combat desertification
NDC	national determined contributions
NGO	non-governmental organization
NPP	net primary productivity
NSIS	National Soil Information System

RESOLAN	Regional Soil Laboratory Networks
RS	remote sensing
SAT	semi-arid tropics
SDG	Sustainable Development Goal
SEALNET	South-East Asia Laboratory Network
SIC	soil inorganic carbon
SLM	sustainable land management
SOC	soil organic carbon
SOM	soil organic matter
SPI	Science-Policy Interface
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UN-Habitat	United Nations Human Settlements Programme
VGSSM	Voluntary Guidelines for Sustainable Soil Management
WOCAT	World Overview of Conservation Approaches and Technologies

Glossary

assessment of SOC	See SOC change (assessed).
baseline	The initial (2015) estimated value of each of the indicators used to monitor progress against the achievement of LDN for each land type.
baseline SOC stocks	The initial quantity of SOC, expressed as mass per unit area (e.g. gm-2), against which SOC stock changes are calculated at the national, sub-national, or local scale. Baseline SOC stocks for the area of interest can be estimated using measurements or the combination of measurements and tools/models for SOC assessment.
benchmark sites (for SOC)	Representative location (in terms of climate, eco-region, soil type, etc.) where an extensive gathering of measured data is used for improvements to tools/models for SOC assessment.
bulk SOC	Total SOC contained in a section of the soil profile, for example from 0 – 30cm.
carbon credits	A permit or certificate granting the right to emit a certain amount of greenhouse gas that is tradable, if not used. Soils theoretically can be managed to store carbon and thus generate carbon credits for trade, if meeting certification requirements.
climate change mitigation	Climate change mitigation is an anthropogenic intervention to reduce the emission or enhance the sequestration of greenhouse gases.
comparing potential impacts of SLM interventions on SOC	The ex-ante estimate of the impact of alternative SLM interventions using tools/models for SOC assessment in land areas where SOC needs to be accumulated to meet LDN objectives.
development community (software)	The benefits that people obtain from ecosystems as defined by the Millennium Ecosystem Assessment (MA, 2005).
indicators/metrics for monitoring LDN	Indicators are variables that reflect a process of interest, in this case, land degradation. Metrics are measures that are used to quantify or assess the state or level of the indicators.

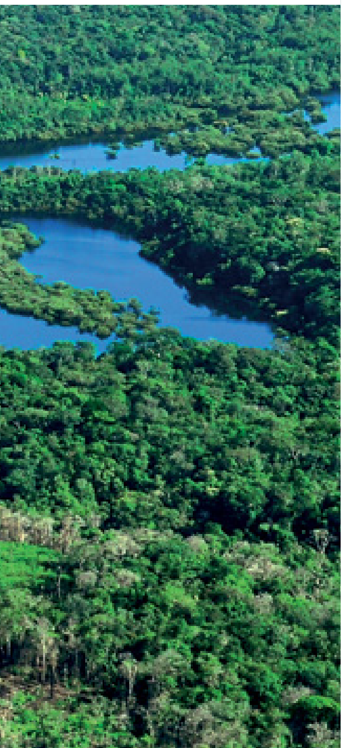
intervention (land degradation, or SLM)	Action taken (for example, starting a new SLM practice) in a specific area to counteract or stop processes causing land degradation.
land use planning	In the LDN context, land use planning that seeks to balance the economic, social and cultural opportunities provided by land with the need to maintain and enhance ecosystem services provided by the land-based natural capital. It also aims to blend or coordinate management strategies and implementation requirements across multiple sectors and jurisdictions (adapted from the United Nations General Assembly, 1992).
land cover	The physical material at the surface of the Earth, which may be vegetated or non-vegetated, natural or managed.
land cover class	A category of land cover differentiated by a combination of diagnostic attributes based on a nationally-refined application of an international standard such as the FAO Land Cover Classification System.
land degradation neutrality (LDN)	A state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems.
land management	The practices applied in managing land resources.
land potential	The inherent, long-term potential of the land to sustainably generate ecosystem services, which reflects the capacity and resilience of the land-based natural capital, in the face of ongoing environmental change.
land type	Class of land with respect to land potential, which is distinguished by the combination of edaphic, geomorphological, topographic, hydrological, biological and climatic features that support the actual or historic vegetation structure and species composition on that land.
land use	Type of activity being carried out on a unit of land, in urban, rural and conservation settings (IPCC, 2006a).
LDN achievement	Proving national-level neutrality in land degradation in terms of, at a minimum, land cover change, LDP, and SOC when comparing 2030 to a 2015 baseline.

LDN target (country level)	The objective to achieve LDN at the national level adopted voluntarily by a country. The country-level ambition for LDN is no net loss of healthy and productive land for each land type, compared with the baseline.
LDN target (global)	The objective to achieve a land-degradation-neutral world (United Nations General Assembly, 2015).
like for like	The principle of counterbalancing losses in one land type with equivalent (or greater) gains in the same land type elsewhere in order to maintain (or exceed) LDN.
model for SOC assessment	Mathematical representation of processes affecting SOC based on biophysical relationships which, when combined with measured data for a given situation or region, can be used to estimate and map SOC changes.
one-out, all-out	A conservative approach to combining different indicators/metrics to assess status, which follows the precautionary principle. The one-out, all-out approach is applied to LDN such that where any of the three indicators pertaining to a piece of land shows significant negative change, it is considered degrading (and conversely, if at least one indicator shows a positive trend and none shows a negative trend it is considered a restoring).
open science principles	Applying the central concept of open access (i.e. availability that is free and public) to all aspects of the scientific process in order to support greater transparency and reproducibility in scientific research, as well as easier collaboration, sharing, reuse, and repurposing of scientific resources (e.g. data, analysis code, models).
productivity	Productivity in this document is used in biological terms. It refers to the rate of production of new biomass by an individual, population, or community.
rehabilitation	Actions undertaken with the aim of reinstating ecosystem functionality, where the focus is on provision of goods and services rather than restoration.

resilience	The ability of a system to absorb disturbance and reorganize itself so as to retain essentially the same function, structure, and feedbacks. Resilience is a neutral property, neither good nor bad.
response hierarchy	The set of prioritized actions/interventions that may be planned and then implemented in response to past or anticipated future land degradation.
restoration	The process of assisting the recovery of land from a degraded state, where the emphasis is on recovery of ecosystem integrity.
significant (with respect to indicators/metrics of LDN)	A change in an LDN metric that is (i) considered to be significant by experts, taking into consideration the precision of the method; or (ii) unlikely to have arisen by chance, according to statistical analysis.
SOC change (assessed)	A positive or negative change SOC projected during land use planning for a specific area of land (e.g., land unit) and a specified timeframe, where change is anticipated due to LDN interventions or lack thereof.
SOC change (monitored)	A positive or negative change in SOC for a specific area of land (e.g. land unit), over a specified timeframe, measured and verifiable.
SOC management	The practices applied in managing land resources to increase SOC.
SOC monitoring	Using measurements or the combination of measurements and tools/models for SOC assessment to track changes in SOC through time at the national, sub-national, or local scale, typically by comparing an initial SOC baseline against SOC at a subsequent time point in the area of interest.
SOC stock change	Change in SOC in mass per unit area (e.g. gm-2), typically following a period of time after land use/land management changes that may change SOC dynamics at the national, sub-national, or local scale.
soil organic carbon (SOC)	Soil material of living origin (e.g. plants, microbes, soil biota) at varying stages of decomposition that acts as a key resource for energy and nutrients, and affects many soil properties such as hydrology, structure, and habitat.

SOC tool/model development:	Improving tools/models for SOC assessment to better represent an area, land characteristic (e.g. soil texture), or SLM practice of interest, typically requiring benchmark SOC monitoring sites to gather adequate data as well as the engagement of development experts.
space-for-time sampling	The direct measurement of treatment effects over time by comparing a treated land unit with an equivalent land unit that is not treated, simultaneously.
standardization	The process of developing an agreed common method, procedure or system for a specific purpose.
Sustainable Development Goals (SDGs)	The 2030 Agenda for Sustainable Development is a set of 17 "Global Goals" with 169 targets between them. The goals are contained in paragraph 54, United Nations Resolution A/RES/70/1 dated 25 September 2015.
sustainable land management (SLM)	The use of land resources, including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions.
SLM interventions	Sustainable land management practices implemented with the purpose of reducing land degradation at the national, sub-national, or local scale. In the case of SOC, SLM interventions would be aimed to increase SOC stocks in the area of interest.
tracking SOC	See SOC monitoring.
tools/models for SOC assessment	A combination of measured data and mathematical relationships used to assess SOC across larger spatial areas and over longer periods of time than is feasible through measurement alone. This includes generalized approaches that may be implemented in software (see: tools for SOC assessment), and more biophysically explicit approaches implemented in models (see: model for SOC assessment).
tool for SOC assessment	Software that uses statistical and empirical relationships to simplify estimation and mapping of SOC changes.

Soil organic carbon plays a critical role in soil productivity as well as a wide array of ecosystem prepossesses, such as nutrient cycling, serving as a repository of resources for below-ground biota, contributing to soil structure and soil hydrology.



Introduction

This report aims to provide guidance to help countries identify suitable locally-relevant sustainable land management practices and approached to maintain or enhance soil organic carbon stocks, as well as guidance on the estimation and monitoring of soil organic carbon for land use planning and monitoring LDN achievement.

According to United Nations Environment Programme, degradation of land and marine ecosystems undermines the well-being of 3.2 billion people and costs about 10 percent of the annual global gross product in loss of species and ecosystem services, (UNEP, 2019). Land degradation is defined by the United Nations Convention to Combat Desertification (UNCCD)[1] as "the reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, grazing land, forest and woodlands resulting from a combination of pressures, including land use and management practices". It is recognized in Sustainable Development Goal 15.3: "By 2030,

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[1] Definition adopted and used by countries that are Party to the UNCCD

combat desertification, restore degraded land and soil, including land affected by desertification, drought, and floods, and strive to achieve a land-degradation-neutral world". UNCCD is the custodian agency of one indicator (15.3.1, the "Proportion of land that is degraded over a total land area"). Land degradation neutrality (LDN) is achieved if new degradation is balanced by reversal of degradation elsewhere in the same land type by restoration[2] or rehabilitation (Cowie et al., 2018; IPBES, 2018). LDN relies on the action at three entry-points in the response hierarchy: avoid – reduce – reverse. The primary instrument for achieving LDN is through sustainable land management (SLM) approaches and technologies introduced in the management of complex socio-ecological systems. In addition to soil organic carbon (SOC), soil inorganic carbon (SIC) is a dominant form of carbon in soils of arid and semi-arid regions and comprises of carbonates and bicarbonates of Ca+2, Mg+2, K+, and Na+. Indeed, SIC forms a larger proportion of total soil carbon (TSC) in drylands and plays an important role in the global carbon cycle (Lal et al., 2000).

> Soil organic carbon is the major constituent of soil organic matter, which plays a critical role in soil productivity and a wide array of ecosystem processes.

Soil organic carbon, the largest carbon pool in the terrestrial biosphere, is an important component of the global carbon cycle. SOC is the major constituent of soil organic matter (SOM), which plays a critical role in soil productivity and a wide array of ecosystem processes. SOM comprises the remains of plants and animals in the soil at various stages of decomposition, along with the microbial biomass and several by-products of complex biotic metabolic processes. Estimated to 3-m depth, and without the permafrost, the SOC stock of 3000 Pg. is ~4 times the atmospheric (800 Pg.) and ~6.5 times the biotic (560 Pg.) stock. Thus, even a slight perturbation of the SOC stock can cause large changes in the atmospheric concentration of CO^2. In general, 1 Pg. of SOC stock is equivalent to about 0.47 ppm of CO^2 in the atmosphere, and vice versa (Lal, 2018). Moreover, SOC plays a critical role in soil productivity and a wide array of ecosystem processes, including nutrient cycling, serving as a repository of resources for belowground biota, contributing to soil structure, affecting soil hydrology, and storing carbon fixed from the atmosphere via photosynthesis.

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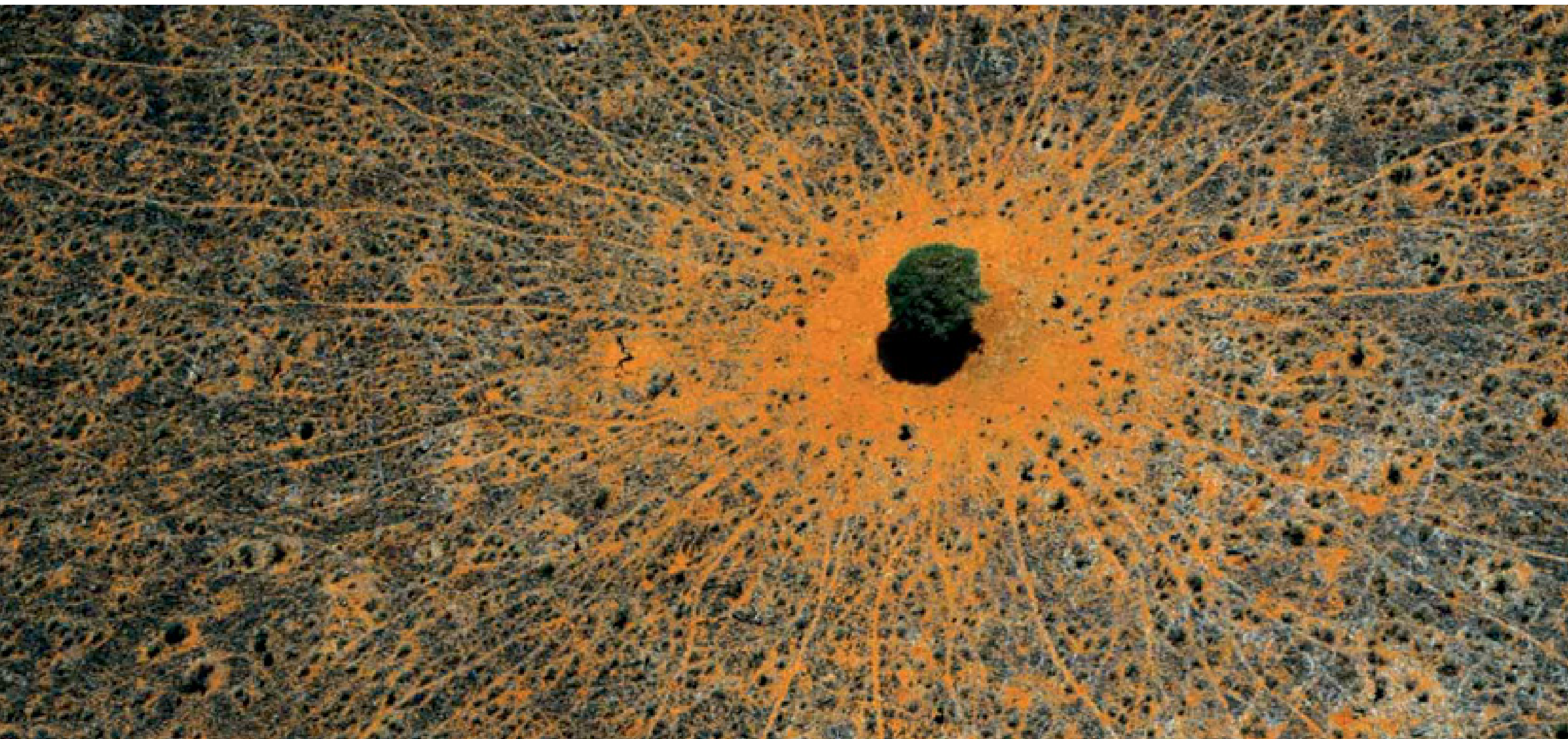
[2] Ecological restoration is most commonly defined as "the process of assisting the recovery of ecosystems that have been damaged, degraded, or destroyed" (SER, 2004). The recovery envisaged here is the re-establishment of as much as possible of the historical structure, composition, and functioning of the ecosystem that existed prior to degradation. Restoration is distinct from rehabilitation, where activities focus on functionality and the delivery of targeted services more than on reinstating the pre-disturbance system condition in all its biological complexity. Rehabilitation may, in fact, be the only option in situations where degradation has passed a point of no return, where species have become extinct, or where seed and soil biota have all been lost (Alexander et al., 2016).

Because of its multifunctional role and its sensitivity to land management, SOC was selected as one of three indicators for LDN, the other two being land cover change (LCC) and land productivity dynamics (LPD), measured as net primary productivity (NPP). As a key ecosystem health indicator, SOC presents unique challenges associated with (1) predicting potential SOC changes associated with SLM interventions and (2) tracking SOC change through time, due to temporal and spatial variability. Software tools and biophysical models for SOC assessment (hereafter referred to as ”tools/models for SOC assessment“) can help ”fill the gaps“ in measured datasets, but these types of assessments can be highly uncertain where data are limited or of low quality.

It is important to note that measured and estimated data have uncertainties. Targeted investments in measurement initiatives and the use of tools/models for SOC assessment are needed to support the deployment of SLM interventions for SOC management, for LDN and for other initiatives such as land-based climate change adaptation and/or mitigation (Batjes, 2004). SOC is a potential centrepiece for collaborative action to improve soil health and functions via SLM. Although SOC is a key soil quality indicator, it alone does not provide sufficient information to guide wise use of land resources, and therefore stand-alone SOC measurement systems will have limited value, especially given the large resources required for field sampling and laboratory measurements. In most cases, it will be more efficient to embed SOC measurement within a broader national land health monitoring system (Shepherd et al., 2015b).

The objective of this technical report is to provide guidance to help countries (i) identify suitable locally-relevant SLM practices and approaches to maintain or enhance SOC stocks, and (ii) to estimate and monitor SOC, for land use planning and for monitoring LDN achievement. The scope includes the use of tools/models for SOC assessment to compare and select SLM approaches and technologies, as well as approaches for monitoring changes in SOC stocks from local to national scales by combining the use of tools/models for SOC assessment as well as measured data. The frameworks and decision trees for planning SLM interventions and SOC assessment will help countries to make better decisions by gaining insights into which SLM practices could increase or maintain SOC and provide other environmental co-benefits and meet stakeholders’ needs while minimizing costs and risks.

The primary instrument for achieving LDN is through sustainable land management approaches and technologies introduced in the management of complex socio-ecological systems.



Soil carbon benefits of sustainable land management practices

Optimize the use of resources to manage soil organic carbon, by using sustainable land management to pursue land degradation neutrality.

2.1. Introduction

According to degradation of land and marine ecosystems undermines the well-being of 3.2 billion people and costs about 10 percent of the annual global gross product in loss of species and ecosystem services (UNEP,2019). The phenomenon is increasingly exacerbated by climate change. Thus, in many ways, it is a globally driven process with local impacts that can lead to a global catastrophe (Vlek, 2005).

> To optimize the use of limited resources to support the management of SOC, this report lays out a rationale for focussing investment in SOC measurement, monitoring, and enhanced capacity for comparative SOC assessment on those land uses and land types for which accurate SOC estimation is most important.

In the conceptual framework adopted by the UNCCD (Orr et al., 2017), LDN is achieved if new degradation is balanced by reversal of degradation elsewhere in the same land type by restoration or rehabilitation. LDN relies on action at three entry-points in the response hierarchy: avoid – reduce – reverse. The primary instrument for achieving LDN is through SLM approaches and technologies. **SLM combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns, so as to simultaneously: maintain or enhance production/services (Productivity); reduce the level of production risk (Security); protect the natural resource base, and avoid degradation of soil and water quality (Protection); be economically viable (Viability); and socially acceptable (Acceptability) (Orr et al., 2017).**

To optimize the use of limited resources to support the management of SOC, this report lays out a rationale for focussing investment in SOC measurement, monitoring, and enhanced capacity for comparative SOC assessment on those land uses and land types for which accurate SOC estimation is most important. Figure 1 presents decision tree 1 which gives practical guidance to target investment in SOC monitoring and comparative SOC assessments to select SLM interventions for LDN and for multiple benefits, using a diversity of resources (e.g. local expertise, available data, SLM database resources like World Overview of Conservation Approaches and Technologies (WOCAT). The first step involves the evaluation of land health, if not already available, which includes assessment of land potential and land degradation status, which are preparatory steps of LDN planning (Orr et al., 2017).

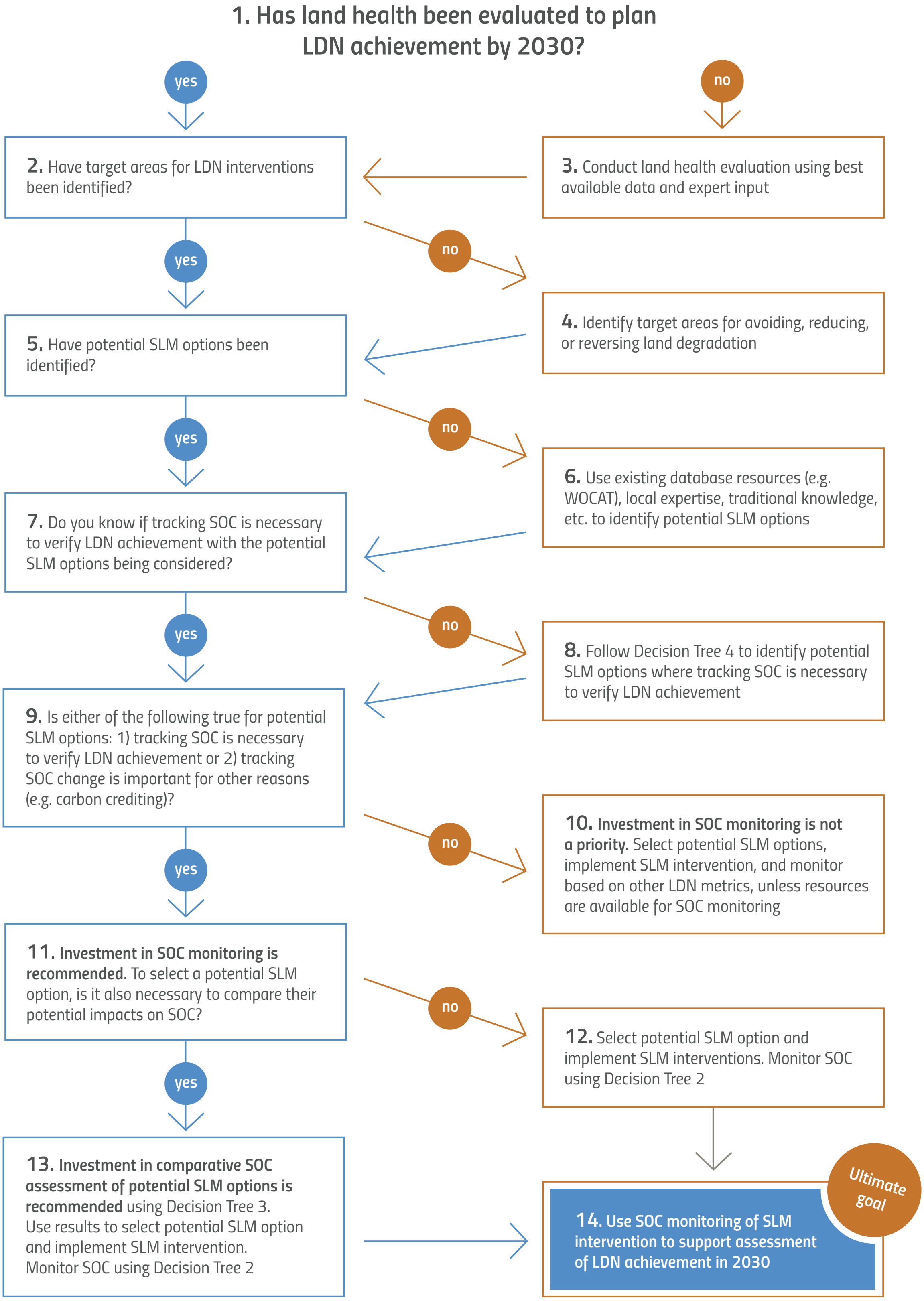


FIGURE 1

Decision tree 1 provides guidance on where investment in soil organic carbon (SOC) assessment and monitoring are recommended to track the impact of sustainable land management (SLM) implementation and to support monitoring of LDN achievement in terms of SOC change in 2030.

These metrics are linked to different aspects of land degradation processes, with LCC indicating more immediate changes in land use and vegetation, LPD the relatively rapid responses of ecosystem function, and SOC the longer term and cumulative responses/resilience to land degradation provided by SOM (Cowie et al., 2018).

2.2. Establishing relationships between soil organic carbon-sustainable land management-land degradation neutrality

Land degradation is assessed through three land-based global indicators as proxies for the capacity of land to deliver ecosystem services: trends in land cover change (LCC), land productivity dynamics (LPD) measured as net primary productivity (NPP), and carbon stocks measured as soil organic carbon (SOC). These metrics are linked to different aspects of land degradation processes, with LCC indicating more immediate changes in land use and vegetation, LPD the relatively rapid responses of ecosystem function, and SOC the longer term and cumulative responses/resilience to land degradation provided by SOM (Cowie et al., 2018).

The rate of SOC increase depends on soil, climate, vegetation, and interaction among them, as altered through anthropogenic interventions. Improvements in SOC through SLM have strong beneficial impacts on soil properties and processes (Table 1).

The net rate of SOC storage for site-specific SLM must be determined by establishing long-term (5–10 year) experiments for key benchmark agro-ecosystems of the world including

Constraint	Impact
Drought	Water conservation, soil temperature moderation, root system proliferation, improved green water supply
Soil fertility	Nutrient retention and availability; reduced losses by leaching, volatilization and erosion; high nutrient use efficiency
Soil health	Disease-suppressive soils, high soil biodiversity, improved plant growth and vigor, soil resilience
Soil tilth	Low risks of crusting and compaction, better soil aeration, favorable porosity and pore size distribution
Production	Sustainable agronomic production, assured minimum yield, better nutritional quality

TABLE 1

Beneficial impacts of SOC/SOM on soil health and functionality

global drylands locations (Lal, 2019). These studies must be conducted with farmer participation from the planning through the monitoring stages. Community-based bench-mark sites should be established for predominant soil orders in an eco-region (Dregne, 1976). Major eco-regions, based on the aridity index (AI)[3] are: i) Hyper-arid (< 0.05), ii) Arid (0.05–0.2), iii) Semi-arid (0.2–0.5) and Dry Sub-humid (0.5–0.65) (UNEP, 1991). Information on predominant soils within these eco-regions (i.e., Inceptisols, Arenosols, Psamments, Vertisols, and Alfisols, Dewitte et al. (2013) can be combined with the climate map of Africa (WMO/UNEP, 2001) to identify bench-mark sites for conducting community-based long-term studies (Table 2).

SOC can be lost much more quickly than it can be regained through improved management. Predicting the potential magnitude of SOC change in either direction – e.g. to optimize the selection of SLM requires the combined use of measured data and tools/models for SOC assessment.[4] **Accurate evaluation of SOC change resulting from SLM interventions is often limited by the availability of data and the performance of tools/models for SOC**

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[3] AI = P/ET, where P and ET are both in mm per year, thus AI is a dimensionless index.

[4] Tools/models for SOC assessment: is an all-encompassing term for the several types of analytical approaches that can be used to assess SOC stocks and stock changes at the national, sub-national, or local scale. Typically, tools/models for SOC assessment combine the use of measured data and mathematical relationships to assess SOC across larger spatial areas and longer periods of time than is feasible through measurement alone. Tools for SOC assessment are software tools that use statistical and empirical relationships to simplify the mapping and estimation of SOC changes. Typically, these tools are designed to make SOC assessment easier, as well as integrate SOC assessment with other factors like carbon accounting or socio-economic analysis. Examples: EX-ACT, Carbon Benefits Project, Cool Farm Tool. Models for SOC assessment we define as a biophysical model that uses biophysical relationships and measured data to estimate and map SOC changes. Typically models for SOC support more certain analyses by better representing biophysical processes. However, they often require expert involvement and extensive data sets at the scale of the area of interest to be used properly. Examples: DAYCENT, DeNitrification and DeComposition (DNDC), Millennial, RothC, EPIC. These models are not presented in detail in this report, refer to FAO, 2019 for more detail. <http://www.fao.org/3/ca2934en/CA2934EN.pdf>

Soil Order	Eco-Region			
	Hyper-Arid	Arid	Semi-Arid	Dry Sub-Humid
Alfisols				
Arenosols				
Inceptisols				
Psamments				
Plinthic				
Vertisols				

Identifying Transects Along AI and Soil Gradients

TABLE 2

Choice of benchmark sites for establishing the relationship between SLM and SOC through participatory research.

A framework to manage SOC for LDN

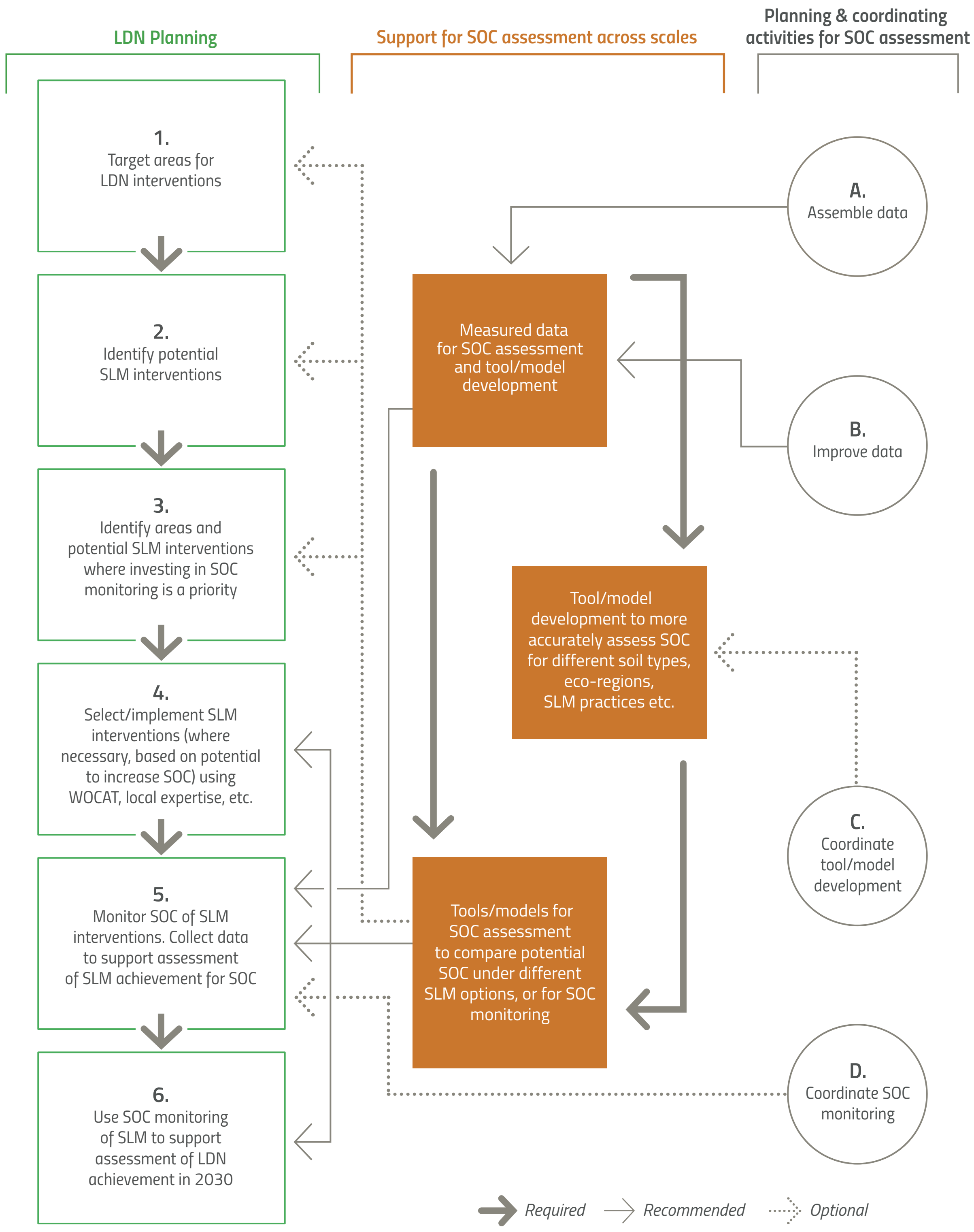

FIGURE 2

A framework for management of SOC for LDN and additional benefits using SLM, showing how the combined use of measured data and tools/models for SOC assessment (orange boxes), supported by planning and coordination activities (grey circles) underpin LDN planning activities leading to LDN achievement (green boxes). Planning activities to (A) assemble data include identifying the best available climate, soil texture, SOC measurements, land use history, LPD, LCC; and (B) improve data include planning and implementing improvements in datasets at the national-scale and scale of land degradation interventions, particularly through SOC measurements and land use information gathering. Coordinating activities (C, D) can occur with scientific, industry, and other activities outside of LDN efforts.

assessment: thus, investment in their improvement may be required to scale up SOC estimation to support LDN.

To optimize the use of limited resources to manage SOC using SLM, to pursue LDN and deliver multiple benefits, this report lays out a framework for matching areas of land to suitable SLM approaches, supported by information from SOC measurements and tools/models for SOC assessment (Figure 2). The framework guides users to develop, test and refine SOC assessment methods for application in SOC monitoring, to support the assessment of LDN achievement.

2.2.1 Processes connecting soil organic carbon to land degradation

The theoretical NPP of the land is given by the position of the land on the globe and the constraints imposed by water and the soil to support plant growth (Del Grosso et al., 2008). Land ecosystems are dynamic in nature and their attributes such as carbon stock and biological diversity as well as their services fluctuate within a bandwidth as a result of climatic cycles and other natural disturbances such as wildfires. The time to recover from such disturbances can range from years for grasslands to decades for tropical forests, dependent on climatic conditions and resilience of the soil (Running, 2008). **However, the intrusion of human beings into pristine environments often results in persistent disturbances and degradation of land at the cost of ecosystem performance by the removal of vegetation, the reduction in NPP and the loss of soil health (Blaikie et al., 2015).**

One of the key impacts of land degradation is the loss of soil productivity, which can be affected by many human interventions, both in a positive and negative sense. Soil degradation results from detrimental changes in the biophysical-chemical conditions of the soil, with the three components, often interacting and affecting ecosystem resilience and NPP. Inversely, a decrease in NPP will affect the biochemical dynamics of the soil, with a reduction in carbon input to soil often a consequence of vegetation removal. With heterotrophic respiration unabated, reduced NPP inputs lead to a decline in SOC and eventually a loss in soil biodiversity. Rates of SOC decline depend on rates of microbial activity and SOC accessibility (e.g., whether SOM is protected from microbial activity, such as due to soil aggregate formation). Further, SOC dynamics is strongly linked to soil texture, with the quantity and type of clay present determining the degree of protection through the formation of clay-organic complexes (Lehmann and Kleber, 2015). SOC integrates many aboveground and belowground processes, making it a useful indicator of soil productive capacity even though it may not capture all forms of degradation (Aynekulu and Shepherd, 2015).

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SOC loss as a result of conversion of land generally follows a negative log function, asymptotically reaching a new equilibrium dictated by the new land use and management (Bernoux et al., 2006). As examples: SOC stocks in tropical semi-arid environments can decrease by 30% in less than five years when native vegetation or grazing lands are converted to cropland (Noellemeyer et al., 2008; Zach et al., 2006), while cultivation of tropical forest soils caused losses of more than 60% of original SOC stocks in just a few years (Brown and Lugo, 1990; Guo and Gifford, 2002). SLM may temper or overcome these declines (Trivedi et al., 2016) but restoring SOC is often slow and it is unlikely to reach pre-disturbance levels, generally staying well under the equilibrium established over decades or centuries under native vegetation. Winowiecki et al. (2016), for example, reported that in Tanzania cultivated plots had, on average, less than half the SOC of paired semi-natural plots. Even a highly productive crop like sugarcane, which has demonstrated potential for increasing SOC compared to grazing lands particularly when they are degraded, still holds less SOC when compared to soils under native vegetation (Bordonal et al., 2018; Mello et al., 2014; Oliveira et al., 2016).

Most soil degradation processes are reflected in SOC change over time, although there are exceptions. For example, the infestation of Alang-Alang (Imperata cylindrica) in Southeast Asia following clearcutting occurred without loss of SOC. However, many drivers of land degradation can trigger soil processes that result in SOC losses. For instance, clearcutting, forest fire, and overgrazing can lead to soil exposure enhancing soil temperature and SOM decay (Crowther et al., 2016), as well as wind and water erosion with SOC displacement (Fernandez-Raga et al., 2017; Goudie and Middleton, 2006). Nutrient mining and export (Grote et al., 2005; Stoorvogel and Smaling, 1990), as well as plant residue removal or burning, lead to soil nutrient depletion, productivity loss and again to soil exposure. Cultivation aerates the soil and favours SOM decay as well as soil erosion on sloping land, displacing SOC (Li et al., 2008; Lobb, 2011). Animal traction facilitates land conversion and cultivation with the consequences discussed above. Mechanization may exacerbate these processes and may cause damage due to soil compaction, in turn diminishing soil aeration and biological activity with concomitant impacts on SOC. The situation is further complicated because in many cases SOC can be lost much more quickly than it can be added or regained. In addition, compared to other indicators, SOC change is more challenging to manage and monitor at large scales than land cover and productivity. **SLM, when deployed appropriately for given locations and situations, can be used to avoid these detrimental actions as well as counter or compensate for their effect.**

2.2.2 Land cover change, net primary productivity, and soil organic carbon are interdependent and often move in unison

Land cover change (LCC) due to the clearing of natural vegetation is generally the first step in the land degradation process, whereas trends in NPP of any subsequent land-use system indicate changes in overall ecosystem function. Theoretically, NPP at any point on the globe is set by daylight hours, solar radiation and elevation, water availability and the productive capacity of the soil which is reflected in the native vegetation. A decline in NPP in native vegetation, corrected for climate change and atmospheric (nitrogen or CO^2) fertilization (Vlek et al., 2010), is a sign of land degradation. The same can be said of systematically declining agricultural productivity, which is monitored and reported by the Food and Agriculture Organization of the United Nations (FAO) annually. SOC inputs are related to aboveground NPP and roots which is related to the vegetation type (Ingram and Fernandes, 2001). Most commonly, such interdependencies will cause LDN indicators to decline and improve in unison, at least up to a point (Oldfield et al., 2019).

There are, however, situations where LDN indicators change at different rates or in different directions. A meta-analysis of the relationship between SOC and crop yields (Oldfield et al., 2019), for example, found that increasing SOC boosts yields until concentrations reach about 2 percent, beyond which the increase in SOC begins to deliver diminishing returns. Below the 2 percent threshold, there is potential to improve SOC and yields in unison using SLM approaches and technologies. For example, approximately two-thirds of agricultural soils dedicated to maize and wheat contain less than the 2-percent threshold, and soils of the semi-arid tropics (SAT) growing sorghum and millets are even poorer in SOC. In such situations, yields strongly relate to SOC levels (MacCarthy et al., 2018). However, above the 2% threshold, there may be capacity to improve SOC even if yields are little affected, requiring separate consideration of NPP or metrics of agricultural productivity versus SOC changes in the context of SLM. **Given limited resources, investing in tracking SOC changes is of greatest priority where a) SOC will be the primary indication of land degradation and LDN achievement with SLM, B) where monitoring SOC is explicitly of value (e.g. carbon trading), and/or C) where SOC is less likely to move in unison with NPP and LCC with SLM.**

2.2.3 Multiple conventions can benefit from maintaining or increasing soil organic carbon

For LDN purposes it is critical to ascertain directional change in SOC in meeting or exceeding 2015 baseline levels, rather than absolute change. As a component of planning and implementing LDN activities, it is important to

> As a component of planning and implementing LDN activities, it is important to know whether an SLM approach or technology deployed in a targeted area will be able to contribute to this goal.

know whether an SLM approach or technology deployed in a targeted area will be able to contribute to this goal. Ultimately LDN achievement is aggregated at a national scale and must be verified. However, SOC management to achieve LDN may differ from managing SOC for other purposes. An important example is SOC management in the context of greenhouse gas (GHG) abatement, which takes into account all GHGs and the overall impact on climate change. For the United Nations Framework Convention on Climate Change (UNFCCC), soil carbon sequestration is considered in the context of net GHG fluxes (including N2O and CH4 which can be emitted from soils and are affected by SOC); thus, any land-use management strategy that increases SOC is of limited value if these gains are offset by increasing emissions of these potent GHGs (Bernoux et al., 2006).

The UNCCD (2015) recognizes the integrative potential of SOC and argues that it should be leveraged wherever possible. For example, initial LDN planning activities could make use of SOC assessments completed as a component of national GHG inventories if the SOC component was estimated using the Intergovernmental Panel on Climate Change (IPCC) Tier 2 or Tier 3 approaches. Shared SOC monitoring and assessment for multiple conventions could contribute towards collective, mutually beneficial resource use. However, the capacity for integrated activities will vary greatly depending on past activities, available resources, and funding opportunities. The urgency of the impact of land degradation is such that the aspiration of integration should not be a constraint for initiating LDN actions on the ground. Instead, the intention for integration can help guide the nature and augmentation of LDN actions through collaborations, where possible.

For the purposes of large-scale coordination, Orr et al. (2017) recommends leveraging existing land planning activities, specifically connecting LDN planning to: “UNCCD National action programmes (NAPs), United Nations Framework Convention on Climate Change (UNFCCC) National Adaptation Plans and nationally determined contributions (NDCs), and mainstreaming into national development plans and other policy processes”. These efforts are ideally grounded in solid, data-based land degradation baseline assessments, which for SOC is a much greater challenge than for NPP or LCC, due to greater limitations in data availability as well as higher analytical demands to track past or estimate potential future changes. The land resource planning for SLM guide developed by FAO can be useful for such multi-sectoral planning (Ziadata et al., 2017).

2.3 Choosing sustainable land management practices to maintain or enhance soil organic carbon

Targeted application of SLM practices (policies, strategies, approaches, and technologies) is the main way to achieve LDN at landscape and national levels. Contribution to the achievement of LDN, and especially enhancing SOC, can be considered as a criterion for the identification of suitable SLM technologies and approaches for a particular territory. SLM practices generally prove to be optimal solutions to simultaneously address land degradation and climate change adaptation and mitigation. These practices tend to show significant adaptation potential (i.e., enhancing resilience and maintaining or enhancing food security) in humid and in semi-arid areas, but may show smaller mitigation (i.e., greenhouse gas emissions and increased carbon sequestration) co-benefits in drylands where addressing land degradation and adapting to climate change has higher relevance as a goal than mitigating climate change (Sanz et al., 2017; UNCCD, 2017a). A more detailed analysis of the contributions of SLM to land-based climate change adaption and mitigation can be found in Sanz et al. (2017).

Information is required on specific SLM practices that contribute to maintaining or increasing SOC, and for identifying areas of land and SLM approaches to prioritize investment in SOC. There is no “one size fits all” SLM option for the 300,000 known soil series and a multitude of site-specific factors. One key decision question that countries often ask is: which allocation of resources among land restoration interventions will provide the best return on investment considering multiple development and environmental objectives? **To answer this, decision-makers could use economic models that project long-term costs, benefits and risks of SLM intervention options, and the cost of inaction** (Shepherd et al., 2015a).

SLM practices generally prove to be optimal solutions to simultaneously address land degradation and climate change adaptation and mitigation.

Figure 2 gives a general guide on choosing SLM interventions for SOC management, which consists of several stages (green boxes), and ideally should be supported by the accumulation of datasets and resources (tools/models for SOC assessment) to scale up SOC evaluations (orange boxes). SLM choices should be validated and fine-tuned under site-specific conditions with due consideration to biophysical (i.e., soil, climate, terrain), socio-economic (land tenure, farm size, infrastructure, institutional support, access to market, gender issues) and cultural issues (faith, traditions, rituals). Restoring the SOC stocks of degraded and depleted soils, which is often as low as 0.05% in croplands of South Asia and Sub-Saharan Africa along with those of the Caribbean and the Andean region, advances LDN. In this context, implementing SLM options (Dumanski, 1997; Hurni, 1997) can enhance SOC, restore and sustain soil health, and achieve LDN (Table 3). Some examples of **SLM include agro-ecology, conservation agriculture with residue retention and cover cropping, mixed farming systems that integrate cropping and livestock production, agroforestry, integrated nutrient management involving the judicious combination of organic and inorganic sources of plant nutrients, and precision agriculture (FAO, 2017).**

Application of appropriate SLM should lead to a positive soil/ecosystem carbon budget such that input of biomass-C (i.e., residue retention, compost, biochar) exceeds the losses of SOC (by erosion, decomposition, and leaching). Under dryland conditions (with aridity index or P/ET of < 0.65) (UNEP, 1991), the rate of SOC sequestration may range from 0.1 to 0.25 MgC ha-1 yr-1 (Lal, 2002). In such environments, the adoption of SLM could also enhance the stock of SIC as secondary carbonates or caliche, and through leaching of bicarbonates into the groundwater (Monger et al., 2015). Dryland ecosystems have biotic and abiotic mechanisms of SIC sequestration, both of which can be enhanced and sustained through the adoption of SLM such as agroforestry (Garrity et al., 2006) and water conservation and management (Rockstrom et al., 2009).

Following identification of those areas with the potential to build SOC, SLM interventions to manage SOC can be identified. Multiple sources of information should be utilised to identify SLM intervention options with the greatest likelihood to fit specific social-ecological contexts and successfully lead to LDN achievement. Databases such as WOCAT, TerrAfrica, the World Bank SLM Sourcebook, and the Voluntary Guidelines for Sustainable Soil Management (VGSSM) provide comprehensive recommendations and examples of SLM practices as well as local expertise and traditional knowledge (Toudert et al., 2018). The choice of intervention expected to be most effective depends on the type of problem it addresses and the SLM approaches and technologies available for the particular land use type (Shepherd et al., 2015a). The GeOC tool provides a means to evaluate the biophysical and socio-economic context for spatial targeting and scaling up of SLM options (Le et al., 2017).

> Though farm-scale adoption of SLM, technologies can lead to an improvement in land quality. Often it is poor management at the landscape or watershed level that sets a context in which farmers are constrained.

While choosing suitable SLM practices to maintain or enhance SOC:

- Characterise the site (agro-ecosystem, land potential, land condition, socio-economic context);
- Identify drivers of land degradation, limitations of current management;
- Target locations where SOC is vulnerable to loss and there is potential for greatest gain;
- Using resources such as WOCAT, identify potentially-suitable SLM practices – considering both technologies and approaches to address the identified drivers of land degradation, and constraints, and also assess suitability for the socio-economic context; and
- Evaluate alternative options for their potential to enhance SOC (use tools/models for SOC estimation where available, and where greater certainty is required)

When deciding on the implementation of any targeted investment in SOC management, it is important to remember that the result can strongly depend on the scale of implementation. Many SLM technologies are implemented at the farm and field level. Though farm-scale adoption of SLM technologies can lead to an improvement in land quality, often it is poor management at the landscape or watershed level that sets a context in which farmers are constrained . Care should be taken when devising policy based on separate successful examples, to ensure that scaling up will not lead to adverse outcomes, for example through revegetation at unsuitable sites resulting in decreased downstream water availability.

Land type and land/soil characteristics can be used to identify priority areas for SOC management, that is (i) areas of low precipitation and/or highly erodible soils where SOC is likely vulnerable to loss and thus may be target of interventions to avoid or reduce land degradation, and (ii) high SOC and/or high clay soils that, through high capacity to increase or store SOC, may be most likely to yield strong economic benefits through carbon trading. This approach can be implemented using the 2015 baseline SOC datasets, information about the land type (land potential) used in LDN planning, together with land cover and land productivity data.

Once general priority areas have been identified, other sources of information for land degradation status and local expertise can be used to identify ‘hotspot’ targets for SLM where “land condition is good but deteriorating” (Orr et al., 2017). The “Trends. Earth” tool could serve as a good resource for this approach, designed to support national-level assessment of land degradation including methods to estimate SOC based on SoilGrids 250m dataset to provide baseline SOC stock, and land cover change to estimate impacts of land use on SOC stock change. Following the identification of target areas, options for SLM interventions to manage SOC can be more effectively identified. Multiple sources of information can be engaged to identify SLM intervention options with the greatest likelihood to enhance SOC: historical data on land use and management; measured SOC data, tools/models to estimate the potential for SOC changes for a specific site, specific socio-economic and ecological contexts. Information sources include, for example, the WOCAT database of SLM and other relevant datasets, as well as local expertise and traditional knowledge. Once SLM options are identified, this can support the selection of SLM interventions in the context of the need for investments in SOC monitoring and/or comparative assessment of SOC impacts, in order to scale up national capacity to manage SOC and achieve LDN.

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TABLE 3

A selection of some of the SLM approaches and technologies as well as collective actions that have relevance in LDN Schemes (modified after Toudert et al., 2018). Each column is an independent list, and each list consists of activities that generally become more individualized in implementation from left to right. Several of the interventions may serve more than one purpose, but the principal LDN Response Action is reflected in the colour coding. The primary monitoring index and (where evaluated) the relative SOC influence are listed for each approach, action, or practice, the latter based on a qualitative assessment derived from literature review and expert judgement, where 1 indicates low or non-impact, 2 indicates medium impact, and 3 indicates high impact (from Sanz et al., 2017). Avoidance schemes should not lead to a change in SOC and therefore were not considered for SOC influence.

Approaches		
Land use regimes and policies		
Name	**Primary monitoring index**	**SOC influence**
Land conversion control	LCC (RS)	-
Declaring National Protection Zones	LCC (RS)	-
Land titling	NPP (RS/ ag stats)	-
Land reform	NPP (RS/ ag stats)	-
Infrastructure planning	LCC (RS)	-
Payment for Ecosystem Services Scheme	LCC (RS)	-
Watershed planning support	LCC (RS)	2
Grazing agreements	NPP (RS/prod stats)	2
Soil and water conservation programs	SOC (monitor/prod stats)	2
Set aside/Resettlement	LCC (RS)	not evaluated
Promoting fertilizer	SOC (monitor/prod stats)	2
Biomass burning regulation	SOC (monitor/prod stats)	2
Extension services	SOC (monitor/prod stats)	not evaluated
Taxation/Subsidies	NPP (RS/prod stats)	not evaluated
Alternative fuel schemes	LCC (RS)	1

Primary Monitoring Index Key:
LCC (RS): Land cover change, using remote sensing,
NPP (RS/ag stats): Net Primary Productivity,
using remote sensing and production statistics,
SOC (monitor/ prod stats): Soil Organic Carbon,
monitoring and production statistics

Collective action						Technologies		
Structural measures			*Vegetative measures*			*Agronomic measures*		
Name	**Primary monitoring index**	**SOC influence**	**Name**	**Primary monitoring index**	**SOC influence**	**Name**	**Primary monitoring index**	**SOC influence**
Community land use planning	LCC (RS)	-	Vegetation corridors	LCC (RS)	-	Rotational or strip Fallowing	NPP (RS/ ag stats)	-
Runoff management	LCC (RS)	-	Sand dune stabilization	LCC (RS)	-	Vegetative strip cover	NPP (RS/ ag stats)	-
Flood control	NPP (RS/prod stats)	2	Natural regeneration	LCC (RS)	2 – 3	Contour ploughing/ planting	NPP (RS/ ag stats)	-
Terracing	NPP (RS/prod stats)	2	Reforestation	LCC (RS)	3	Agroforestry	SOC (monitor/ prod stats)	3
Tile Drainage	NPP (RS/prod stats)	1	Afforestation	NPP (RS)	3	Live fencing	SOC (monitor/ prod stats)	2
Irrigation schemes	NPP (RS/prod stats)	2	Wetland restoration	LCC (RS)	not evaluated	No/minimum tillage	SOC (monitor/ prod stats)	2
Gully control	NPP (RS/prod stats)	2	Woodlot/ plantations	NPP (RS/prod stats)	1	Crop rotation	SOC (monitor/ prod stats)	2
			Exclosures	LCC (RS)	3	Intercropping	SOC (monitor/ prod stats)	3
			Tree nurseries	NPP (RS/prod stats)	3	Green manuring	SOC (monitor/ prod stats)	3
			Reduce herd densities	NPP (RS/prod stats)	2	Composting/ Mulching	SOC (monitor/ prod stats)	3
						Manuring	SOC (monitor/ prod stats)	3
						Integrated crop/ Livestock systems	NPP (RS/ prod stats)	2
						Conservation agriculture	SOC (monitor/ prod stats)	2-3
						Fertilizer use	SOC (monitor/ prod stats)	2

*SOC influence low or none=1; medium=2; high=3; = not considered

Colour Key for types of Response Actions: ■ Avoid ■ Reduce ■ Reverse

2.3.1 Choosing SLM practices for SOC management at sub-national and local level

SLM technologies implemented at the farm and field level are agronomic, vegetative, structural and management measures that control land degradation and enhance productivity in the field, while *SLM approaches* are ways and means of support that help to introduce, implement, adapt and apply SLM technologies in the field (WOCAT, 2007). The literature lists hundreds of SLM technologies that can be deployed in various ecosystems. In addition, it discusses numerous approaches to create an enabling environment so that such technologies will diffuse and be adopted in the targeted environment. The choice of particular interventions expected to be most effective depends on the type of problem to be addressed, the SLM approaches and technologies available for the specific land use and land type, and local expertise/familiarity to support adoption and dissemination. Detailed qualitative assessment of the potential to increase SOC of about 100 different SLM practices applied in agriculture, forestry, grazing management, and mixed land use is provided in the Science-Policy Interface (SPI) report "SLM contribution to successful land-based climate change adaptation and mitigation" (Sanz et al., 2017).

Table 3 lists some of the SLM approaches and technologies that policymakers consider in LDN planning. Although the response strategies apply to all scales of intervention, those SLM interventions listed closer to the right-hand side in Table 3, are more suited to on-ground implementation by individual land managers. For instance, land use planning is not normally done at the individual farm level, nor do communities decide on cropping systems or animal management on the farm. It is in this spectrum of approaches and technology options that policymakers decide which entry point is most likely to further the national LDN goals and, in the context of this report, which will optimize the accrual of SOC.

Scaling-up of farm-level interventions that are beneficial to the environment and the public can be slow if there are no private benefits to the landholder, or if the private benefits are slow to be realized (Stevenson and Vlek, 2018). The actual benefits of SLM technologies in terms of SOC accrual at national level will thus depend on the extent of adoption. Land managers often use combinations of SLM interventions on their farms.

Investment in monitoring of LDN progress will depend on the LDN strategy deployed (Figure 6). Different analyses are relevant in different places, depending on which part of the response hierarchy (avoid, reduce, or reverse land degradation) is being applied at the target location. Avoidance of land degradation in natural and unmanaged lands (forests and grasslands) can be accomplished by avoiding negative LCC, i.e. conversion of natural and unmanaged lands to managed lands. If land cover is not changed, LDN indicators presumably remain constant and can be checked through remote sensing (RS) with proper climate change corrections, **making monitoring SOC (through measurement) optional.** Avoidance is not always feasible, however, as the conversion of natural and unmanaged lands remains a mechanism for meeting demands for food and other land-based products. Further, when productive lands are already in use, communities move into more marginal land with vulnerable soils. Such land conversion can be tracked with remote sensing tools. **Avoiding land degradation** also applies to **cultivated lands and mixed lands** including woodlots, plantations, and grasslands that are not degrading under current management practices. If it is anticipated that these systems will be stable, even in the context of climate change, this suggests that SLM is in place **and investments in detailed monitoring of SOC (involving measurement) may not be necessary or cost-effective.**

Reducing land degradation on cultivated land with the help of SLM technologies is a desirable outcome, but unless at least one of the LDN indicators is significantly improved over the baseline it will not enter the gain side of the ledger. Nutrient mining is rather common in agriculture (Stoorvogel and Smaling, 1990), and reducing the rate of nutrient depletion, for example by eliminating straw burning and returning residues to the land, may alleviate the problem. However, as long as produce is exported from the farm, so, too, are nutrients meaning that land degradation will continue unless exported nutrients are replaced. Some farmers profitably combine straw restitution with other SLM technologies such as green manuring and fertilizer use to turn this land degradation process around (McDaniel et al., 2014). As long as these situations are found in comparable land use units, the gains may be counted against the continuing degradation to achieve LDN as outlined by Orr et al. (2017). UNCCD and WOCAT have documented numerous successful SLM technologies tailored to the land use systems concerned, be it grassland, cropland, or mixed systems. Their success may be location- and context-specific and **SOC monitoring is indispensable in verifying the recovery of SOC levels in the soil.**

Reversing land degradation using restoration and rehabilitation are comprehensive measures largely applied to land that is no longer delivering ecosystem services and has lost its productive capacity prior to the 2015 baseline date. Depending on the root cause of this degradation, measures may involve retrofitting pipe drainage in irrigation schemes, terracing, contour dams, check dams, Zai pits or retaining wall construction often combined with organic amendments and fertilizer application and re-vegetation, measures listed in Table 3 under collective action. The often-complex nature of such measures involving soil redistribution and change in soil surface (zero point) make tracking of the SOC status challenging (Nie et al., 2017). Given that the primary objective of such measures is to restore the productive capacity of the land, **monitoring of LCC and or NPP may be sufficient.**

The full spectrum of potential SLM activities (Table 3) need due consideration in implementing LDN. The impact of SLM interventions on SOC cannot be captured equally by currently available tools/models for SOC assessment. It varies across biophysical and ecological contexts, and it becomes more diffuse and challenging to track particularly with large-scale institutional or collective actions (e.g. grazing agreements, community land use planning). The ability to accurately predict potential SOC impacts is strongly tied to the availability of existing data, due to the combination of costs and logistical difficulties in collecting and measuring soil characteristics, particularly SOC, as well as other relevant ecosystem metrics.

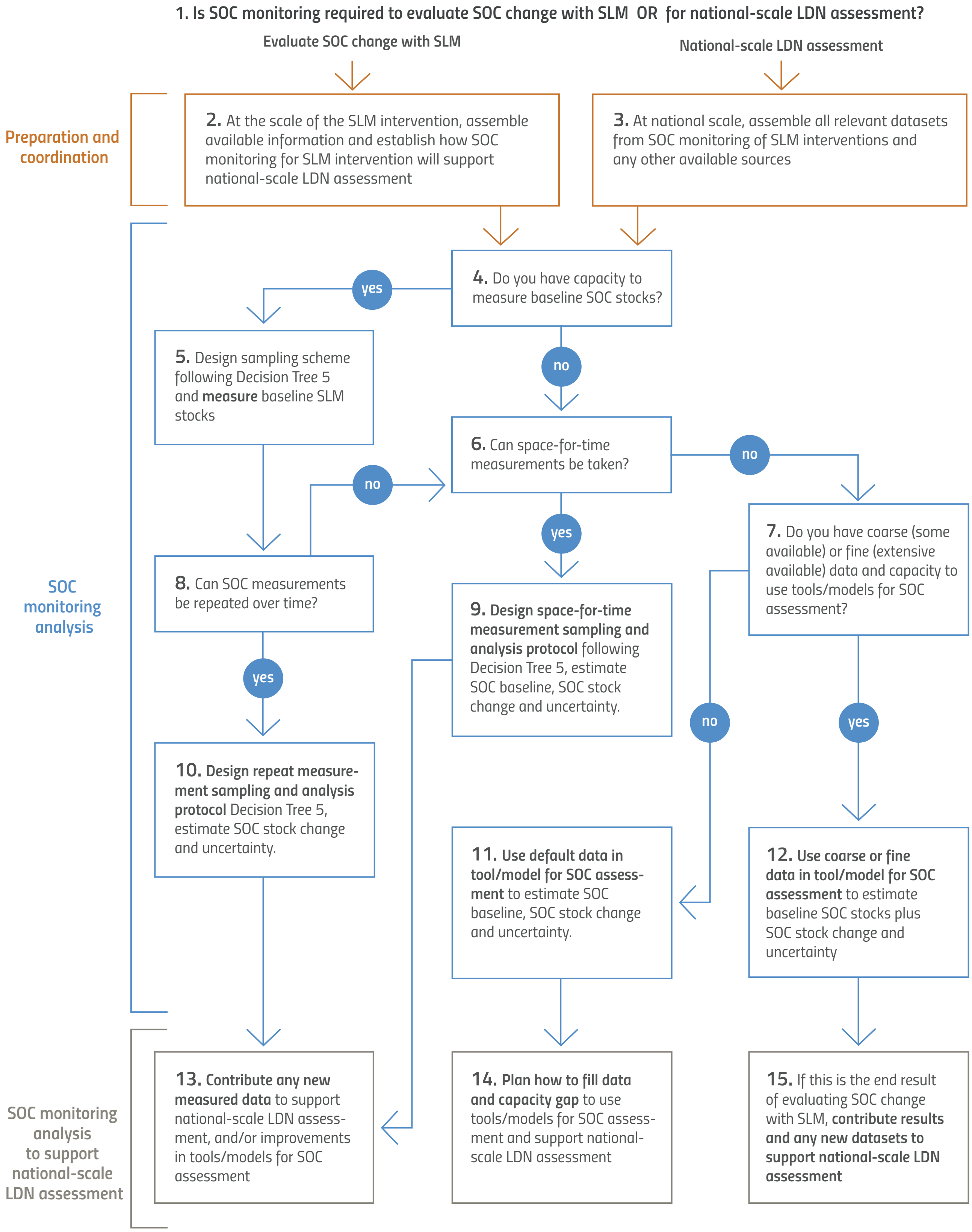


FIGURE 3

Decision tree 2 guides the use of SOC monitoring to assess and verify SLM impacts on SOC – using direct measurements, tools/models for SOC assessment, or some combination – and contribute these efforts to national-scale LDN assessment (Boxes 11-13). This decision tree is intended for repeated use through the LDN process as SLM practices are deployed. It can be adapted for the final national-scale LDN assessment, by first assembling all relevant datasets from SOC monitoring of SLM interventions and any other available data sources before proceeding through the decision tree Boxes 2-10-. This figure is adapted for LDN from (FAO, 2019).

2.3.2 The gender dynamics of SLM

The Scientific Conceptual Framework for Land Degradation Neutrality states that the drivers of land degradation are not gender neutral, with gender inequality playing a significant yet underestimated role in the processes that lead to land degradation.

Men and women relate to land differently and their unique perspectives are driven by varying roles, responsibilities, access to resources and control. Understanding the roles and responsibilities of men and women, along with power relations in land management, is a primary requirement for achieving effective outcomes when combating land degradation

Focus/benefits of a gender-responsive LDN	Risks of ignoring gender issues in LDN
Identifying legitimate stakeholders and capturing relevant experiences/skills/knowledge of women and men.	Increased women's work burden; reinforcing their status as victims of degradation rather than champions of restoration.
Understanding and accounting for the different women's and men's roles, rights and responsibilities as land users and managers, including their particular land access and use patterns.	Imprecise identification of i) men and women stakeholders in land use practices; ii) socially-just options for neutrality interventions, and iii) benefit sharing leading to the increased marginalisation of women in decision making.
Clear identification of drivers of degradation, guaranteed accuracy of information and potential synergies/coordination to address challenges.	Drawback in project sustainability and long-term effectiveness, e.g. due to maintenance of existing inequality in tenure security.
Joint planning, implementation, and monitoring of LDN options and outcomes, ensuring sustainable land conservation/restoration and equitable sharing of benefits e.g. in line with a human rights-based approach to development.	Discriminatory planning systems and risk of unfair cost/benefit sharing reinforcing social divisions.

TABLE 4

Gender-responsive LDN benefits and risks of ignoring gender issues in LDN (Okpara et al., 2019).

Criteria	Example of evaluation questions for the criteria
Equal participation by women and men and gender-responsive governance	Is the decision-making process in developing the land tool, and in using the land tool itself, transparent and inclusive for both women and men?
Capacity development, organization, and empowerment of women and men to use, access, and benefit from the tool	Is the information clear, and does it empower both women and men to utilize the tool, and to know their rights related to this tool?
Legal and institutional considerations in regard to women and men's access to land	Does the tool provide gender-responsive dispute resolution?
Social and cultural considerations in regard to women and men's access to land	Does the tool take into consideration statutory and customary laws and practices affecting women's land rights?
Economic considerations in regard to women and men's access to land	Does the tool promote economic opportunities for both women and men?
Scale, coordination, and sustainability to reach more women and men	Can the tool be implemented consistently (rather than ad-hoc)?

TABLE 5

Examples from gender evaluation criteria (from UN-HABITAT, IIRR, GLTN., 2012).

Understanding the roles and responsibilities of men and women, along with power relations in land management, is a primary requirement for achieving effective outcomes when combating land degradation and implementing SLM/LDN initiatives.

and implementing SLM/LDN initiatives. Thus, mainstreaming gender into land related activities in particular LDN or SLM activities offers considerable opportunities for leveraging synergies between LDN commitments and global commitments to sustainable development, such as the Sustainable Development Goal #5 (Okpara et al., 2019). Equitable participation in LDN/SLM initiatives – in terms of decision making and influence, and the distribution of (labour) costs and benefits, improves prospects for both human and socio-economic development and environmental outcomes.

Efforts to mainstream gender as proposed by UNCCD Gender Action Plan (GAP) as well as recommendations from UNFCCC, CBD, UN Women, IUCN, CEDAW (among others) convey the importance of gender equality and gender inclusive action. The recent United Nations Environment Assembly of the United Nations Environment Programme (UNEA) conference held in March 2019, proposed numerous recommendations promoting gender equality and human rights and empowerment of women and girls in environmental governance (UNEA, 2019). These publications, among numerous others, emphasise that women form a major part of agricultural development (UNCCD, 2017b) with traditional knowledge and skills in farming being closely tied to the maintenance and improvement of land productivity (UNCCD – Global Land Outlook: Gender-responsive Land Degradation Neutrality, 2017). These vital roles of women need to be understood and addressed to enable, on the one hand, communities to support women as farmers and as leaders, and on the other hand, to ensure that men and women benefit equally, and inequality is not perpetuated.

Referring to the principles related to achieving neutrality presented in the LDN scientific conceptual framework, LDN planning should focus on understanding the overall roles and opportunities of women and men within LDN. Ensuring social equality, especially gender equality, is critical to achieving LDN (Orr et al., 2017). It is important to enable more equal access to natural resources and to facilitate women to become active users and managers of natural resources. Despite potential synergies between SLM and gender equality, SLM land health improvement initiatives rarely address complex gender inequalities (Broeckhoven and Cliquet, 2015; Collantes et al., 2018; Samandari, 2017). In order to address this, the UNCCD Gender Action Plan provides an agreed framework for the full and effective participation of both men and women in planning, decision-making, and implementation at all levels in order to empower women, girls, and youth in the affected areas. Also, recent publications by Collantes et al., 2018 as well as Okpara et al.,2019, identify entry points for gender integration into LDN actions. Additionally, Okpara et al. (2019) introduced associated gender-responsive LDN benefits of integrating gender issues and the risks of not doing so, which provides strong support for gender inclusion (Table 4).

Gender-responsive actions can be incorporated into project activities, thereby pro-actively addressing gender differences and promote gender equality and women empowerment. Guidance on incorporating and promoting gender equality on a project level is provided by the 2018 GEF publication (GEF, 2018); as well as the Green Climate Fund publication “Mainstreaming Gender in Green Climate Fund Projects”, and publication by UN Women (UN Women, 2017). Gender-responsive actions not only contribute to equitable access, participatory decision making but also improve the ability of women to invest in natural resources (Okpara et al., 2019).In line with the above-mentioned recommendations, a publication developed by UN-Women, IUCN, and the UNCCD Global Mechanism (GM) titled "Manual to support the integration of gender equality in LDN project development" will be launched at the COP14 in New Delhi, India. This manual provides step-by-step guidance to parties in integrating gender issues and promoting gender equality in the design of transformative LDN projects.

In order to move forward with gender equality in LDN, Collantes et al. (2018) made two main recommendations:

1. To enhance understanding, and to advance gender-responsive LDN plans and programs
    - Ensure representation to women in SLM and desertification, land degradation and drought (DLDD) policy-making and finance strategies including women from affected countries,
    - Make funding for LDN programs and UNCCD related initiatives conditional on the integration of a gender perspective in implementation, and ensuring outcomes that promote gender equality and women's and girls' empowerment,
    - Develop concrete practical guidance and tools for designing, implementing, monitoring and assessing gender-responsive LDN interventions
    - Equip female and male delegates of CCD with technical know-how on gender perspectives and SLM, LND and DLDD, as well as with the skills and capacity to participate effectively in Convention’s meetings
    - Monitor large-scale land-based investments to ensure gender-responsive, socially-responsible consultation and consent by indigenous people and communities
    - Conduct regular assessments of how gender inequality and its impacts are addressed in LDN and DLDD implementation plans

Gender-responsive actions can be incorporated into project activities, thereby pro-actively addressing gender differences and promote gender equality and women empowerment.

2. To include gender considerations in the design of preliminary LDN assessments

   - Ensure gender-responsive, socially-responsible consultation and consent by indigenous peoples and communities with respect to large-scale land-based investments that affect them,
   - Facilitate women's equal and meaningful participation and leadership in land and natural resource governance, decision making and in conflict resolution mechanisms addressing land and natural resource disputes through government mandates or otherwise,
   - Mandate consultations with rural and indigenous women's, women's organizations and other concerned civil society groups, as well as academics, researchers and practitioners in designing SLM, land rehabilitation, land restoration, and water management projects and programs,
   - Bolster and resource rural livelihood schemes to teach and incentivize sustainable land use management, soil conservation, and drought proofing water harvesting and other green measures that at the same time strive to empower women,
   - Implement data collections that are sex-disaggregated and gender-sensitive, and monitor effects of gender mainstreaming policies on all genders to flag policy and programmatic shortfalls for course-corrections,
   - Sustain awareness-raising and capacity-building for UNCCD focal point ministry staff and those who are engaged in implementing the land conservation/restoration policies at the local and national levels on gender-responsive LDN and gender-responsive implementation of the Convention including the 2017 UNCCD Gender Action Plan,
   - Sustain outreach and capacity-building to enhance women's and communities' legal literacy about land rights and to ensure that rural and indigenous women are equipped with skills and new technologies to conserve and manage their land and related resources,
   - Fund and conduct large-scale, longitudinal, comparative or multi-country quantitative studies to build the evidence base on gender-responsive LDN interventions and their impact and outcomes in promoting gender equality, women's empowerment and community resilience.

These recommendations could be a starting point to further develop accountability indicators to cover gender equality in environmental governance and particularly in LDN actions. As an example, the Global Land Tool Network (GLTN) UN-HABITAT, IIRR, GLTN., 2012 has developed criteria to evaluate gender tools used to check whether SLM interventions to achieve LDN incorporate gender issues (Table 5).

2.3.3 Selecting sustainable land management practices to benefit soil organic carbon: (i) without investment in a comparative assessment

Selecting SLM interventions to benefit SOC may not require investment in a comparative assessment of SOC impacts if there is ample evidence of positive SOC impacts and quantification of SOC gains is not a priority in the region of interest. However, in this scenario, investment in SOC monitoring is recommended to assess and verify positive impacts on SOC. Figure 3 presents decision tree 2 to guide the establishment of SOC monitoring and investment in measurement schemes (using Figure 7) that most effectively contribute to national-scale LDN assessment.

Sanz et al. (2017) made a qualitative assessment of potential for specific SLM practices to increase or maintain SOC. While specific practices and their influence on SOC were presented in Table 3, in Table 6 these are now grouped by land use category to further illustrate their potential contribution towards LDN.

Further, in 2012, the World Bank published a meta-analysis including over 1000 SOC sequestration estimates and a host of SLM technologies (World Bank, 2012). Nearly all interventions were reported to lead to SOC accrual of 0.2^{-2} MgC ha-1 yr^{-1}. More recently, some meta-analyses have been completed evaluating SOC change with LDN actions and activities, although they are limited in scope due to high uncertainties and limited data. A summary of some of the salient findings from these sources is provided in Table 7.

Review of published data on the impact of interventions on SOC (Börner et al., 2016) shows clear improvements in forest cover as a result of protection, enforcement, disclosure, payment for ecosystem services and certification, with the latter two being the more effective measures. In the area of collective action, no studies have been reported that link structural measures to SOC accrual, but several meta-analyses deal with a range of revegetation measures. By and large, a shift from forest to grassland and cropland will be at the expense of SOC whereas restoring forest offers SOC benefits. Conversion of grassland to cropland comes with a loss in SOC stock whereas changing cropland to grassland or fallow lead to SOC accrual. These meta-studies overall confirm that, at least under experimental conditions, the on-farm technologies reported tend to favour SOC accrual, but actual benefits are strongly context-specific.

LDN practitioners may invest in comparative assessment of SOC, based on the lowest level of certainty required to yield results useful for SLM decision making.

Land use category and SLM groups of technologies	Degree of influence on SOC ranging from low (1) to high (3)	Example SLM practices	Potential impacts on LDN
Crop lands			
Vegetation management	2.4	**Conservation agriculture** (minimum tillage and soil disturbance; permanent soil cover with crop residues and live mulches; crop rotation and intercropping) **Contour hedges**	Erosion control, water conservation, SOC sequestration, soil fertility replenishment
Integrated soil fertility management	2.3		
Minimum soil disturbance	2.3		
Integrated pest management	2.2		
Soil erosion control	2		
Water management	1.6		
Grazing land			
Integrated soil fertility management	2.5	Nutrient management	Erosion control, SOC sequestration, nutrient cycling, restore degraded grazing land
Vegetation management	2.3	Contour hedges	
Grazing pressure management	2.2		
Animal waste management	2		
Forest/woodland			
Forest restoration	3	Assisted regeneration	Erosion control, SOC sequestration, nutrient cycling
Afforestation/ Reforestation	2.8	Establishment of protected forest areas	
Reducing deforestation	2.5		
Fire control, pest and disease control	2		
Soil erosion control	1.8		
Sustainable forest management	1.7		
Drainage	1		
Mixed			
Agroforestry systems	3	Plantation crop combinations, multipurpose trees on crop and grazing lands	Nutrient cycling, moderation of micro-climate, windbreak, biodiversity
Vegetation management	2.3	Home gardens	Biological nitrogen fixation, high use efficiency, sustainable production, high biodiversity
Grazing pressure management	2.2		Nutrient cycling, sustainable production, resource efficiency

TABLE 6

SLM influence on SOC: Qualitative assessment of SLM groups of technologies (Sanz et al., 2017).

Type of LDN Action	Targeted Activity	Description	SOC Layer	SOC Change	Unit	Ref
Collective Action	Revegetation	from cropland	(0-20cm)	42	%	1
Collective Action	Revegetation	from cropland	(>20cm)	11 - 19	%	1
Collective Action	Revegetation	from non-cropland	(0-20cm)	48	%	1
Collective Action	Revegetation	from non-cropland	(>20cm)	29 - 51	%	1
Collective Action	Land use change (tropics)	Primary forest -> grassland	0-20/50 cm	-12.1	t/ha	2
Collective Action	Land use change (tropics)	Primary forest -> cropland	0-20/50 cm	-25.2	t/ha	2
Collective Action	Land use change (tropics)	Primary forest -> perennial	0-20/50 cm	-30.3	t/ha	2
Collective Action	Land use change (tropics)	Primary forest -> second. forest	0-20/50 cm	-8.6	t/ha	2
Collective Action	Land use change (tropics)	Secondary forest -> grassland	0-20/50 cm	-6.4	t/ha	2
Collective Action	Land use change (tropics)	Secondary forest -> cropland	0-20/50 cm	-21.3	t/ha	2
Collective Action	Land use change (tropics)	Grassland -> secondary forest	0-20/50 cm	17.5	t/ha	2
Collective Action	Land use change (tropics)	Cropland -> secondary forest	0-20/50 cm	50.3	t/ha	2
Collective Action	Land use change (tropics)	Grassland >- cropland	0-20/50 cm	-10.4	t/ha	2
Collective Action	Land use change (tropics)	Cropland -> grassland	0-20/50 cm	25.7	t/ha	2
Collective Action	Land use change (tropics)	Cropland -> fallow	0- 20/50 cm	32.2	t/ha	2
LDN technologies	Fertilizer addition	Fertilizer	NR	1.2 - 2.3	g/kg	3
LDN technologies	Fertilizer addition	Fertilizer + straw	NR	1.9 - 2.2	g/kg	3
LDN technologies	Fertilizer addition	Fertilizer + manure	NR	3.2 - 3.8	g/kg	3
LDN technologies	Agroforestry	Pasture -> AF	(0-30cm)	9	%	4
LDN technologies	Agroforestry	Agricult -> AF	(0-30cm)	40	%	4
LDN technologies	Agroforestry	Pasture -> AF	(0-60cm)	10	%	4
LDN technologies	Agroforestry	Agricult -> AF	(0-60cm)	10	%	4
LDN technologies	Agroforestry	Pasture -> AF	(0-100cm)	0	%	4
LDN technologies	Agroforestry	Agricult -> AF	(0-100cm)	35	%	4
LDN technologies		Native -> Cultivated	(0-60cm)	-22	t/ha	5
LDN technologies	Tillage	Conventional -> No Till	(0-10cm)	3.2	t/ha	5
LDN technologies	Tillage	Conventional -> No Till	(10-20cm)	0	t/ha	5
LDN technologies	Tillage	Conventional -> No Till	(20-30cm)	-2.4	t/ha	5
LDN technologies	Tillage	Conventional -> No Till	(30-40cm)	-0.9	t/ha	5
LDN technologies	Tillage	Conventional -> No Till	(<40cm)	0	t/ha	5
LDN technologies	Tillage	Conventional -> No Till	NR	4.61	g/kg	6
LDN technologies	Tillage	Conventional -> Min. Till	NR	3.85	g/kg	6
LDN technologies	Manure	Alone	(0-30 cm)	9.4	t/ha	7
LDN technologies	Manure	with fertilizer	(0-30 cm)	5.6	t/ha	7
LDN technologies	Crop Rotation	Monocrop -> rotation	NR	3.60	%	8

TABLE 7

The impact of collective actions and SLM technologies on SOC derived from meta-analysis and expressed in the units reported. Positive values for SOC change indicate SOC accrual, while negative values indicate SOC losses. 1 (Gong et al., 2017); 2 (Don et al., 2011); 3 (Han et al., 2016); 4 (De Stefano and Jacobson, 2018); 5 (Luo et al., 2010); 6 (Haddaway et al., 2017); 7 (Maillard and Angers, 2014); 8.

Note: NR = not reported; AF = agro-forestry

Figure 3 presents decision tree 2 to guide the establishment of SOC monitoring and investment in measurement schemes (using Figure 7) that most effectively contribute to national-scale LDN assessment.

2.3.4 Selecting sustainable land management practices to benefit soil organic carbon: (ii) with investment in a comparative assessment

The use of tools/models for SOC assessment to compare the potential impacts of SLM on SOC tends to become more time and resource intensive as the need for certainty increases. Therefore, for the sake of practicality, LDN practitioners may invest in a comparative assessment of SOC based on the lowest level of certainty required to yield results useful for SLM decision making (guidance provided in decision tree 3, Fig 4). Comparative SOC assessment for the sake of guiding the discussion, for example, may use simple software tools for SOC assessment and default datasets with low levels of certainty. Comparative SOC assessments to coordinate with SOC management for carbon trading, on the other hand, might require identifying and filling data gaps in order to attain high levels of certainty required to select SLM options that optimize economic returns (Figure 4).

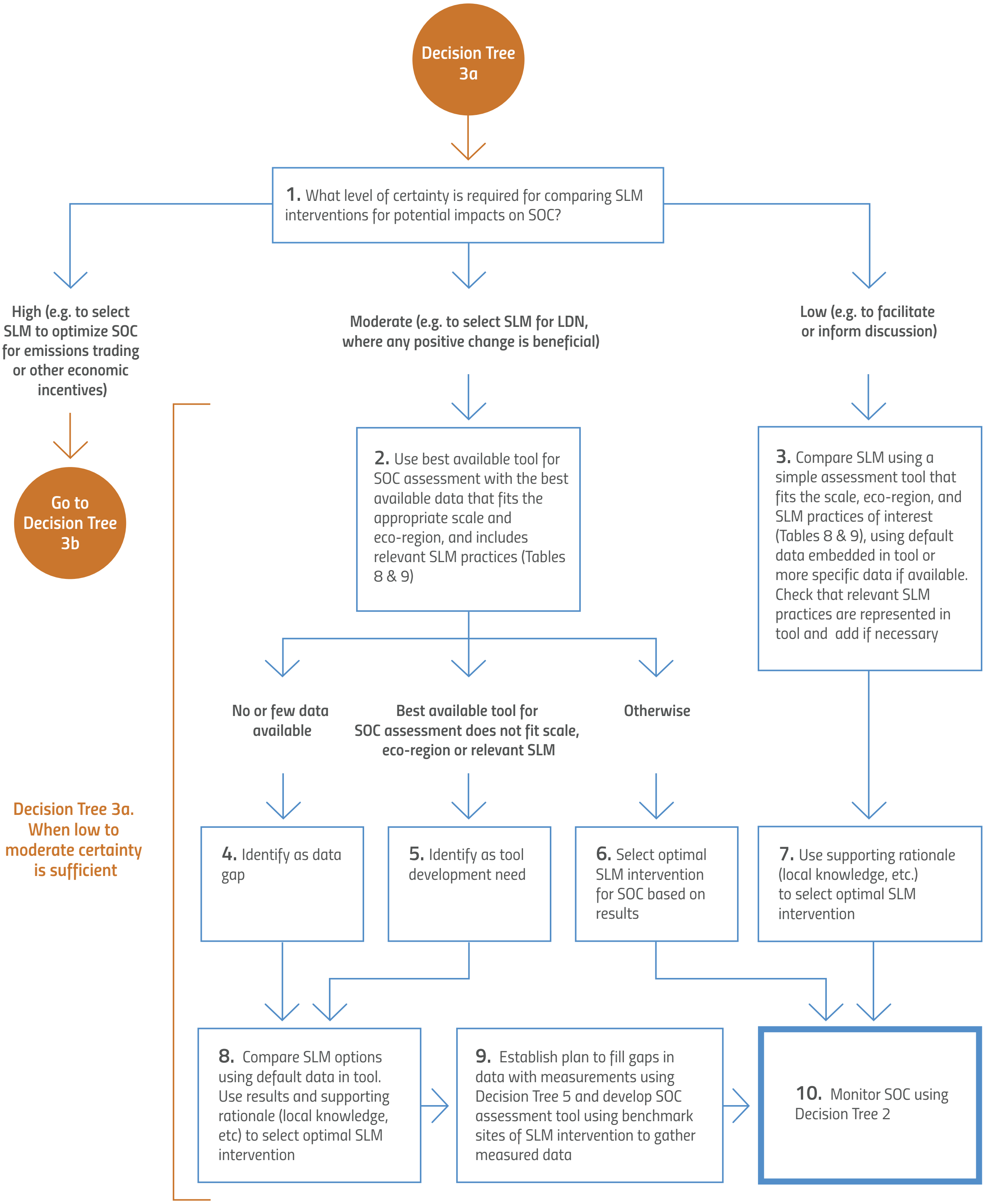
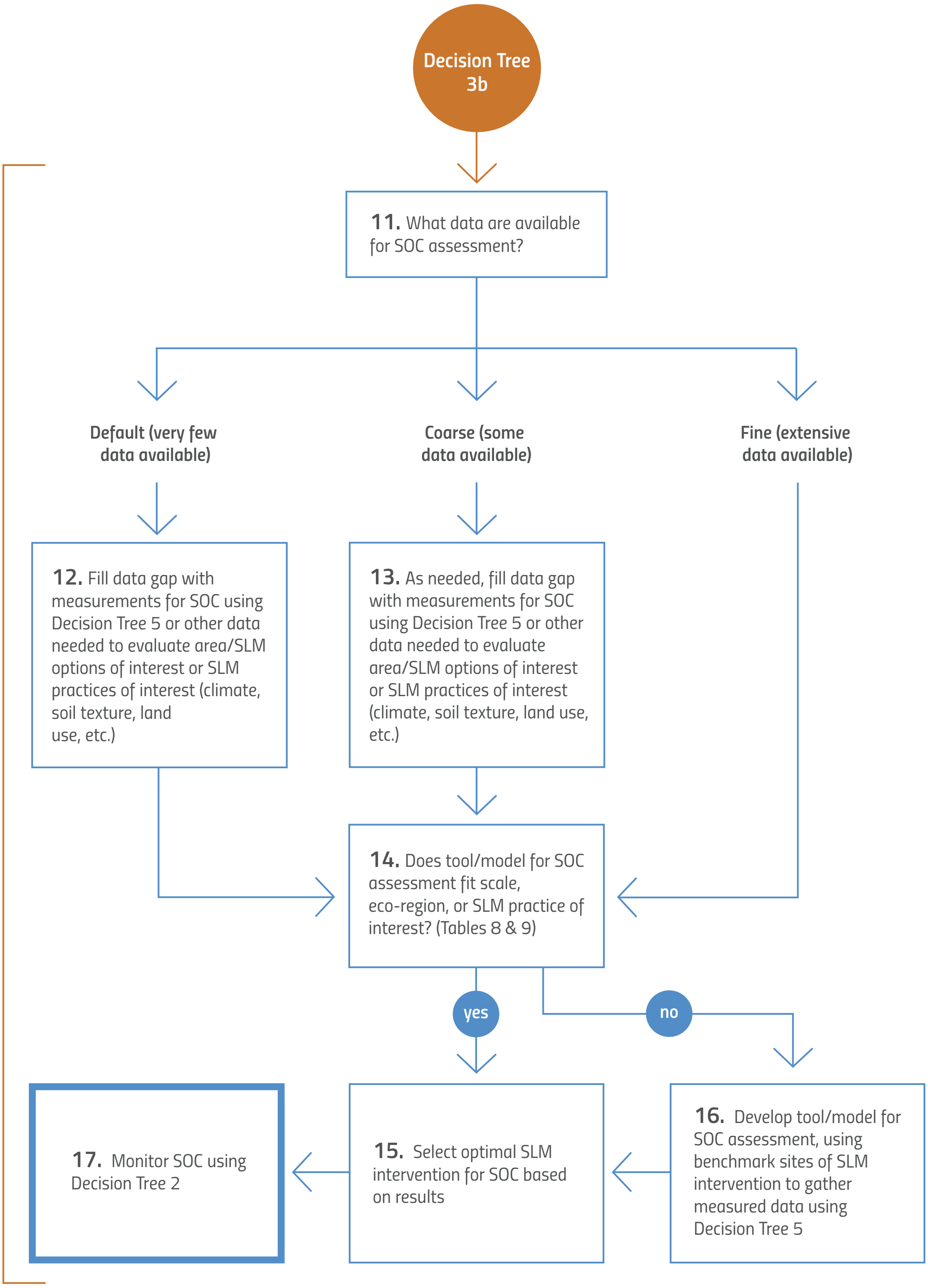


FIGURE 4

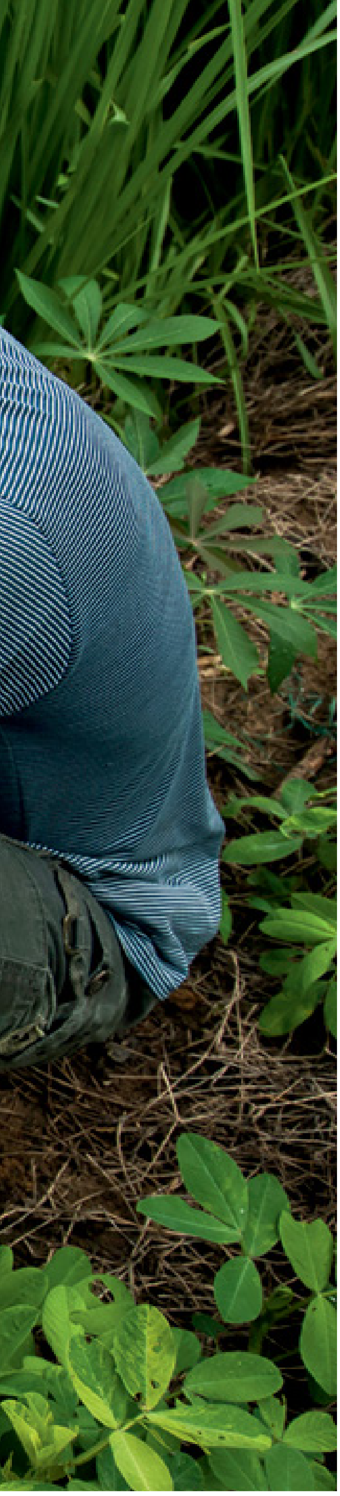
Decision tree 3a) and 3b) support the use of tools/models for SOC assessment and measured data to comparatively assess SOC impacts of potential SLM practices, based on low to moderate (decision tree 3a), and high (decision Tree 3b) levels of certainty in the results.

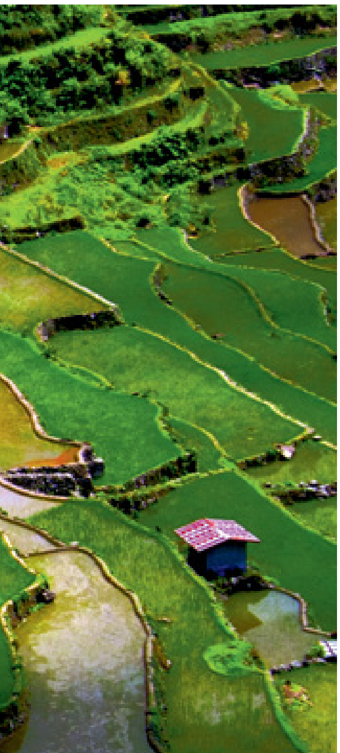


Decision Tree 3b. When high certainty is required

FIGURE 4 (Cont'd)

Support the use of tools/models to comparatively assess soil organic carbon impacts on potential sustainable land management practices.





Estimating and monitoring soil organic carbon stocks

Prioritization of tools and methods to monitor, estimate and evaluate soil organic carbon and assess land degradation neutrality achievement.

3.1 Introduction

Accurate estimation and evaluation of SOC change resulting from SLM interventions are often limited by the existence and availability of standardized/harmonized data and the performance of tools/models for SOC assessment. Thus, investment in their improvement may be required to scale up analyses to support LDN. In addition, SOC in soils can vary greatly spatially, even on the scale of meters. Tracking SOC dynamics through time (i.e. SOC monitoring) and effectively mapping SOC changes at large scales, requires the combination of accurate soil sampling schemes, standardized soil sampling methods, and high-quality data to use with tools/models for SOC assessment. Thus, verifying LDN achievement at a national scale in terms of SOC will require targeted investment in SOC monitoring, combining the use of direct measurements and tools/models for SOC assessment.

Measurement-based monitoring of changes in SOC is achievable but may not always be desirable given limited resources and the usually high costs of measurement programmes. FAO published guidelines for the establishment of soil sampling frameworks that address the many challenges of soil variability (FAO, 2019;

Mäkipää et al., 2012), stratified sampling, minimum detectable difference, and resampling frequency that such schemes need to consider. Whereas developed countries may already have extensive sampling schemes in place, for a developing economy, the long-term commitment to such a scheme may be daunting. More recent efforts of quantifying SOC using MODIS-based remote sensing models appear promising for mapping purposes of SOC stocks, but so far they lack the accuracy to track SOC dynamics (Vågen et al., 2016). **Quantities of SOC vary so much over space and time that it is often impractical to measure to the degree of accuracy and resolution required for LDN monitoring and assessment. Therefore, other approaches besides direct measurements are required, combining good soil datasets with sound modelling approaches and modern scaling technologies based on remote sensing (Winslow et al., 2011).**

SOC tracking, both ex-ante and ex-post implementation of SLM, can be done through tools/models for SOC assessment. However, the accuracy of such assessments and the scale at which they can be applied are dependent on soil datasets available to calibrate SOC assessment tools and models to local conditions. Whereas assessments of SOC at large scales (national) are useful in setting national LDN priorities and targets as demonstrated by Milne et al. (2007), this is not the scale at which LDN is made actionable through SLM (local, subnational). **Thus, for the purposes of LDN, the generation of measured SOC datasets must be considered in conjunction with the use (and steady improvement) of tools/models for SOC assessment, both at the scale of LDN activities (project to sub-national) and at the scale of monitoring LDN achievement (national).**

Given widespread challenges with limited SOC data, targeted investment in SOC monitoring is vital (Shepherd et al., 2015b). Land systems are inherently spatial, and many land degradation problems are due to poor matching of land use with the attributes of the land. Thus, any improvements that do not effectively scale up (at least to the level of matching degrading activities), or cannot be effectively verified at a national level will have limited practical value for LDN even if they are highly successful at smaller scales. SOC estimation and monitoring efforts should be grounded in solid, data-based land degradation baseline assessments. Estimating and monitoring SOC is a much greater challenge than for NPP or LCC, due to greater limitations in data availability as well as higher analytical demands to track past or potential future changes. Many countries face deficiencies in existing national SOC data, resulting in additional challenges in LDN implementation (Solomun et al., 2018).

Although global SOC data are available (e.g. SoilGrids, discussed in section 3.4), these data are sometimes uncertain and often do not reflect the actual state of SOC on the ground. However, given that SOC does not always track NPP and LCC (Oldfield et al., 2019), it is important to identify where and at what scales SOC monitoring is essential to effectively track and scale up assessments of SOC changes. Countries can estimate SOC using offered tools/models for country (region) specific circumstances, with limited national data on SOC, and prioritize degraded areas with potential to increase SOC applying SLM. Investing in tracking SOC changes is of greatest priority where SOC will be the primary indication of land degradation and LDN achievement with SLM, where monitoring SOC is explicitly of value (e.g. carbon crediting), and finally where SOC is less likely to move in unison with NPP and LCC with SLM.

3.2 Review of tools for soil organic carbon estimation and monitoring

Tools/models for SOC assessments combine the use of measured data with analytical approaches to estimate SOC dynamics and are used for two central purposes: 1) 'filling the gaps' in SOC measurement schemes through interpolation and extrapolation, 2) and guiding decision making for SLM implementation by predicting SOC changes under possible SLM scenarios. SOC assessment for land-based climate change adaption and/or mitigation has driven the development of tools/models for SOC assessment tied to global, national, and sub-national initiatives including national GHG inventories (e.g., Ogle et al., 2013) and carbon crediting (e.g., Climate Action Reserve, 2017). However, the use of such tools/models for SOC assessment for LDN must begin by considering several LDN-specific factors, including:

> SOC assessment for land-based climate change adaption and/or mitigation has driven the development of tools/models for SOC assessment tied to global, national, and sub-national initiatives including national GHG inventories.

1. The nature of how LDN is defined (i.e. to include all human and nature-driven degradation processes (Cowie et al., 2018) in relation to current scientific understanding of linkages between land degradation processes and SOC dynamics;
2. The spatially-explicit land types used to meet "like-for-like" LDN criteria, and;
3. The need to estimate SOC stocks as well as potential and future SOC stocks changes to select and implement LDN projects.

Carbon crediting, for example, is only certified for practices that are well understood and, where analytical approaches that include the estimation of SOC change are involved, good performance of those analytical approaches are thoroughly verified (e.g., Alberta Environment and Water, 2012; Climate Action Reserve, 2017). For this reason, agricultural activities were largely omitted from carbon credit certification until the most recent decade (González-Ramírez et al., 2012). National GHG inventories are spatially explicit but do not have to address future change, as they are designed to take stock of historic and current emissions and removals (IPCC, 2006b). Indeed, spatially-explicit estimates of anticipated SOC change at sub-national scales for LDN purposes are widely acknowledged as highly challenging due to a pervasive lack of data (Campbell and Paustian, 2015), and are a critical consideration in the evaluation of SOC for the purposes of LDN commitments.

The costs and practical constraints associated with monitoring SOC are well-recognised as a barrier and can be prohibitive when carrying out landscape-scale assessments. In some cases, the cost of demonstrating the change in carbon stocks in soils to the required accuracy and precision may exceed the benefits that accrue from the increase in stocks (IPCC, 2006b). Although infrared spectroscopy (Shepherd and Walsh, 2007), a technique which can correlate the absorption of light with carbon content, significantly reduces the analytical cost and speed of measuring soil carbon content, costs incurred in soil sampling and preparation still form the largest component of the total monitoring cost (Aynekulu et al., 2011; Milne et al., 2016).

The impact on SOC cannot be captured equally by currently available tools/models for SOC assessment. For instance, the effect of institutional and collective action interventions on SOC are difficult to track. Even for SLM technologies, the ability to accurately predict potential SOC impacts or monitor SOC changes after implementation is strongly tied to the availability of data, due to the combination of costs and logistical difficulties in collecting and measuring soil characteristics, particularly SOC, as well as other relevant ecosystem metrics. Thus, to evaluate SOC in the context of LDN the use of tools/models for SOC assessment needs to be considered in the context of their current capacity as well as the datasets available for their use. Targeted investments may be needed to improve either or both, to enhance the capacity for large-scale SOC evaluations and ultimately to support national-scale assessment of LDN achievement in terms of SOC.

Software tools for evaluating SOC stocks and changes vary; some are dedicated to SOC alone while others include SOC stocks and change as one or two metrics among many. At either end of this spectrum, such tools often make use of SOC biophysical models to represent the complex interactions of processes affecting SOC dynamics. SOC biophysical models may be used *indirectly*, whereby model results are the sources of values in the tool (for example, percentage SOC loss with land use change from a native ecosystem into cropland in soils of varying clay content). Indirect use of SOC biophysical models in this manner is common, and software tools dedicated to GHG assessment provide many such examples (e.g., Climate Action Reserve, 2017). It is also possible for SOC biophysical models to be used *directly*[5], although this is typically more difficult and far less common. The scientific basis of SOC biophysical models, as well as their current capacity to represent land degradation processes, are both key to understanding 1) SOC biophysical model limits and, 2) how to best dedicate resources to improve tools/models for SOC assessment, where necessary and feasible.

SOC biophysical models vary from the very simple (e.g. treating SOC as a single pool, as shown in Figure 5 to the more complex (e.g. considering food webs or multiple SOC pools (Stockmann et al., 2013). No one model has yet emerged that satisfies all needs. Instead, different modelling approaches are used at different scales and situations (e.g. for global scale simulations of climate change, versus farm-scale simulation of management practices (Campbell and Paustian, 2015). A common approach used in well-known models like CENTURY and RothC defines SOC pools by their rates of decay (fast = annual or less, slow = years to decades, passive = decades to centuries). However, it is recognized that models that better reflect explicit mechanisms governing SOC accessibility (Abramoff et al., 2017; Lehmann and Kleber, 2015) may improve our capacity to predict SOC dynamics.

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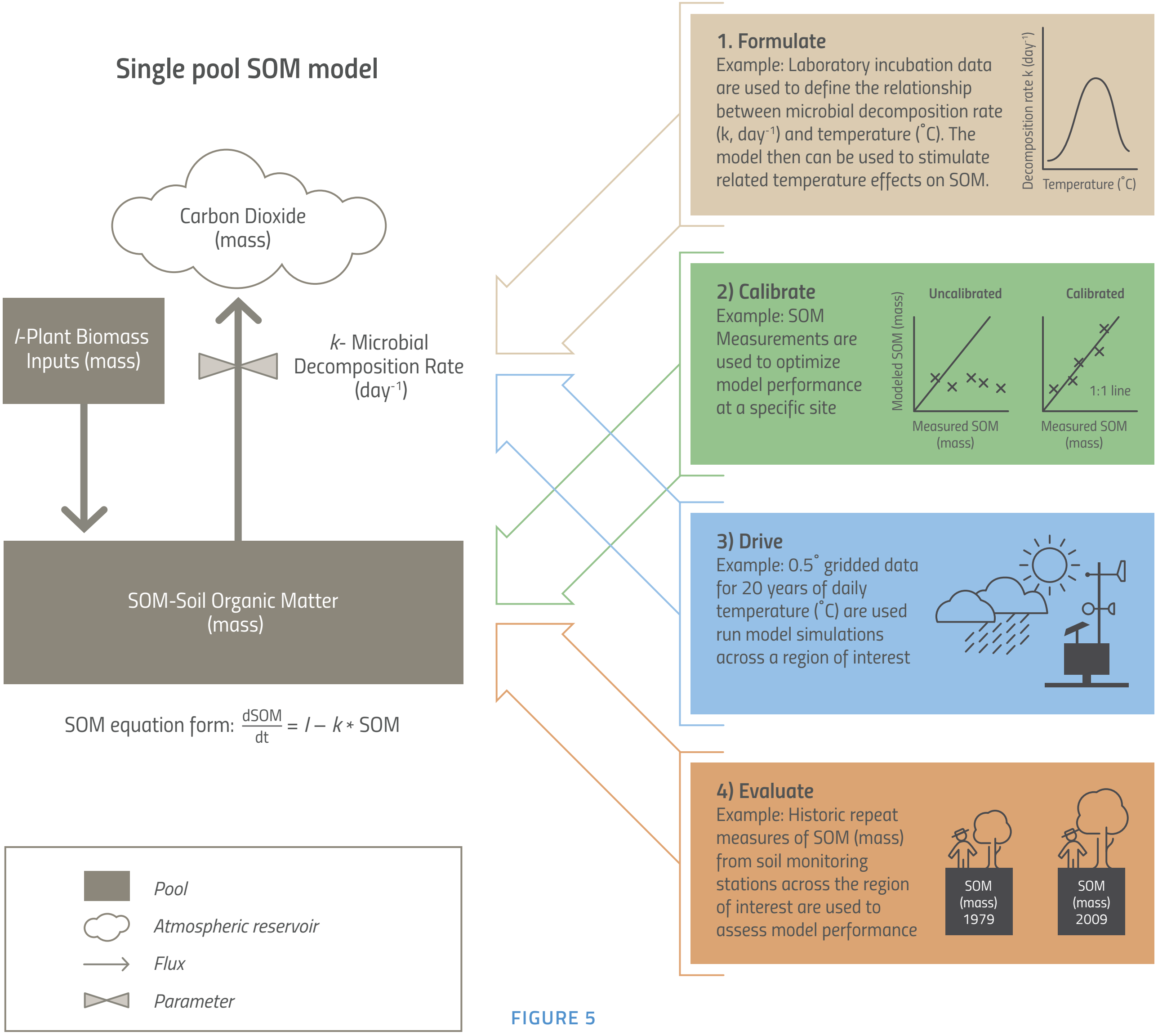
[5] One example can be found in the CBP tool, which has the option for users to interact directly with the CENTURY model, a classic and widespread approach to simulating SOC (Parton et al., 1988). However, direct CENTURY use in CBP is unlikely to be pursued by most practitioners, as the use of this option is far more labour intensive than the use of simpler analysis options that make indirect use of SOC model results (E. Milne, pers. comm).

Theoretically, models of SOC, particularly as a component of full ecosystem models that include both aboveground and belowground physical, biological, and chemical processes, can simulate degradation (e.g. nutrient depletion in soils and associated decreases in plant growth) as well as potential for resilience (e.g. plant growth under current versus future changes in precipitation). However, not all degradation processes are equally, comprehensively,



SOM equation form: $\frac{dSOM}{dt} = I - k * SOM$

1. Formulate
Example: Laboratory incubation data are used to define the relationship between microbial decomposition rate (k, day^{-1}) and temperature (˚C). The model then can be used to stimulate related temperature effects on SOM.

2) Calibrate
Example: SOM Measurements are used to optimize model performance at a specific site

3) Drive
Example: 0.5˚ gridded data for 20 years of daily temperature (˚C) are used run model simulations across a region of interest

4) Evaluate
Example: Historic repeat measures of SOM (mass) from soil monitoring stations across the region of interest are used to assess model performance

FIGURE 5

The structure of a simple soil organic matter (SOM) biophysical model showing how modelled pools, sinks, fluxes and parameters (defined in the bottom left box) are interconnected, as well as how different forms of data are used to (1) formulate the model, (2) calibrate the model, (3) drive the model over large spatial domains, and (4) evaluate model performance. Adapted from Campbell and Paustian (2015).

or dynamically represented in SOC biophysical models. **Currently, the degradation processes most robustly represented in SOC model simulations are those related to land cover change, changes in soil fertility, and declines in aboveground biomass.** Degradation caused by land cover change, for example, can be simulated if a given SOC model is structured to represent the relevant processes affected by this modification. Soil fertility decline related to soil nitrogen is well reflected and linked to simulated declines in SOC, although few models consider other nutrients. Declines in biomass can be simulated dynamically within SOC models where they are linked to soil water and nutrients or can be measured using remote sensing and used as inputs to drive SOC simulations.

SOC biophysical models are constrained in representing other degradation processes due to various factors including limited available data, limited understanding of linkages to SOC processes, computational limitations, or limited sensitivity of SOC to these forms of degradation. Addressing these constraints could improve models and reduce uncertainties in their use for SOC assessment and monitoring. For example, some chemical forms of degradation like acidification and alkalinisation are rarely dynamically modelled but can be represented as pH and cation exchange capacity, common inputs used to define the soil chemical environment for SOC simulations. Other types of soil contamination and processes like salinization are rarely considered. Further, many physical forms of degradation are not dynamically represented in many SOC modelling approaches due to computational complexity. For example, bulk density is used to define the physical soil environment in many SOM simulations, but, for the sake of simplicity, it is often assumed to be constant, thus ignoring compaction (Campbell et al., 2018). Processes like erosion and changes in groundwater levels depend on computationally demanding lateral flows. Hydrological or erosion-specific models exist but are not commonly integrated with dynamic SOC simulations, which introduces substantial uncertainty in global terrestrial C flux estimates (Campbell et al., 2018). Dynamic representation of physical processes in SOC models is recognized as an important need (Campbell et al., 2018).

Despite these limits, **developments in tools/models for SOC assessment are rapid, widespread, and ongoing.** Even though, SOC biophysical models are highly constrained in their capacity to represent many forms of land degradation and their mitigation; protocols for improvements are well established, through data-intensive processes of model development, calibration, and validation (e.g. Figure 5, panels 1, 2, and 4; e.g., Del Grosso et al., 2008). **Where tools/models function poorly or yield highly uncertain results in predicting SOC change for LDN scenarios, and where resources are available, investment in tool/model development[6] i.e. through targeted data gathering at benchmark sites and engagement of experts for model/tool improvements should be incorporated into LDN schemes.**

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[6] tool/model development: an all-encompassing term for the process of improving tools/models for SOC assessment to better represent the areas, land characteristics (e.g. soil texture), and SLM practices of interest. Typically, if tool/model development is necessary, benchmark SOC monitoring sites are needed to gather extensive data that can support development and testing to ensure accuracy. Also, often experts need to be engaged to most support development that most effectively improves analysis of the national, sub-national, or local area of interest.

3.3 Where SOC monitoring is a priority

Given widespread challenges due to limited SOC data, targeted investment in SOC monitoring is vital. National soil inventories are also important SOC information providers that may require harmonization of data and methods to document LDN progress. LDN achievement is assessed at a national scale. Thus, any improvements that do not effectively scale up, at least to the level of matching degrading activities, or cannot be effectively verified at a national level, will have limited practical value for LDN even if they are highly successful at smaller scales. The decision tree in Figure 6 can be used to define where tracking and monitoring of SOC is necessary for verifying LDN achievement.

> The scientific basis of SOC biophysical models, as well as their current capacity to represent land degradation processes, are both keys to understanding 1) SOC biophysical model limitations and, 2) how to best dedicate resources to improve tools/models for SOC assessment, where necessary and feasible.

3.4 Choosing tools for soil organic carbon stocks estimation and monitoring

Measurement-based monitoring of changes in SOC is achievable but may not always be desirable. It is also possible for SOC biophysical models to be used *directly*[7], although this is typically more difficult and far less common. The scientific basis of SOC biophysical models, as well as their current capacity to represent land degradation processes, are both keys to understanding 1) SOC biophysical model limitations and, 2) how to best dedicate resources to improve tools/models for SOC assessment, where necessary and feasible .

3.4.1 Spatial soil organic carbon stocks analyses for land degradation neutrality: data and computational gaps

Achieving LDN requires changing a multitude of activities across large areas and evaluating the impact of these changes at a national scale through the lens of the LDN indicators. From a scientific standpoint, sub-national scale estimates of SOC change are widely recognized as highly challenging (Campbell and Paustian, 2015; Field et al., 2018). SOC models directly or indirectly used for sub-national scale analyses are often limited by the quality and availability of spatially-explicit data to run the model across the area of interest, as well as data to evaluate its performance (e.g. panels 3 and 4, Figure 5). Further, it can be computationally difficult to

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[7] One example can be found in the CBP tool, which has the option for users to interact directly with the CENTURY model, a classic and widespread approach to simulating SOC (Parton et al., 1988). However, direct CENTURY use in CBP is unlikely to be pursued by most practitioners, as the use of this option is far more labour intensive than the use of simpler analysis options that make indirect use of SOC model results (E. Milne, pers. comm).

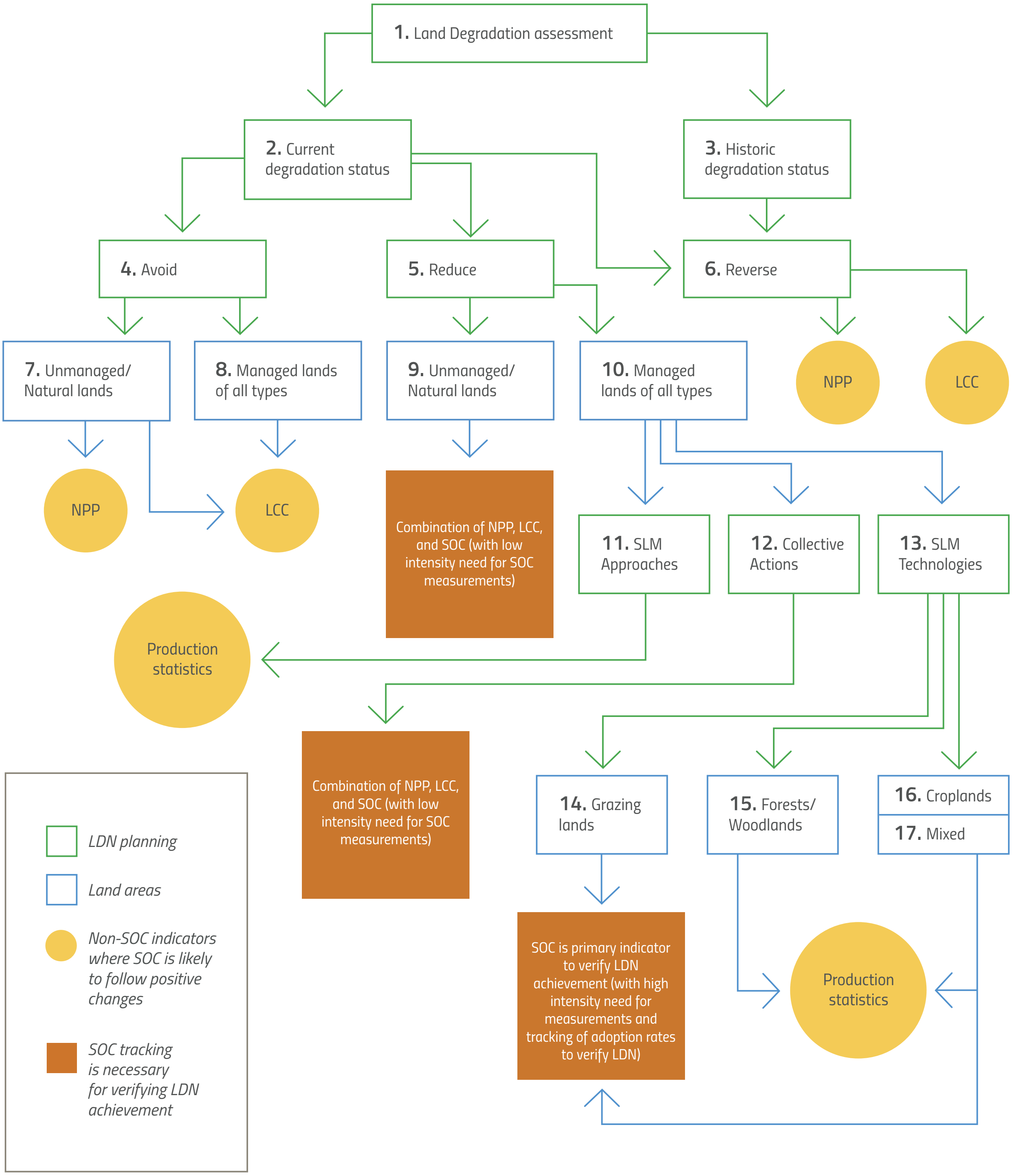

FIGURE 6

Decision tree 4 assists to identify essential areas of SOC monitoring (orange) in the context of other indices of tracking land degradation (yellow), as distributed across degradation status following land degradation assessment and response actions (green) by land types (blue). Low-intensity SOC monitoring would occur over larger or relatively uniform areas, whereas more intensive SOC monitoring is needed in lands that are more variable and where other indicators (LCC, NPP) are not the best metric for land degradation. Production statistics are related to NPP and can be valuable in this context.

represent lateral flows in addition to the complex processes occurring vertically in the soil profile. The use of tools/model for SOC assessment at large scales (sub-national, national) are thus generally constrained by either *data limitations* about spatially-explicit characteristics of the area, or *computational limitations* representing complex spatially-explicit interactions (e.g. topography and lateral soil movements with erosion). **Thus, the quality of the spatial data available for a land area is an important determinant of how well SOC changes within it can be estimated. However, practitioners should be aware of computational limits, as for incorporating soil erosion, that introduce uncertainties that cannot be addressed by improving spatial datasets alone.**

> Improved spatial mapping and model estimates of SOC changes at large scales are recognised as important needs and active areas of development.

Improved spatial mapping and model estimates of SOC changes at large scales are recognised as important needs and active areas of development . For the purposes of LDN, this is an area where targeted gathering of SOC measurements can be very valuable for LDN as well as for other SLM initiatives. Often, land use history (e.g. date of conversion, fallowing) and land management (e.g. grazing practices, fertilizer additions) are among the most difficult pieces of information to gather for the purposes of spatially-explicit SOC evaluation. Many aspects of land management cannot be remotely sensed, and in many areas, there are few resources to collect this information. **Given the impact of human activities on land, limited spatial data on land management practices will very likely be a large source of uncertainty in SOC assessments. LDN practitioners are strongly recommended to create and implement a plan to gather information about land management, particularly with SLM interventions, in order to effectively and accurately scale up SOC assessments for LDN.**

3.4.2 Establishing a national-level strategy to invest in SOC assessment and monitoring

The concept of LDN allows nations to unify around a central goal of halting the loss of healthy, productive lands while maintaining great flexibility in how this goal is achieved. Whereas LDN is ultimately reported at a national level, it will be built out of a highly diverse combination of interventions at sub-national and project-specific scales. This requires responsible parties to consider from the outset, the integration between national-level analyses and site-specific activities, which for SOC is often challenging due to the limited availability of data to evaluate specific combinations of ecotypes, soil textures, SLM interventions, etc., with sufficient accuracy to support decision making and reporting. **Given limited resources, it is important to target investment in (1) comparative assessment of SOC impacts with SLM interventions and (2) SOC monitoring (Figure 1). In practice, these investments will involve varying combinations of direct measurements, remote sensing, and tools/models for SOC assessment. If strategically organized at a national level, such investments will greatly improve the national capacity to manage SOC for LDN and multiple benefits.**

To support the management of SOC for LDN and multiple benefits, a framework (Figure 2) is proposed, where components of LDN planning are supported by the accumulation of datasets and resources (tools/models for SOC assessment) to scale up SOC evaluations, created through planning and coordinating activities to assess, manage, and monitor SOC. National-level infrastructure should be established to organize data and SOC assessment resources based on current and anticipated future needs (e.g. for storage of remote sensing images or spatial datasets).

National-level infrastructure should be established to organize data and SOC assessment resources based on current and anticipated future needs.

Measured data used for SOC assessments (either existing data or acquired from the investments described above) add greatly to the national capacity to manage SOC. Thus, projects targeted for SOC investments require a protocol for contributing new data to a centralized data repository that is easy and clearly defined and supported with sufficient time and funding. National-level accumulation of measured data for SOC assessment could be achieved by requiring all newly gathered data to be organized and submitted to the responsible party for national-level LDN planning, where it can be stored in a centralized, accessible location that is secured from loss. One relatively long-standing example (including what may be a useful template) is provided by the Greenhouse gas Reduction through Agricultural Carbon Enhancement network (GRACEnet) which pairs a freely available, centralized web-based database with a downloadable Excel template, that can be used to organize land management, soil, biomass, and greenhouse gas flux data, that is then submitted back to the database (Jawson et al., 2005). Such harmonized efforts could help countries to measure and report SOC stocks for multiple global land restoration initiatives like the Bonn Challenge (Bonn Challenge, 2017), 4 per 1000 (4 per 1000, 2017), regional ones like African Forest Landscape Restoration Initiative to restore 100 million hectares of degraded land (AFR100, 2017) and initiative to restore 20 million hectares of degraded land in Latin America and the Caribbean (Initiative 20x20, 2017).

There is a global effort to compile soil information in the Global Soil Information System (GLOSIS) of the Global Soil Partnership (GSP) of FAO. GLOSIS fosters the development and strengthens the National Soil Information Systems (NSIS). In this regard, the GSP is offering countries the support necessary to develop and harmonize their NSIS under GLOSIS. This process ultimately aims to reduce data uncertainty and it works in conjunction with the development of Standard Operating Procedures and the execution of global proficiency testing under the Global Soil Laboratory Network (GLOSOLAN), another activity the GSP launched in 2017.

A national-level strategy to invest in SOC assessment and monitoring, as well as in organizing the associated datasets and resources (tools/models for SOC assessment), can support all aspects of LDN planning to manage SOC.

A national-level strategy to invest in SOC assessment and monitoring, as well as in organizing the associated datasets and resources (tools/models for SOC assessment), can support all aspects of LDN planning to manage SOC (Figure 2). SOC assessment can be considered optional in early stages of LDN planning (targeting areas for land degradation interventions and identifying potential SLM interventions, boxes 1–2, Figure 2), instead using other resources (e.g. expert input, local knowledge, other types assessments) when support for SOC assessment is in the early stages of development. Subsequently, it is then critical to identify target areas and potential SLM interventions to invest in SOC monitoring, as this is necessary to scale up SOC assessments to national levels. Where a comparative assessment of SOC impacts with SLM options is recommended to choose and implement SLM (Figure 1, box 13), this report provides guidance on using tools/models for SOC assessment based on the level of certainty required for decision making, drawing on a review of a selection of existing tools.

Establishing baseline SOC for the purposes of LDN planning has the advantage of overlapping with existing protocols for national greenhouse gas inventories.

For general guidance, software should be robust in at least in three areas:

1. interlinkages to other SOC programs, as this diversifies potential avenues for productive collaboration and shared resources;

2. stable software infrastructure and a strong development community, that together can support tool dependability and longevity, and;

3. commitment to open science principles, as related efforts to improve data/results accessibility can greatly simplify collaboration and integration.

3.4.3 Using the initial baseline SOC and land potential to identify priority areas for sustainable land management interventions

Countries are in widely different positions in establishing the state of land degradation on and around the baseline year 2015. Most developed countries have invested in land inventories over many decades and have reliable databases to draw from. The other extreme, are data-poor countries with limited resources to spare for this endeavour. Establishing baseline SOC for the purposes of LDN planning has the advantage of overlapping with existing protocols for national greenhouse gas inventories . It also has the potential to strengthen partnerships aiming to address the widespread need for better global SOC maps. The UNCCD methodological note on setting voluntary LDN targets establishes three tiers for considering indicators for monitoring LDN, described as:

Tier 1 (default method): Global/regional earth observation, geospatial information and modelling;

Tier 2: National statistics based on data acquired for administrative or natural reference units (e.g. watersheds) and national earth observation;

Tier 3 (most detailed method): Field surveys, assessments and ground measurements (Global Mechanism of the UNCCD, 2016).

Here LDN Tiers 1 – 3 are used to differentiate these from IPCC Tiers 1 – 3 which are based on sources of data and analytical complexity,[8] and are referenced in the discussion of tools/ models for SOC assessment below.

For the purposes of SOC, LDN Tier 1 is achieved using global soil maps, LDN Tier 2 using national legacy soil maps, and LDN Tier 3 by creating new maps using new field data. Combining global soil maps with new field data is a 'hybrid' LDN Tier 2 option, that will likely be used in many regions (Nijbroek et al., 2018). The LDN Tier 1 baseline set by the UNCCD relies on the International Soil Reference and Information Centre (ISRIC) 250m resolution SoilGrids soil data product (Hengl et al., 2017). SoilGrids is designed as a globally consistent, data-driven system that predicts soil properties using global covariates and globally fitted models. Other resources for baseline SOC mapping include the Harmonized World Soils Database, the Land Degradation Surveillance Framework, and the Joint Research Centre Threats to Soil (Aynekulu et al.,2017).

Additional global carbon mapping is rapidly advancing on various fronts such as FAO's Global Soils Partnership, which brought the Global Soil Organic Carbon (GSOC) map online in 2017. In the future, FAO's Global Soil Partnership Pillar 4 activities (which aim to "Enhance the quantity and quality of soil data and information: data collection (generation), analysis, validation, reporting, monitoring and integration with other disciplines") may lead to a much improved SOC database. Further information about resources for estimating the SOC baseline is provided in supplementary information "SOC Inventory Tools".

Currently, SoilGrids continues to act as a good resource for initial baseline SOC at an LDN Tier 1 or Tier 2 level. Soil Grids has ongoing software development, commitment to open source software infrastructure, FAIR data principles, and links to the World Soil Information Service [9] soil profile database that is actively collecting and harmonizing soil profile data. It also maintains linkages to a compendium of higher resolution datasets through national, regional, local and non-governmental organizations (NGOs) that may be of use for project-specific activities and sub-national analyses. The GSOCmap is also a useful resource but is coarser in resolution (~1km, as compared to SoilGrids 250 m). It is based on a collaborative national-level data gathering effort. It is due to be updated in the near future and should be considered for more extensive use at that point. Regardless of what resource is used, **the initial baseline SOC should not be considered**

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[8] IPCC Tier 1 using IPCC default emission factors, IPCC Tier 2 using country-specific emission factors, and IPCC Tier 3 using higher level datasets and models with greater certainty (IPCC 2006). It should be noted that IPCC guidelines are due for revision in 2019. Thus, the IPCC Tiers discussed in this report may change and require revision re-align and differentiate from LDN Tiers 1 – 3.

[9] World Soil Information Service

definitive, but instead should be updated as relevant data are accumulated through investments in SOC monitoring, so that the 2030 LDN assessment uses a 2015 baseline for SOC that is at the highest possible LDN Tier. The GSP working group for developing guidelines for measuring, mapping, monitoring and reporting on SOC stocks and stock changes could also contribute to this purpose.

Ideally, the initial baseline SOC would be used alongside an estimation of historic trends in SOC to identify target areas for land degradation interventions (i.e. where to avoid changes, reduce losses, or restore land), and then monitor their subsequent effects. However, for SOC, analysis of historical trends in SOC losses depends on the availability of historical data of SOC levels and land use history and is likely to be very coarse and/or uncertain at national levels, especially in the initial stages of LDN planning. **It may not be practical to invest in this type of top-down analysis of historic SOC degradation at national levels to identify target areas for LDN intervention for SOC, as it is resource-intensive and may not be certain enough to be useful.** The exception would be if such SOC analyses have already been undertaken by other parties and are readily available, in which case they should be considered.

As a practical alternative where soil data are limited, **it is possible to use a subset of land cover types and land characteristics as a coarse but simple method to identify priority areas where, in addressing land degradation, soils and SOC management may be the primary focus.** Specifically, it is important to identify (1) grazing lands/croplands as targets where SOC accrual is likely the primary metric of successful SLM interventions (i.e. Figure 6), (2) areas of low precipitation and/or highly erodible soils where SOC is likely vulnerable to loss and thus may be targets of interventions to avoid or reduce land degradation, and 3) high SOC and/or high clay soils that, through higher capacity to increase or store SOC, may be more likely to yield strong economic benefits through carbon trading. This approach can be implemented at an LDN Tier 1 level using the initial 2015 baseline SOC, land cover and land potential datasets used in LDN land typing (Orr et al., 2017).

Once priority areas for LDN projects have been identified, other sources of information for land degradation status and local expertise can be used to identify 'hotspot' targets for SLM where, as described in Orr et al. (2017), "land condition is good but deteriorating" (pg. 71). A 'LDN Tier 1' approach to assessing land degradation status for land areas would use global level information about land degradation, as from FAO's Global Land Degradation Information System (GLADIS), a coarse global-level database of land status, or from Global Land Degradation Assessment (GLADA) as it becomes available beyond the initial six pilot countries of Argentina, China, Cuba, Senegal, South Africa, and Tunisia. A 'LDN Tier 2' approach could use national-level information based on trends in LCC and NPP. For example, recent negative changes in LCC or NPP (<5 years) may not have led to a large decrease in SOC, while mid-term changes (5 – 15 years) may have ongoing SOC declines, and long-term changes (>20 years) may have stabilized at a lower SOC equilibrium. Recent-decline regions might be priority areas for SLM to reduce SOC losses before they become severe or irreversible. The Trends. Earth tool may be a good resource for this approach, designed to support national-level assessment of land degradation including methods to estimate SOC based on SoilGrids 250m dataset to provide baseline SOC stock, and land cover change to estimate impacts of land use on SOC stock change. An 'LDN Tier 3' approach would use land use/management historic data, measured SOC data, and tools/models for SOC assessment to estimate historic SOC changes for a specific area. This 'LDN Tier 3' approach would likely be substantially more resource-intensive. Therefore, if selected for investment, it is recommended that it should be closely linked with the process of selecting SLM interventions for SOC and establishing SOC monitoring.

Comparative SOC assessments can be completed with either simplified software tools or more detailed biophysical models. Software tools generally are designed to evaluate SOC using simpler statistical and empirical approaches, often allowing use of embedded default datasets, and often in the context of more comprehensive carbon accounting or socio-economic analyses. Software tools are generally more suitable when low to moderate levels of certainty are required, although some can be used with high levels of certainty. Biophysical models, in contrast, more explicitly represent processes impacting SOC and can yield results that are of relatively high certainty. However, their use often requires investment in more extensive training or expert involvement. The FAO's (2019) review of SOC modelling approaches is an excellent resource in the case biophysical models are called for.

To help guide LDN practitioners, this report provides an overview of existing software tools for SOC assessment. To select tools for review, the analysis started with the recent World Bank Group review of carbon accounting tools for SLM, which considered seven carbon accounting tools selected according to criteria of availability, geographical coverage, activities scope, data requirements, time requirements, and skill requirements. For this report, the six tools that included evaluation of SOC were reviewed: Agriculture, Forestry and Other Land Use (AFOLU) carbon calculator, Carbon Benefits Project (CBP), Climate Change, Agriculture and Food Security Mitigation Options Tool (CCAFS-MOT), Cool Farm Tool (CFT), and EX-Ante Carbon balance Tool (EX-ACT) (Toudert et al., 2018, Table 8). For each tool, the documentation was reviewed and, where possible, experts involved in tool development were interviewed to identify (1) whether tools could connect SOC assessments across national, sub-national, and project-specific scales, and (2) whether tools accommodated interlinkages, had stable software infrastructure, a strong development community, and commitment to open science principles. During this review process, the Trends. Earth tool was also considered in the review. Where applicable, interconnected tools and resources useful in LDN were also reviewed. **Resource cards based on these reviews were written for each tool. The summaries in Table 8 and Table 9 can be used by practitioners to select which tools or suite of tools will best fit their needs (Figure 4). Further information about each of the tools is provided in supplementary information "SOC tool resource cards".**

TABLE 8

Comparison of tools for SOC assessment and monitoring showing recommended (+++), possible (+) or not recommended/not possible (-) uses at different spatial scales and types of SOC assessments for LDN.

Tool	Review date	Spatial Scale			
		Project	Subnational	National	Linking across scales
AFOLU Carb	2/8/19	+	+++	-	+
CBP	2/11/19	+++	+++	+++	+
CCAFS-MOT	2/4/19	+++	+	-	+
CFT	2/1/19	+++	+	-	+
Ex-ACT	2/13/19	+	+++	+++	+
Trends. Earth	3/7/19	-	+++	+++	+

CBP is a viable option for more intensive, quantitatively robust analyses of SOC. It is also appropriate for use in SOC monitoring. CBP is directly connected to the WOCAT database and LandPKS, a mobile app that focuses on what a landowner can collect or needs to know to make more sustainable choices about how to manage their land. This suite of tools uses standardised language across multiple platforms to facilitate interconnections. CBP software is designed for expansion and additional linkages in the future. The software is hosted by Colorado State University and maintains stable accessibility to users even when funds for development are not available. However, it is comparatively time-intensive to use and is better suited to SOC assessments that require moderate to high levels of certainty.

Trends. Earth is a stable web-based tool designed to support Sustainable Development Goal (SDG) 15.3.1 and thus is ideal for national scale SOC monitoring and reporting. It is also recommended as a resource for the initial evaluation of land degradation status, as a component of targeting areas to consider SLM options. Trends. Earth allows the input of higher resolution spatial data to replace default global datasets and therefore can be used to improve SOC mapping as data are collected through sub-national and project-level measurement and SOC monitoring investments. It does not currently support the input of SLM practices, as spatially-explicit datasets for land use and land management are not sufficiently available. However, Trends. Earth is developing linkages with WOCAT and LandPKS to help address this need, and there will likely be developments to allow users to input this information.

* i.e. to facilitate or inform discussion
** i.e. to select SLM for LDN, where any positive change is beneficial
*** i.e. to select SLM to optimize SOC for carbon crediting or other economic incentives

Recommended uses of SOC assesment tools

	To compare potential SLM with different required levels of certainty in SOC			*To monitor SOC*		
	Low certainty required*	Moderate certainty required**	High certainty required***	Use	SOC model	Description of default data and SOC estimation (for use when no data are available)
	+++	-	-	-	-	global datasets, all climates, IPCC Tier 1 emission factors
	+	+++	+++	+++	CENTURY	global datasets, all climates, IPCC Tier 1 emission factors
	+++	+	-	-	-	empirical relationships at global scale or sub-national if available
	+	+++	+	-	-	global datasets, all climates, IPCC Tier 1 emission factors or literature values if available
	+++	+++	+	-	-	global datasets, all climates, IPCC Tier 1 emission factors
	-	-	-	+++	-	global datasets, all climates, SOC mapping either input directly or using Tier 1 IPCC emission factors

(+++ recommended, + possible, - not recommended/not possible)

The **EX-ACT** and **CCAFS-MOT** tools are both Excel-based, making them good selections if practitioners want to use tools that do not require web access. The CCAFS-MOT tool could be considered for discussion-based SLM selection at specific sites. It is straightforward and easy to use, designed to be a resource in policy and discussion setting. It is also stable and reasonably easy to adapt to local information or scenarios. It has been used successfully in this regard in Ethiopia. The EX-ANTE tool supports a more comprehensive assessment of carbon footprints within development projects. It performs comparably to CBP in terms of ex-ante carbon assessments, can be easily updated to IPCC Tier 2 emission factors that allow for higher levels of national-specificity, and is associated with other tools that provide additional resources for small-scale development projects (EX-ANTE MRV) and food value chain analysis (EX-ACT tool for value chains).

AFOLU can offer support to guide discussions at larger scales (communities, watersheds), by its design to assess carbon impacts across large administrative units. However, the future of the software is uncertain beyond 2020. AFOLU should certainly be considered for use if it remains accessible at the time it is needed. However, it will not be a dependable resource until continual online access is more certain.

Software				World Bank Group 2018 comparison of carbon assessment tools for SLM			
Tool	**Platform**	**Users**	**Linkages**	**Summary of activities included in tool**	**Time need**	**Data need**	**Skill need**
AFOLU Carb	Web-based	USAID project managers for oversea programs	Winrock International, USAID, Applied GeoSolutions	Croplands (Temperate crops, tropical crops, rice cultivation) Grazing land (grassland, livestock) Forest/Woodlands (orchards/vineyards, forests) Mixed (field trees/hedges/agroforestry)	Med	Low	Low
CBP	Web-based	SLM Project managers, SLM program officers, SLM experts	WOCAT, LandPKS, 4 per 1000, VERRA carbon crediting (possible)	Croplands (Temperate crops, tropical crops, rice cultivation) Grazing land (grassland, livestock) Forest/Woodlands (orchards/vineyards, forests) Mixed (field trees/hedges/agroforestry) Other (wetlands, settlements)	High	Low	Med
CCAFS-MOT	Excel	Multi-stakeholder (climate change/ag decision makers, educators, researchers, project managers)	Cool Farm Tool	Croplands (Temperate crops, tropical crops, rice cultivation) Grazing land (grassland, livestock) Forest/Woodlands (orchards/vineyards) Mixed (field trees/hedges/agroforestry)	Low	Low	Very Low
CFT	Web-based	Paying members (Industry), land managers, project managers	50+ commercial partners, Cool Farm Alliance, (Possible) Gold Standard Foundation	Croplands (Temperate crops, tropical crops, rice cultivation) Grazing land (livestock) Forest/Woodlands (orchards/vineyards) Mixed (field trees/hedges/agroforestry)	Med	Low	Low
Ex-ACT	Excel	Trained program officers and consultants working with development projects and agencies	FAO suite of programs- EX-ACT MRV for a smaller project, EX-ACT for value chains	Croplands (Temperate crops, tropical crops, rice cultivation) Grazing land (grassland, livestock) Forest/Woodlands (orchards/vineyards, forests) Mixed (field trees/hedges/agroforestry) Other (wetlands, settlements)	Med	Low	Med
Trends. Earth	Web-based	Conservation International for internal projects, managers of LDN reporting, researchers	WOCAT, LandPKS, UNCCD reporting, NASA, ISRIC	NA (SLM practices not included in tool)	NA	NA	NA

TABLE 9

Comparison of tools for SOC assessment and monitoring describing the current status of the software platform, users, and linkages to other programs. Activity information and needs in terms of time (low = 0 - 10 min, med = 10 - 30 min, high = >30 min), data, and skill were drawn from the 2018 World Bank Group report (Toudert et al., 2018) where available.

Of all of the tools evaluated, the *CFT* is most strongly linked with industry partners and should be considered if industry collaborations are a consideration in SLM selection at local scales. If it is approved for carbon crediting by Gold Standard, where it is currently under review, CFT is recommended for application in priority zones where the potential for SOC accrual is high.

All tools included in this review can be used globally in all climates, with a general summary of activities included in Table 9. **Data gaps and tool development needs are likely to be identified in the process of completing comparative SOC assessments within a specific national context** (Figure 4). Where high certainty in SOC assessment is required, addressing data gaps and model/tool development needs may be necessary in order to complete comparative SOC assessment and select SLM options for implementation. Where lower levels of certainty are required for SLM decision making, however, it may be optional to fill data gaps or address tool development needs. Addressing these data gaps and tool development needs may, however, be necessary to support national-scale SOC assessment for LDN. In either case, benchmark sites i.e. where key SLM practices have been implemented, or in eco-regions/soil textures/etc where little data are available can be used to target intensive, high-value data gathering. Datasets from benchmark sites can support the development of tools/models for SOC assessment for greater accuracy in a specific national context, and improve national capacity to assess, manage, and monitor SOC.

3.4.4 Soil organic carbon stocks measurement to support monitoring

A challenge with monitoring increases in SOC is the required level of precision, i.e. that the monitoring precision needs to be high enough to detect SOC change due to SLM with enough certainty that it can be considered real. Figure 7 offers a decision tree to arrive at the type of soil sampling scheme that is fit for the challenge at hand. If financial and human resources are not a constraint, it is recommended to establish a national SOC monitoring network that includes a carefully designed distribution of plots for SOC measurements, of which there are existing examples supporting initiatives like national GHG inventories (e.g., Spencer et al., 2011). A large number of countries have no or very limited soil sampling schemes and will need to allocate resources to that end (Shepherd et al., 2015b). If, as is likely, such resources are limited, the decision tree presented in Figure 6 will help decide where these resources are best deployed.

If financial and human resources are not a constraint, it is recommended to establish a national SOC monitoring network that includes a carefully designed distribution of plots for SOC measurements, of which there are existing examples supporting initiatives like national GHG inventories.

SOC estimation, both ex-ante and ex-post, can be done through tools/models for SOC assessment. However, the accuracy of such assessments and the scale at which they can be applied are dependent on soil datasets available to calibrate SOC assessment tools and models to local conditions. Whereas assessments of SOC at large scales (national) are useful in setting national LDN priorities and targets as demonstrated by Milne et al. (2007), it is not the scale at which LDN is made actionable through SLM (local, sub-national). **Thus, for the purposes of LDN, the generation of measured SOC datasets must be considered in conjunction with the use (and steady improvement) of tools/models for SOC assessment, both at the scale of LDN activities (project to sub-national) and at the scale of monitoring LDN achievement (national).**

> SOC measurements in native and unmanaged vegetation would be helpful if, following conversion, re-vegetation efforts are undertaken before extensive soil degradation has occurred in order to reduce land degradation.

For the purposes of large-scale coordination, Orr et al. (2017) detail procedures for leveraging existing land planning activities, specifically connecting LDN planning to: “UNCCD NAPs, United Nations Framework Convention on Climate Change (UNFCCC) National Adaptation Plans and Nationally Determined Contributions (NDCs), and mainstreaming into national development plans and other policy processes” (pg. 62). These efforts are ideally grounded in solid, data-based land degradation baseline assessments. **Given that the three baseline indicators of LDN often track in unison: in areas where analysis and tracking of LCC and/or NPP through remote sensing are sufficient, investment in monitoring SOC change (via measurement alone or combined measurement and tools/models for SOC assessment) may not be necessary unless there are co-benefits to be gained. However, given that SOC does not always track NPP and LCC (Oldfield et al., 2019), it is important to identify where and at what scales, for the purposes of supporting LDN, SOC monitoring is essential to effectively track and scale up assessments of SOC changes. However, vegetation indices should be carefully interpreted. An increase in above ground biomass (greenness), for example, could be a sign of land degradation due to bush encroachment into grazing lands (Aynekulu et al., 2017).**

In LDN activities to avoid land degradation, SOC may not be the indicator of choice. However, SOC measurements in native and unmanaged vegetation would be helpful if, following conversion, re-vegetation efforts are undertaken before extensive soil degradation has occurred in order to reduce land degradation . Afforestation or secondary regrowth will gradually restore SOC, and affirmation of this process would be warranted for LDN accounting. Measuring baseline SOC levels would be essential if the vegetation is eliminated entirely. If not, vegetation remains can be sampled together with the recovered stands 10 – 15 years following the implementation of the measure. As such disturbance normally affects rather large and uniform areas, representative sampling schemes can be of low density as long as landscape conditions are considered.

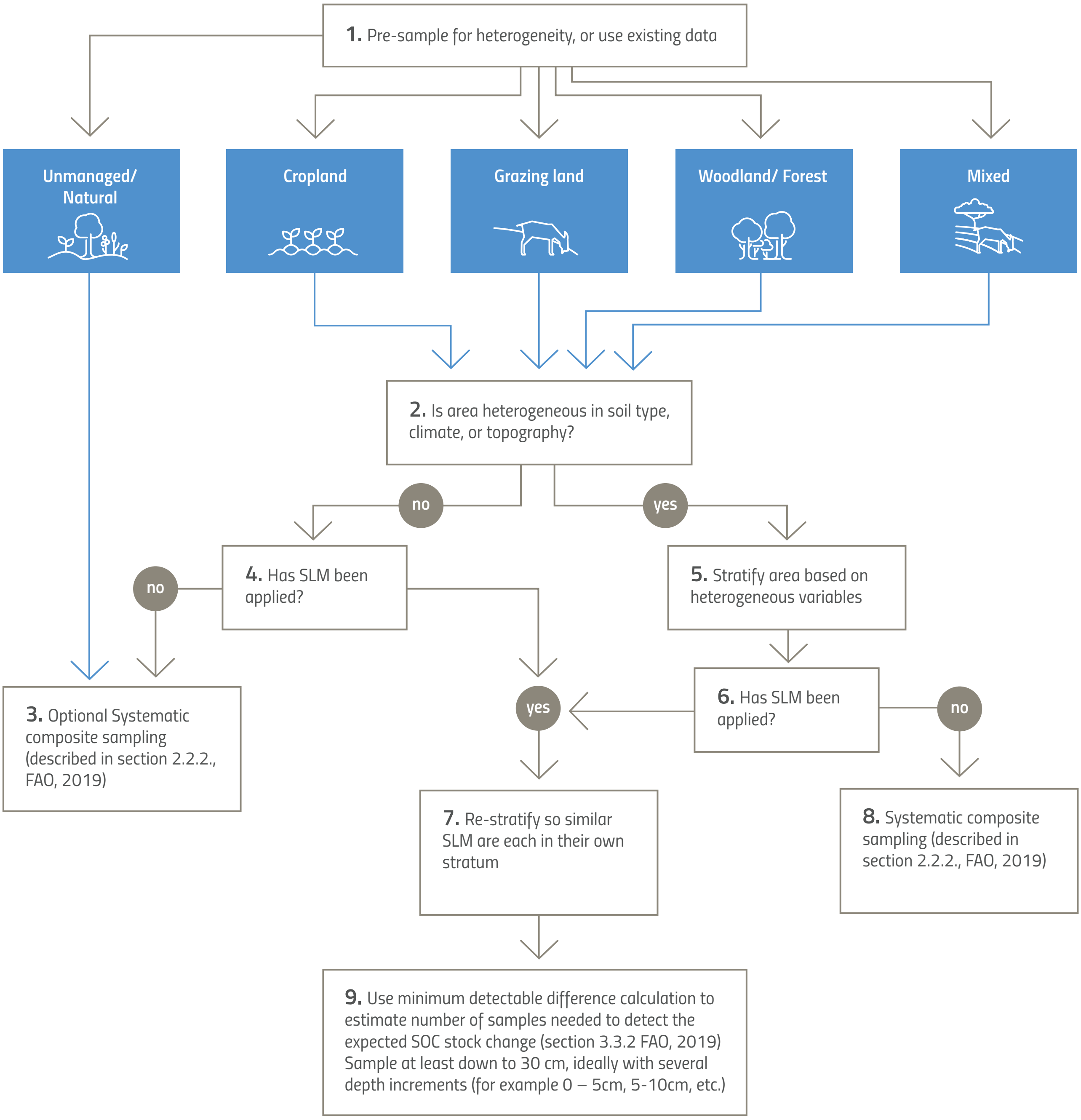
Avoiding land degradation in stable managed vegetation, ranging from near natural parklands to checkerboards of small plots with different farming systems or large-scale farming or animal operations, also can be monitored using other indices of land degradation, i.e. without investing in SOC sampling schemes. If funds allow, including such areas in a soil monitoring system will help certify that the management of such areas is sustainable. However, lacking such funds, stable agricultural production statistics combined with remotely sensed NPP are likely to be reflective of stable soil conditions.

Efforts to reduce land degradation in managed vegetation such as cropland and grazing lands can be rather different in nature. If a government opts for institutional SLM approaches such as a fertilizer subsidy scheme (e.g. Malawi) the impact may be reflected in agricultural production statistics, and SOC accrual may be implied there where it is adopted. If the selected SLM approach is decided at a lower administrative level or targeted to a region with land degradation hotspots, the impact should be measured within the relevant administrative boundaries. A more direct connection exists with LDN schemes focused on land use planning, which often involve structural or vegetation measures crossing numerous property lines or commons. Such programs will greatly benefit from establishing a baseline for SOC with the highest possible level of precision, prior to SLM implementation. Any such sampling schemes should target the areas within the watershed/administrative unit that will see structural or vegetation changes. Even though improvements in NPP or yields may be easy to track, in areas where NPP remains unchanged it is possible for SOC stocks to build up. Farmers may react differently to the new land conditions and thus the sampling frame needs to capture this diversity. Investment in SOC monitoring may be considerable but is valuable for verification of LDN achievement in areas where LC is not changing and SOC cannot be assumed to follow trends in NPP.

Reductions in land degradation by SLM technologies at the farm level, whether it involves animal production, wood or fruit plantations, crop production or combinations thereof, will be reflected in agricultural production statistics over time if adopted on a large enough scale.

Reductions in land degradation by SLM technologies at the farm level, whether it involves animal production, wood or fruit plantations, crop production or combinations thereof, will be reflected in agricultural production statistics over time if adopted on a large enough scale. However, to claim the success of such technologies, baseline SOC levels are to be measured representatively, preferably prior to the promotion of the technology in a designated land degradation hotspot. The sampling should be repeated at intervals, latest in 2030, the year of national reporting on LDN. Absent such a measured SOC baseline, paired "space-for-time" sampling can be done at the designated resampling time ensuring that both adopters and non-adopters are properly represented (Figure 3).

The need for harmonized and comparable soil data and indicators that can be used to monitor the impacts of SLM has been broadly recognized and forms one of the pillars of FAO's Global Soil Partnership (e.g. Pillar 5: "Harmonization of methods, measurements and indicator for the sustainable management and protection of soil resources"). This so far has guided the establishment of the Global Soil Laboratory Network (GLOSOLAN) that will be able to coordinate the activities of the Regional Soil Laboratory Networks (RESOLANs); the South-East Asia Laboratory Network (SEALNET), and the Latin American Network of Soil Laboratories (LATSOLAN) are already active and several more should be created in 2019. Increasingly, resources are made available to standardize procedures for gathering and reporting soil data to centralized databases that collectively improve soil data availability. Recognizing the mutual SOC benefits across the UN Conventions may help stretch available resources in what is likely a relatively laborious and costly undertaking. Where possible, measurement standards should be used that yield data that are generalizable to multiple efforts in sustainable soil management. If measurement standards are recommended by specific SOC inventory or evaluation tools selected for LDN analyses, or by GLOSOLAN/RESOLANs, using those standards as guidance is recommended. **If SoilGrids is used for SOC inventories, for example, it may be efficient to use ISRIC soil measurement standards to directly augment the database used for SoilGrids calculations. CBP, if used to evaluate SOC stocks and changes, integrates recommendations for updating baseline IPCC values with region-specific information and references back to ISRIC procedures. Another valuable resource is provided by the World Agroforestry Center** (Aynekulu et al., 2011). In fact, the existence of so many analytical procedures worldwide acts as its own constraint; thus, it is strongly recommended to support harmonization standards from FAO's Global Soil Partnership Pillar 5 activities, as they develop.



FAO. 2019 "Measuring and Modelling Soil Carbon Stocks and Stock Changes in Livestock Production Systems Guidelines for Assessment." Rome. <http://www.fao.org/3/I9693EN/i9693en.pdf>

FIGURE 7

Decision tree 5 assists to select types of sampling approaches to measure SOC and evaluate SOC changes with SLM. It is recommended at a minimum to sample 0 – 30cm to align with UNFCCC requirements. Deeper measurements of SOC change can be useful but may not be as cost-effective or feasible.

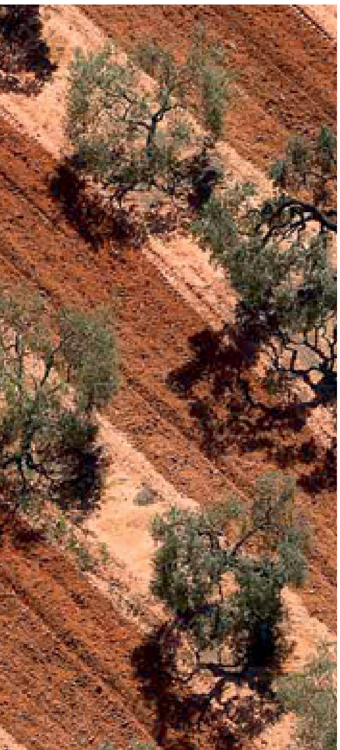
3.4.5 Assessing land degradation neutrality achievement

LDN achievement through maintaining or enhancing SOC should be assessed using all information accumulated during the LDN process, i.e. SOC measurements, land management information, and supporting datasets for SOC assessments (Figure 3). These efforts should be used to improve the baseline SOC for 2015 to the highest possible level of resolution. For example, the initial 2015 SOC assessments may not have had explicit information about land management history. This may motivate national-level LDN planners to acquire this information during deployment of LDN activities. A useful tool to consider for this purpose is LandPKS (, discussed in Section 5.4.3). Baseline SOC assessments for 2015 can thus be retroactively updated for greater accuracy.

LDN achievement through maintaining or enhancing SOC should be assessed using all information accumulated during the LDN process, such as SOC measurements, land management information, and supporting datasets for SOC assessments.

For the purposes of the 2030 SOC assessment to verify LDN achievement, the most valuable datasets would combine spatially-explicit adoption rates with repeat measurements of SOC at sites with the adoption of a given SLM, ideally with > 5-year intervals from SLM implementation. A less ideal but still useful data resource would be provided by measurements that substitute space for time in paired assessment, in other words one-time measurements of land areas with and without adoption that are co-located on similar soils and climates, and assuming that any differences between them are due to differences in management (Figure 3). Ideally, the 2030 SOC assessment to verify LDN achievement would be at an LDN Tier 2 or 3 level. The greatest levels of certainty will be in land types and areas where SOC monitoring was established.

Achieve the soil organic carbon monitoring and measurement standards harmonization for the purpose to assess land degradation neutrality achievement.



Guidance for land managers

Target SLM to maintain or increase soil organic carbon practices to avoid, reduce and reverse land degradation.

4.1. Implementation of sustainable land management to maintain or enhance soil organic carbon and achieve land degradation neutrality

1. Select SLM practices to suit the local socio-economic conditions, including gender and equality, and the biophysical context:

   a. Suitable SLM practices should be identified by the national/local land-related stakeholders, utilizing local and traditional knowledge, hybrid knowledge and relevant scientific evidence.

   b. Selection of suitable SLM practices should take into consideration gender-responsive actions including project activities that proactively address gender sensitivities and promote gender equality and women's empowerment.

   c. Utilize information on current land condition including land degradation status, inherent potential of land to maintain or increase SOC (i.e., where there is a substantial "SOC gap", and the land is likely responsive to management), and to deliver other socio-economic and ecological co-benefits to target **SLM interventions to avoid, reduce and reverse land degradation.**

   d. Learn and apply adaptive management: While the relationship between SLM and increase in SOC is often not "proven", it is reasonable to assume – at first pass - that SLM practices will maintain or increase SOC. Learn the contributions of SLM practices to maintain or increase SOC and deliver other socio-economic and ecological co-benefits and refine proposals for SLM practices when necessary.

2. Apply **integrated landscape management:** Use integrated land use planning tools to estimate cumulative impacts of land use decisions and current land management on SOC and other LDN indicators; plan interventions across landscapes to balance areas of anticipated SOC loss with areas of restoration/rehabilitation in same land use type. Use economic tools/models to project long-term costs, benefits and risks of SLM intervention options;

3. While there is increasing scientific evidence of the potential of SLM practices to create multi-functional landscapes that simultaneously address LDN, land-based climate change adaptation and mitigation, and the conservation of biological diversity, while also securing the quantity and quality of soil and water resources, assessments of SLM adoption should include **assessments of co-benefits and trade-offs between ecosystem services provided by land**, to contribute to the evidence base of quantified examples of the multiple benefits of SLM.

4. Consider management impacts on the soil inorganic carbon (SIC) component, which is of particular relevance to drylands, where it forms a large proportion of total soil carbon stock. Although SIC is relatively stable, inappropriate land management (irrigation, chemical fertilization) may be responsible for the release of CO^2 derived from SIC into the *atmosphere, negating efforts to sequester carbon in soil through SLM.*

While there is increasing scientific evidence of the potential of SLM practices to create multi-functional landscapes that simultaneously address LDN, land-based climate change adaptation and mitigation, and the conservation of biological diversity, while also securing the quantity and quality of soil and water resources, assessments of SLM adoption should include assessments of co-benefits and trade-offs between ecosystem services provided by land, to contribute to the evidence base of quantified examples of the multiple benefits of SLM.

4.2 Estimating and monitoring soil organic carbon

LDN is monitored using three global indicators land cover change; change in net primary productivity; change in soil carbon stocks, plus nationally-relevant indicators. Often SOC is correlated with NPP and LCC; intensive effort for measurement of SOC is less important where NPP and land cover are changing; therefore

1. **Focus SOC measurement on sites where SOC is the key indicator** (e.g., in croplands and grazing lands where NPP and LCC are less reliable indicators of Land degradation – such as between different cropland management practices; or where specific land degradation processes are not readily reflected in trends in land cover and land productivity);

2. **Use tools/models** for SOC assessment to estimate SOC and map SOC, where SOC is not a key indicator. Choose an appropriate tool/model according to the purpose: different tools/models are relevant for planning and monitoring;

    a. **Use national/local data and local expertise** to apply SOC tools/models for SOC assessment for estimation and monitoring. There are several existing and free global datasets that could offer soil SOC information. Perform a stocktake of national/local data and expertise; where gaps are identified, allocate resources to build national capacity for soil sampling and analysis; develop/enhance national SOC data and strengthen collaboration with international bodies like the Global Soil Partnership (GSP);

    b. **Investment in measurement and capacity-building can improve tools/models for SOC assessment and reduce model uncertainties, to reduce costs of SOC estimation in the longer term.** Use available data to test and enhance models, and where SOC tools/models for SOC assessment are not adequate, allocate resources to enhance tools/models: establish benchmark sites in key ecosystems, undertake sampling, build capacity for tool/model development **Regional cooperation and partnership** could enable an efficient approach to model testing and development for key agro-ecosystems and SLM practices;

3. **Combining measurement and tools/models for SOC assessment** can be an efficient and robust approach to minimize cost: use measurement to establish the baseline, apply tools/models to estimate SOC change. (Measure the baseline at the accuracy required, depending on whether SOC change is to be estimated by tool/model or re-measurement – higher accuracy is required for the latter). Quantify and report measurement and model uncertainties .

> Investment in measurement and capacity building can improve tools/models for SOC assessment and reduce model uncertainties, to reduce costs of SOC estimation in the longer term.

Combining measurement and tools/models for SOC assessment can be an efficient and robust approach to minimize cost.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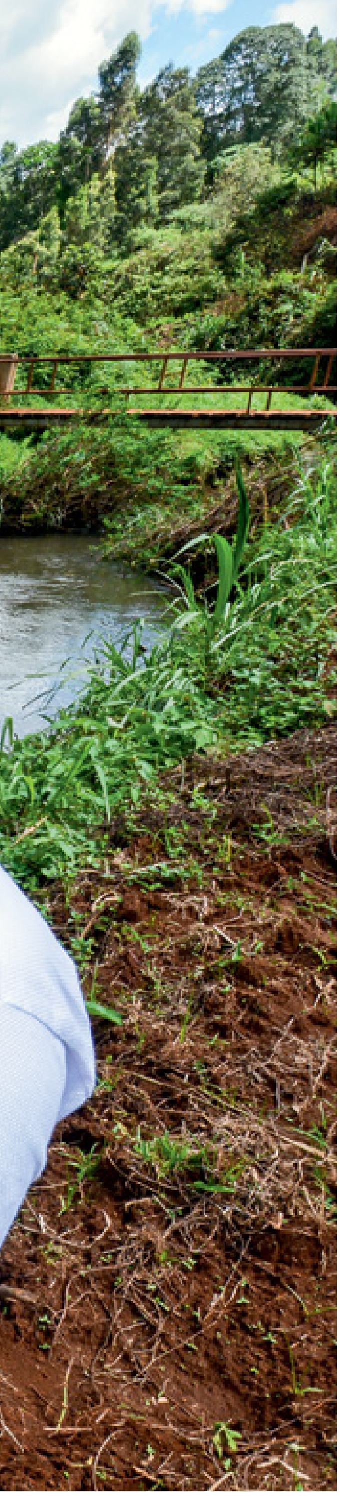
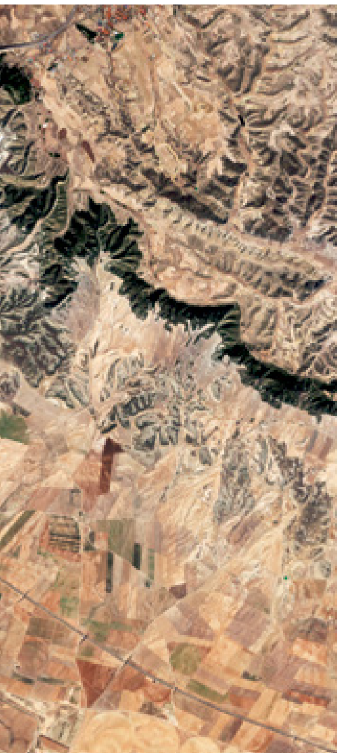




Conclusion and policy-oriented proposals

Policy-oriented options for immediate actions to achieve LDN through SLM technologies and approaches to maintain and enhance SOC stocks.

Sustainable land management (SLM) is one of the main mechanisms to achieve LDN (Orr et al., 2017). SLM can maintain and enhance SOC levels by enhancing plant growth, utilizing organic matter resources for soil amendments, and reducing SOC losses (Sanz et al., 2017). The SPI technical report for sub-objective 1.1 provides a scientific foundation for managing SOC through SLM interventions designed to achieve LDN and deliver multiple environmental and development benefits. It also provides guidance to address the challenges in measuring and monitoring SOC. This report can help countries identify suitable context-specific SLM technologies and approaches to maintain and enhance SOC stocks, and help countries estimate and monitor SOC, for land use planning and for monitoring LDN. There are four main conclusions with corresponding policy-oriented proposals:

Conclusion 1: SOC is a fundamental ecosystem health indicator, and with its multifunctional roles, its sensitivity to land management, and its direct relevance to the missions of all three Rio conventions, constitutes a key criterion for the identification of suitable SLM technologies to contribute to the achievement of LDN;

Proposal 1. Encourage country Parties to:

1. employ SLM technologies and approaches that are designed to maintain or increase SOC with the aim of achieving multiple benefits;
2. use SOC as an indicator to monitor SLM-based LDN interventions to support the achievement of LDN;
3. align SOC monitoring to national LDN monitoring; and
4. share the guidance for land managers at national and sub-national levels.

Conclusion 2: The challenges of (i) predicting potential SOC changes with SLM interventions and (ii) tracking SOC changes on temporal and spatial scales, can be addressed with the use of tools/models developed to estimate SOC dynamics. Management of SOC for LDN requires a framework designed to support investment decisions (national to project level), to focus LDN interventions in zones at risk, and to support the selection of appropriate SLM technologies and approaches. Such a framework would provide a structured approach, enabling the integration of measured data and tools/models for SOC assessment, to support the planning of locally-suited SLM and rehabilitation/restoration interventions in the context of integrated land use management to achieve LDN.

Proposal 2. Invite technical partners specializing in SLM, in collaboration with relevant scientific mechanisms (e.g., the Intergovernmental Technical Panel on Soils (ITPS) of the Global Soil Partnership (GSP)) to design a framework for management of SOC for LDN to support investment decisions, to focus interventions on area at risk, and to support selection of locally appropriate SLM technologies and approaches. This framework would guide country Parties in their efforts to:

1. Evaluate land potential and current land condition, as the basis for identifying priority areas for avoiding, reducing and reversing land degradation;
2. Identify SLM interventions appropriate to local conditions;
3. Focus SLM interventions on areas where SOC is at risk of loss, or where there is high potential to increase SOC stocks; and
4. Invest in SOC monitoring where SOC tracking is recommended for LDN achievement, and to develop knowledge on the relationship between SLM and SOC to identify SLM practices the build SOC and quantifying their co-benefits.

Conclusion 3. A framework for management of SOC to support the achievement of LDN will be most effective if it promotes gender equality and inclusive development, enables women to invest in natural resources, builds capacity of local institutions and involves stakeholders in identifying suitable SLM practices.

Proposal 3. Urge country Parties and other stakeholders to:

1. Integrate gender-responsive actions to promote gender equality and female empowerment through gender-inclusive design of preliminary LDN assessments recommended by the Scientific Conceptual Framework for Land Degradation Neutrality;

2. Develop gender-responsive LDN interventions based on women's participation in decision-making for enabling inclusive land governance; and

3. Include gender dimensions in land use planning and in the design of interventions towards achieving LDN;

4. Employ the gender evaluation criteria such as those developed by the Global Land Tool Network facilitated by the UN-Habitat.

Conclusion 4: The level of certainty required in SOC assessment varies depending on the objective of the assessment. Moreover, national capacity to measure and monitor SOC is highly variable. Measurement and monitoring programs should assess SOC at the level of certainty suited to the application. Efforts should be made to enhance the capacity of countries for SOC measurement and modelling to address identified data gaps and limitations in tools/models.

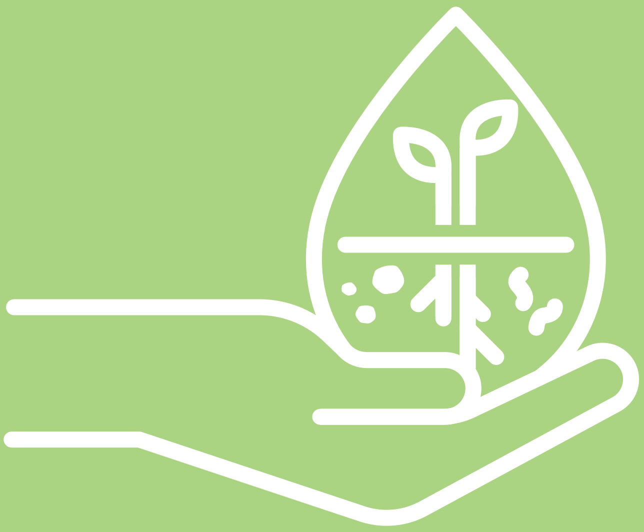
Proposal 4. Encourage country Parties, in collaboration with relevant technical and financial partners, to strengthen national-level coordination and capacity for SOC measurement and monitoring by:

1. Strengthening capacities of technical institutions and human resources by providing guidance on estimating, monitoring and reporting SOC for land use planning, LDN monitoring, and other applications;

2. Developing/reinforcing capacities in the design of soil sampling strategies and implementing measurement and monitoring programs;

3. Developing/enhancing processes for quality assurance, sample storage, and data retention, to support the development of tools/models for SOC estimation, and

4. Invite interested relevant technical partners to develop/refine tools/models for SOC estimation, for application in LDN assessment on sites where detailed measurements of SOC are not required .



Soil organic carbon is a fundamental ecosystem health indicator and a key criterion for the identification of suitable SLM technologies to contribute to the achievement of LDN.

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Optimizing land-based interventions for multiple benefits requires the capacity to do the right thing, in the right place, at the right time, at the right scale. Organic carbon is central to healthy productive soils and the mitigation and adaptation to climate change, but it is not easy to manage without effective measurement.

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The UNCCD-SPI technical report “Realising the Carbon Benefits of Sustainable Land Management Practices: Guidelines for Estimation of Soil Organic Carbon in the Context of Land Degradation” provides decision guidance for the estimation of soil organic carbon (SOC) in support of appropriate deployment of sustainable land management (SLM) technologies, in order to maintain or increase carbon in the soil and contribute to the achievement of land degradation neutrality (LDN). The report was produced to support the need for policy tools that provide guidance on harmonized methods for accurate estimations of changes in soil (SOC) stocks resulting from SLM interventions.

The report provides a framework and a set of decision trees to help countries i) identify suitable and region-specific SLM practices and approaches to maintain or enhance SOC stocks, and ii) estimate and monitor SOC for land use planning and for monitoring LDN. It also provides a comparative list of tools and models for SOC assessment and selection for SLM approaches and technologies, including approaches for monitoring changes in SOC stocks from local to national scales.

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