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Soil Organic Carbon – An Appropriate Indicator to Monitor Trends of Land and Soil Degradation within the SDG Framework?

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Soil Organic Carbon – An Appropriate Indicator to Monitor Trends of Land and Soil Degradation within the SDG Framework?

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Abstract

The 17 Sustainable Development Goals (SDGs) and related 169 Targets, adopted by the United Nations in September 2015, aim to end poverty, protect the planet, and to ensure prosperity for all. Due to their various functions, land and soil are addressed by several SDGs and Targets. In particular, Target 2.4 "By 2030, ensure sustainable food production systems and implement resilient agricultural practices . . . that progressively improve land and soil quality", and Target 15.3 "By 2030, combat desertification, restore degraded land and soil . . . strive to achieve a land degradation-neutral world" refer to sustainable use of land and soil.

However, soil related indicators are still lacking. These are fundamental to the implementation of the SDGs as they are needed to measure performance towards achieving them. In this context, the soil organic carbon (SOC) stock, which supports critically important soil-derived ecosystem services, is discussed as indicator for land and soil degradation. The SOC plays a fundamental role in the function, fertility and productivity of terrestrial ecosystems, the quality of soil and water, as well as in climate protection.

This report takes a close look at the importance of SOC and its potential as indicator for land and soil degradation. Furthermore, it illustrates challenges to be met and conditions to be created in order to establish the SOC stock as a globally relevant and feasible indicator for the implementation of the SDGs.

Kurzbeschreibung

Die im September 2015 von den Vereinten Nationen verabschiedeten 17 globalen Nachhaltigkeitsziele (Sustainable Development Goals – SDGs) und die zugehörigen 169 Unterziele sollen die Armut beenden, den Planeten schützen und allen Menschen Wohlstand sichern.

Land und Böden werden aufgrund ihrer vielfältigen Funktionen von verschiedenen SDGs und Unterzielen adressiert. Insbesondere die Unterziele 2.4 („Bis 2030 die Nachhaltigkeit der Systeme der Nahrungsmittelproduktion sicherstellen und resiliente landwirtschaftliche Methoden anwenden, die … die Flächen- und Bodenqualität schrittweise verbessern“) und 15.3 („Bis 2030 die Wüstenbildung bekämpfen, die geschädigten Flächen und Böden … sanieren und eine Welt anstreben, in der die Landverödung neutralisiert wird“) beziehen sich auf die nachhaltige Land- und Bodennutzung. Bislang existieren jedoch keine bodenbezogenen Indikatoren. Diese sind für die Umsetzung der SDGs von entscheidender Bedeutung, da mit ihnen der Fortschritt bei der Realisierung gemessen wird.

In diesem Kontext wird der Vorrat an organisch gebundenem Kohlenstoff (Soil Organic Carbon – SOC), der Grundlage für wichtige bodenbürtige Ökosystemdienstleistungen ist, als Indikator für Land- und Bodendegradation diskutiert. Der SOC nimmt eine Schlüsselrolle in Hinblick auf Funktion, Fruchtbarkeit und Produktivität terrestrischer Ökosysteme, bei der Qualität von Boden und Wasser sowie beim Klimaschutz ein.

Dieses Gutachten beleuchtet die Bedeutung des organisch gebundenen Kohlenstoffs und sein Potenzial als Indikator für Land- und Bodendegradation. Zudem wird aufgezeigt, welche Herausforderungen in diesem Zusammenhang überwunden und welche Rahmenbedingungen geschaffen werden müssen, um den SOC-Vorrat als global relevanten und praktikablen Indikator zur Umsetzung der bodenrelevanten SDGs zu etablieren.

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Acronyms

AFOLU	Agriculture, Forestry and Other Land Use
CAP	Common Agricultural Policy
DPSIR	Drivers Pressures States Impacts Responses
DSMW	Digital Soil Map of the World
ENVASSO	Environmental Assessment of Soil for Monitoring
EC	European Commission
ES	Ecosystem Service
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse Gas
GIS	Geographical Information System
GLADIS	Global Land Degradation Information System
GPP	Gross Primary Production
GSP	Global Soil Partnership
HANPP	Human Appropriation of Net Primary Productivity
HLPF	High-Level Political Forum
HWSD	Harmonized World Soil Database
IAEG	Inter-agency and Expert Group
ICSU	International Council for Science
IGBP	International Geosphere-Biosphere Programme
INS	Inelastic Neutron Scattering
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
ISRIC	International Soil Reference and Information Centre
ISSC	International Social Science Council
ITPS	Intergovernmental Technical Panel on Soils
LDN	Land Degradation Neutrality
LIBS	Laser-induced Breakdown Spectroscopy
LIC	Lithogenic Inorganic Carbon
LOI	Weight-loss-on-ignition
LTER	Long-term Ecological Research
MEA	Millennium Ecosystem Assessment
MIR	Mid-infrared
MRT	Mean Residence Time
NCSCDB	Northern Circumpolar Soil Carbon Database
NIR	Near-infrared

NPP	Net Primary Production
NRCS	Natural Resources Conservation Service
OM	Organic Matter
PIC	Pedogenic Inorganic Carbon
PLSR	Partial Least Squares Regression
RothC	Rothamsted Carbon Model
SDG	Sustainable Development Goal
SDSN	Sustainable Development Solutions Network
SIC	Soil Inorganic Carbon
SMW	Soil Map of the World
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SOTER	Soil and Terrain Database
SQI	Soil Quality Index
TSC	Total Soil Carbon
UNCCD	United Nations Convention to Combat Desertification
USSR	Union of Soviet Socialist Republics
WISE	World Inventory of Soil Emission Potentials

Zusammenfassung

Die globalen Nachhaltigkeitsziele (engl. Sustainable Development Goals, SDGs) sollen die Armut beenden, den Planeten schützen und allen Menschen Wohlstand sichern. Zum ersten Mal in der Geschichte gibt es in Form von 17 Zielen (engl. Goals) und 169 Unterzielen (engl. Targets) eine globale Übereinkunft darüber, wie sich die Welt in den kommenden 15 Jahren ökonomisch, ökologisch und sozial entwickeln soll. Die SDGs sollen in den kommenden Jahren von den staatlichen Regierungen realisiert werden und der Fortschritt bei deren Umsetzung soll anhand eines Monitoringsrahmens verfolgt werden. Indikatoren sind dabei von entscheidender Bedeutung, da damit der Fortschritt bei der Verwirklichung der SDGs gemessen werden wird.

Land und Böden werden aufgrund ihrer vielfältigen Funktionen von verschiedenen SDGs und Unterzielen adressiert. So beziehen sich insbesondere Unterziel 2.4 „Bis 2030 die Nachhaltigkeit der Systeme der Nahrungsmittelproduktion sicherstellen und resiliente landwirtschaftliche Methoden anwenden, die … die Flächen- und Bodenqualität schrittweise verbessern“ und Unterziel 15.3 „Bis 2030 die Wüstenbildung bekämpfen, die geschädigten Flächen und Böden … sanieren und eine Welt anstreben, in der die Landverödung neutralisiert wird“ auf die Querschnittsthemen Land- und Bodendegradation, die bei der Verwirklichung nachhaltiger Entwicklung zu berücksichtigen sind. Aufgrund der allgemein bekannten Mängel an Grundlagendaten zu Bodeneigenschaften und fehlender Bodenmonitoringprogramme in vielen Nationalstaaten, gibt es jedoch keine SDG-Indikatoren, die sich ausdrücklich auf Böden beziehen.

Unter den Bodenbestandteilen nimmt der organisch gebundene Bodenkohlenstoff (engl. Soil Organic Carbon, SOC) eine Schlüsselrolle in Hinblick auf Funktion, Fruchtbarkeit und Produktivität terrestrischer Ökosysteme sowie der Qualität von Boden, Wasser und Atmosphäre ein. Der SOC-Vorrat ist Grundlage für wichtige bodenbürtige Ökosystemdienstleistungen einschließlich Wasserreinigung, Erosionskontrolle, Erhalt von Bodengefüge und -stabilität, Sicherung der Nährstoffversorgung, Denaturierung und Festlegung von Schadstoffen, Lebensraum und -grundlage für Bodenorganismen, Regulierung von Schädlingen und Krankheiten, und Anpassung und Minderung des Klimawandels aufgrund der Speicherung von Kohlendioxid aus der Atmosphäre. Geschätzte 3000 Gigatonnen Kohlenstoff sind in Bodenprofilen der eisfreien Landoberfläche als SOC gebunden. Ein Rückgang dieser Vorräte kann Indiz für Land- und Bodendegradation sein. Deshalb wird der SOC-Vorrat als Indikator für Umfang und Schwere der Land- und Bodendegradation diskutiert.

Die Querschnittsfunktionen des organisch gebundenen Bodenkohlenstoffs (SOC)

Verbessert Wasserversickerung und -speicherung	▶ Pufferung des Ertrags gegen Wassermangel
Stabilisiert Bodenstruktur und verbessert die Aggregierung	▶ Reduktion des Bodenverlusts durch Erosion
Verbessert Nährstoffumsatz und -speicherung	▶ Erhöhung der Bodenfruchtbarkeit
Verbessert Absorption und Speicherung von Pestiziden und anderer organischer Schadstoffe	▶ Immobilisierung und Abbau organischer Schadstoffe

Dient als Lebensraum und Nahrungsgrundlage der Bodenorganismen	► Verbesserung von Bodenbiodiversität und Bodengesundheit
Speichert Kohlendioxid der Atmosphäre	► Minderung des Klimawandels

Bevor Informationen zum SOC-Vorrat als ein global relevanter und praktikabler Indikator zum Monitoring der Land- und Bodendegradation mit Bezug zu den SDGs eingesetzt werden können, sind folgende Hindernisse zu überwinden.

Erstens gibt es nur für wenige Regionen und Nationen Datensätze zu SOC-Vorräten, die ohne weiteres zugänglich sind. Unklar ist, ob die vorhandenen Daten zum Monitoring von Veränderungen der SOC-Vorräte geeignet sind. Zur Verbesserung der Vertrauenswürdigkeit der Daten sind eine Überarbeitung der Methoden zur Bodenprobenahme und die Aktualisierung von Informationen der Fernerkundung und von Geländedaten erforderlich. Beispielsweise basieren viele vorhandene Daten der SOC-Konzentrationen auf der ungenauen Walkley-Black-Methode, wohingegen die automatisierte Trockenveraschung die genaueste Methode darstellt. Außerdem gibt es viele Unklarheiten in der Anwendung spektroskopischer Methoden zur Bestimmung der SOC-Konzentrationen im Gelände sowie bei Fernerkundungsmethoden und bei Proxymethoden wie beispielsweise SOC-Modellen. Auch fehlen oft Daten zur Lagerungsdichte, Bodenprobenahmetiefe, und zu den Anteilen an Bodenskelett (Gestein) und Wurzelfragmenten. Diese Daten werden jedoch benötigt, um die SOC-Daten auf die Fläche umzurechnen, i.e. zur Berechnung des SOC-Vorrats in Tonnen Kohlenstoff je Hektar (Mg C ha^{-1}). Es gibt dementsprechend keine allgemein anerkannte Standardvorschrift zur Bestimmung von Veränderungen der SOC-Vorräte.

Zweitens gibt es keine einheitlichen Definitionen für Land- oder Bodendegradation und keine einheitlichen Verfahren zu deren Bestimmung auf lokaler, regionaler und globaler Ebene. Bodendegradation ist Folge des Zusammenspiels bio-pysikalischer, sozio-ökonomischer und politischer Faktoren, definitionsgemäß standortspezifisch und unterschiedliche Skalenebenen betreffend. Kartierung und Bestandsaufnahme degradierter Landoberflächen basieren des weiteren auf unterschiedlichen Methoden wie (i) Expertenbefragungen, (ii) Daten zur Nettoprimärproduktion (NPP) abgeleitet aus Satellitendaten, (iii) biophysikalischen Modellen und (iv) der Kartierung aufgegebenen Ackerlandes.

Drittens und am wichtigsten ist der unklare direkte quantitative Zusammenhang zwischen Veränderungen der SOC-Vorräte und den vielen Ursachen und Prozessen von Land- und Bodendegradation. Beispielsweise sind nicht alle Formen der Bodendegradation im gleichen Ausmaß von SOC-Verlusten beeinträchtigt. So hat in Mineralböden Europas ein Rückgang der organischen Bodensubstanz (engl. SOM) oder ein SOC-Verlust negative Auswirkungen auf Versalzung, Genpool (Biodiversität), Erosion, Wüstenbildung, Überflutungen, Erdrutsche, Biomasseproduktion, und die Bodenfunktion Speicherung, Filterung, Umsetzung von Nährstoffen, Substanzen und Wasser. Im Gegensatz dazu hat eine SOM-Abnahme positive Auswirkungen auf die Biomasseproduktion genutzter europäischer Moorböden in Abhängigkeit von deren Management, und auf die Fruchtbarkeit und physikalischen Eigenschaften der Böden unter den ursprünglichen Moorhorizonten. Allerdings kann es in Moorböden abhängig vom Management auch zu negativen Auswirkungen auf die Biomasseproduktion, Erosion, Versalzung, Genpool (Biodiversität), und die Bodenfunktionen Rohstofflieferant, und Speicherung, Filterung, Umsetzung von Nährstoffen, Substanzen und Wasser kommen. Unklarheit besteht darüber, wie Prozesse der Landdegradation durch Veränderungen des SOC beeinträchtigt werden, da beispielsweise SOC-Verluste nur eine der vielen Ursachen der Landdegradation sind. Unmittelbare Ursachen sind Topografie, Landbedeckung und Vegetation, Bodenelastizität, Klima und schlechtes Management. Zugrunde liegende Ursachen der Landdegradation sind beispielsweise Armut, Dezentralisierung, Zugang zum landwirtschaftlichen Beratungsdienst, Landnutzungsänderungen und Zugang zum Rohstoffmarkt. Insgesamt ist es fraglich, ob eine Veränderung des SOC-Vorrates alleine die

Komplexität von Land- oder Bodendegradation widerspiegeln kann. Möglicherweise sind Indices der Land- und Bodendegradation, die SOC-Daten neben anderen Daten zu Land- und Bodenveränderungen beinhalten, besser für das Monitoring von Land- und Bodendegradation geeignet.

Zusammenfassend lässt sich festhalten, dass der SOC-Vorrat das Potenzial hat, ein global relevanter und praktikabler Indikator im Zusammenhang mit einem Monitoringsystem der Land- und Bodendegradation zu sein, denn der SOC-Vorrat ist (i) wichtig für viele Bodenfunktionen, (ii) unter den Indikatoren der Bodengesundheit, und (iii) steht im Nexus vieler bodenbürtiger Ökosystemdienstleistungen. Der Verwendung des SOC-Vorrats als Messgröße für die nicht direkt messbaren Phänomene Land- und Bodendegradation steht jedoch die Vielzahl der oben erwähnten Mängel entgegen. Aufgrund fehlender Erkenntnisse und Daten kann der SOC-Vorrat deshalb gegenwärtig lediglich als konzeptioneller Indikator dienen, um die Aufmerksamkeit von Entscheidungsträgerinnen und -trägern für Land- und Bodendegradation im Rahmen der SDG zu gewinnen. Dies kann durch den Entwurf von Rahmenkonzepten und gedanklichen Akteursmodellen erreicht werden, vor allem bei (i) Dialogen, öffentlichen Debatten, und Diskussionen; (ii) der Bereitstellung von Hintergrundinformationen; und (iii) beim Entwickeln eines gemeinsamen Verständnisses. Der Indikator SOC-Vorrat kann eine breite und indirekte Rolle als Randbedingung beim Kombinieren reiner Fakten und Modellergebnisse mit gemeinsamen Schlussfolgerungen und Ansichten spielen. Dieser Ansatz würde Unsicherheiten, Unklarheiten und vernachlässigte Themen bei der Politikgestaltung mit Bezug zur nachhaltigen Entwicklung hervorheben. Dadurch kann der Indikator SOC-Vorrat auf indirektem Wege Einfluss auf die Politik zur Land- und Bodendegradation nehmen.

Auf Grundlage dieses Berichtes werden folgende Schlussfolgerungen abgeleitet:

- **Der SOC ist von zentraler Bedeutung für die Leistungsfähigkeit terrestrischer Ökosysteme**
- **Der Anstieg des SOC-Vorrats fördert die Nahrungsmittelsicherheit und trägt zur Anpassung und Minderung des Klimawandels bei**
- **Die wirtschaftliche, politische und gesellschaftliche Wahrnehmung der überragenden Bedeutung des SOC muss durch eine verbesserte Datengrundlage und mehr Őffentlichkeitsarbeit gefördert werden**
- **Land- oder Bodendegradationen sollten auf Grundlage von Indices unter Einbeziehung von SOC-Daten und weiterer Bodendaten sowie Daten zur Landbedeckung und -produktivität bewertet werden**
- **Der SOC soll zur Bewusstseinsbildung und Sensibilisierung für Land- und Bodendegradationen dienen, insbesondere bei der Identifizierung von ‚hotspots‘**
- **Um die Akzeptanz für den Indikator SOC zu erhöhen, muss das Wissen um Prozesse, die den SOC beeinträchtigen, sowie deren Zusammenhang mit Land- und Bodendegradation verbessert werden**
- **Routinemäßige, harmonisierte und vergleichbare Methoden (Standardmethoden) für die systematische Gewinnung von SOC-Daten müssen entwickelt werden**
- **Es besteht weiterer Diskussions- und Forschungsbedarf zur Bewertung der Eignung des Indikators SOC bei der Verwirklichung der SDGs mit Bezug zu Nahrung, Gesundheit, Wasser, Klima und Landnutzung**

Summary

The Sustainable Development Goals (SDGs) aim to end poverty, protect the planet, and ensure prosperity for all. For the first time, globally agreed priorities (i.e., 17 SDGs and 169 Targets) have been adopted to guide how the world should develop economically, environmentally and socially within the next 15 years. The SDGs have to be implemented by national governments during the next years, and progress towards achieving them measured by a monitoring framework. Indicators are of fundamental relevance to the implementation and evaluation phase of the SDGs as those will be used to measure performance towards achieving them.

Due to their various functions, land and soil are addressed by several SDGs and Targets. Specifically, Target 2.4 "By 2030, ensure sustainable food production systems and implement resilient agricultural practices . . . that progressively improve land and soil quality", and Target 15.3 "By 2030, combat desertification, restore degraded land and soil . . . strive to achieve a land degradation-neutral world" refer to land and soil degradation as cross-cutting issues that must be addressed to achieve sustainable development. However, introducing soil related indicators for the SDGs that explicitly mention soil as a component faces the well known lack of basic soil data and adequate soil monitoring systems in many nations of the world.

Among soil components, soil organic carbon (SOC) plays a fundamental role in the function, fertility and productivity of terrestrial ecosystems, and the quality of soil, water and air resources. Specifically, the SOC stock supports critically important soil-derived ESs, including water filtration, erosion control, soil strength and stability, nutrient conservation, pollutant denaturing and immobilization, habitat and energy source for soil organisms, pest and disease regulation, and climate change adapation and mitigation by sequestration of atmospheric CO2. Thus, a decline in the SOC stock, currently estimated at ~3000 Pg C for soil profiles of the ice-free land area, may indicate land and soil degradation. In fact, some have proposed the SOC stock as indicator to monitor extent and severity of land and soil degradation.

The Integrating Function of Soil Organic Carbon (SOC)

Improves soil water infiltration and retention	▶ Buffering crop production against water shortages
Stabilizes soil structure and improves aggregation	▶ Reducing soil loss by erosion
Increases nutrient cycling and storage	▶ Improving soil fertility
Improves absorption and retention of pesticides and other organic pollutants	▶ Immobilization and degradation of organic pollutants
Provides habitat and food source for soil organisms	▶ Improving soil biodiversity and soil health
Stores atmospheric carbon dioxide	▶ Mitigating climate change

However, before the SOC stock can serve as a globally relevant and feasible indicator within a monitoring system on land and soil degradation with regard to the SDG framework the following challenges need to be coped with.

First, major readily available datasets on SOC stock are available only for some regions and nations. However, the suitability of exisiting data for monitoring changes in SOC stocks is uncertain. Specifically, revised methodology including those for soil sampling, and updated remote sensing and field information are needed to enhance the credibility of the data. For example, automated dry combustion technique is the most reliable method for measuring SOC concentration but many available datasets are based on the not sufficiently accurate Walkley-Black method. Further, there are numerous uncertainties about the use of spectroscopic measurements of SOC concentrations in the field, remote sensing and proxy methods such as SOC models. Frequently not reported are measurements of soil bulk density (ρ_b), depth increments for soil sampling, and rock and root fragments but those are needed for expression of SOC data on an area basis, i.e., for the calculation of the SOC stock (Mg C ha^{-1}). Thus, there is no agreed standard protocol to measure the dynamics of SOC stocks.

Secondly, there are no common definitions of land and soil degradation, and no common procedures on how to assess land and soil degradation on local, regional and global scales. Soil degradation is caused by the interplay of bio-physical, socio-economic and political factors, and soil degradation problems are by definition site-specific and occur at different scales. Further, mapping and quantification of degraded lands has been done by a range of methods based on (i) expert opinion; (ii) satellite derived net primary productivity (NPP); (iii) biophysical models; and (iv) mapping abandoned cropland.

Third and most importantly, quantiative evidence for the link between changes in SOC stocks and the numerous land and soil degradation drivers and processes is scanty. For example, not all types of soil degradation are equally affected nor to a similar degree by a loss of SOC. Specifically, SOM decline (SOC loss) in mineral soils in Europe has negative effects on salinization, the gene pool (biodiversity), water erosion, wind erosion, desertification, flooding and landslides, biomass production, and the soil function storing/filtering/transforming nutrients, substances and water. In comparison, SOM decline (SOC loss) in European peat soils can have positive effects on biomass production depending on peat management, and the fertility and physical properties of the soil underneath the original peat layer but can also have negative effects on biomass production, wind erosion, salinization, the soil function source of raw materials, water erosion, gene pool (biodiversity), and the soil function storing/filtering/transforming nutrients, substances and water. Further, it is unclear how SOC changes may affect land degradation processes as, in particular, SOC losses are among the many drivers of land degradation. Drivers of land degradation include also proximate drivers, such as topography, land cover and vegetation, soil resilience, climate, and poor management, and underlying drivers, e.g., poverty, decentralization, access to agricultural extension service, land cover changes, and commodity market access. Thus, it is unlikely that a change in SOC stock alone can reflect the complexity of land and soil degradation. A land and soil degradation index including data on SOC loss among other land and soil changes may be more suitable for monitoring land and soil degradation.

In conclusion, the SOC stock has the potential to be a globally relevant and feasible indicator within a monitoring system on land and soil degradation because the SOC stock (i) is related to many fundamental soil functions, (ii) among the indicators of soil health, and (iii) at the nexus of many soil-derived ESs. However, using the SOC stock as a measurable parameter to assess the not directly measurable phenomena of land and soil degradation is confronted with a myriad of challenges discussed previously. In face of the lack of understanding and data scarcity, the SOC stock may currently only be a conceptual indicator to raise awareness among policy makers for land and soil degradation within the SDG framework. This may be achieved by helping to shape the conceptual frameworks and mental models of actors, mostly through (i) dialogue, public debate, and argumentation; (ii) by providing background information; and (iii) by creating shared understandings. Specifically, the indicator SOC stock may serve in a broader, indirect role as a boundary object by combining 'hard facts' and modelling with collective reasoning and 'speculation'. This would highlight uncertainties, trade-offs and neglected issues in policy making towards sustainable development. More often than influencing policy on land and soil degradation directly, the indicator SOC stock can produce its effects through various indirect pathways.

The following recommendations are made:

- **The SOC is crucial for the performance of terrestrial ecosystems**
- **Increasing SOC stocks strenghtens food security, and contributes to climate change adaptation and mitigation**
- **Both the database and public relations must be strenghtened to enhance recognition of the crucially important SOC by business, politics and society**
- **Land or soil degradation should be assessed by composite land or soil degradation indices including data on SOC among other data for soil properties, land use cover and land productivity**
- **The SOC should be used for awareness raising on land and soil degadation, in particular, for indicating degradation hotspots**
- **To increase the acceptance of the indicator SOC knowledge on processes affecting SOC and their relation to land and soil degradation must be improved**
- **Routine, harmonized and comparable approaches for systematic SOC data collections must be established**
- **Additional research is needed to assess the suitability of SOC as indicator to monitor progress towards realization of the SDGs with reference to food, health, water, climate and land management**

1 The Importance of Soil Organic Carbon

Soils contain more carbon (C) than the global vegetation and the atmosphere combined (Eswaran et al. 2000; Köchy et al. 2015b). The soil C stock is comprised of the soil inorganic C (SIC) and soil organic C (SOC) stocks. The SIC stock consists of lithogenic inorganic C (LIC) or primary carbonates derived from the soil parent material, and pedogenic inorganic C (PIC) or secondary carbonates formed through soil processes (Monger et al. 2015). The SOC is contained in materials that have been derived from a variety of biological sources (Johns et al. 2015). Much of the SOC is derived from plants and, particularly, their roots while soil microorganisms, and animals and their excreta also contribute to the SOC stock. The term SOC is often used interchangeably with the term soil organic matter (SOM), often known as humus, which has been described as „our globe's most important natural resource" (Paul 2016). Thus, SOC is a proxy for SOM.

The term SOC stock refers to the quantity of SOC in a reservoir or system. On the other hand, the term SOC pool refers to a reservoir or system which has the capacity to accumulate or release C. In this document the term SOC stock will be used as differences in the amount (i.e., stock) of SOC may serve as indicator for the degree of land and soil degradation while all soils feature an SOC pool, independently from the degree of land and soil degradation.

1.1 The Soil Organic Carbon Stock and its Dynamics

Carbon enters the SOC stock via the inputs of C from photosynthetic fixation of atmospheric carbon dioxide (CO_2) by vegetation, deposition of microbial and plant residues, and organic amendments (animal manure, biosolids) to agricultural soils. The main C input to soil is the net primary production (NPP) as a major fraction of the CO_2 fixed during plant photosynthesis by gross primary production (GPP) which is respired autotrophically and returned back to the atmosphere. NPP enters the soil by rhizodeposition and decomposition of plant litter, and the major fraction is converted back to CO_2 by soil respiration and some lost as methane (CH_4). Aside from the microbial decomposition enhanced by soil disturbance (e.g., tillage), C losses from soils are associated with erosion, fire, harvest and leaching (Ciais et al. 2010). Site-specific factors (e.g., climate, physicochemical characteristics, soil, and vegetation management) determine the balance between soil C input and losses.

Table 1: Global estimates of the soil carbon stock (Pg C)*

Depth (m)	Soil organic carbon			Soil inorganic carbon	
	Batjes (2016)	Jobbágy & Jackson (2000)	Köchy et al. (2015b)	Batjes (1996)	Eswaran et al. (2000)
0-0.3	755			222-245	
0-1	1408	1502	1325	695-748	940
0-2	2060	1993			
0-3		2344			
Entire profiles			3000		

*For the ice-free land area. Total estimated SOC stock for the permafrost region is ~1300 Pg C, i.e., ~500 Pg C in non-permafrost soils, seasonally thawed in the active layer or in deeper taliks, while ~800 Pg C is perennially frozen (Hugelius et al. 2014)

Globally, the GPP flux is ~123 Pg C yr^{-1} and the NPP flux is ~64 Pg C yr^{-1}, while ~2 Pg C yr^{-1} remain in soil (Ciais et al. 2013; Lehmann & Kleber 2015). Total SOC stock in ice-free land is 1,325 – 1,408 Pg C to 1-m depth and ~3,000 Pg C in soil profiles (Batjes 2016; Köchy et al. 2015b; Table 1). However, routine soil surveys are restricted to about 1-m depth, and exploring greater depths of profile development, and measurements of SOC stocks below 1-m depth are rare. Further, issues of quality and comparability of soil analytical data, collated from disparate sources, are critical in any analysis of soil profile data (Batjes 2016). Thus, estimates for the vertical distribution of SOC are highly uncertain. In addition, the reliability of estimates of SOC storage is affected by unreliable *in-situ* measurements of SOC, soil depth and bulk density. Variability in estimates of global SOC distribution is due to variation in definitions of soil units, differences in soil property databases, scarcity of information about SOC at depths >1m in peatlands, and variation in definitions of "peatland" (Köchy et al. 2015b). In conclusion, consensus is lacking on the size of the global SOC stock and its spatial distribution (Scharlemann et al. 2014). Even more uncertain are data on the SIC stock of soil profiles with ~940 Pg C stored to 1-m depth (Eswaran et al. 2000; Table 1).

The SOC dynamics are not completely understood as land use and land cover changes, and climate change affect the SOC stock. However, about 25 to 30% of the SOC stock stored in the top meter of soil may be released by cultivation of native soils, whether under forest or prairie vegetation (Houghton 2010). For example, SOC stocks to 1-m depth decreases by 42% when native forest and by 59% when pasture is converted to cropland, respectively (Guo & Gifford 2002). However, soil depth is not always adjusted to account for changes in soil bulk density (ρ_b) with land use change (equivalent soil mass method; Mikha et al. 2013). In temperate regions, conversion from forest to cropland and from grassland to cropland causes the loss of 31% SOC to 28.5-cm depth and of 36% SOC to 27.1-cm depth, respectively (equivalent soil mass method; Poeplau et al. 2011). Otherwise, SOC stocks may increase by 128% to 23.5-cm depth, by 117% to 28-cm depth and by 28% to 38.9-cm depth when cropland is converted to grassland and forest, and when grassland is converted to forest, respectively. However, no new equilibrium in SOC stocks may be reached even within 120 years in temperate regions by such land-use changes (Poeplau et al. 2011).

In tropical regions, SOC losses of 25% to 36-cm depth and of 30% to 48-cm depth may occur by conversion of primary forest to cropland or perennial crops, respectively (equivalent soil mass method; Don et al. 2011). Losses of 21% of SOC to 39-cm depth have been reported when secondary tropical forest is converted to cropland but with no changes observed to 51-cm depth when converted to perennial crops. However, 10.4 % of SOC may be lost to 38-cm depth when tropical grassland is converted to cropland. In some situations, SOC stocks have reportedly increased by 17.5% to 35-cm depth and by 50.3% to 44-cm depth when grassland or cropland are converted to secondary forest, respectively. When tropical cropland is converted to grassland or fallow, SOC stocks can increase by 25.7% to 40-cm depth and by 32.2% to 20-cm depth, respectively (Don et al. 2011).

The response of SOC stocks to land-use changes in sub-soil layers is poorly understood. For example, afforestation of grasslands may lead to only minor SOC losses up to 80-cm depth (equivalent soil mass method; Shi et al. 2013). In contrast, afforestation of croplands may increase SOC stocks by 87.6%, 40.5% and 33.3% at 0-20, 20-40 and 40-60 cm depths, respectively. Thus, land-use change may affect SOC stocks not only in the top 30-cm of mineral soil (topsoil) but also in the deeper subsoil layers (Shi et al. 2013).

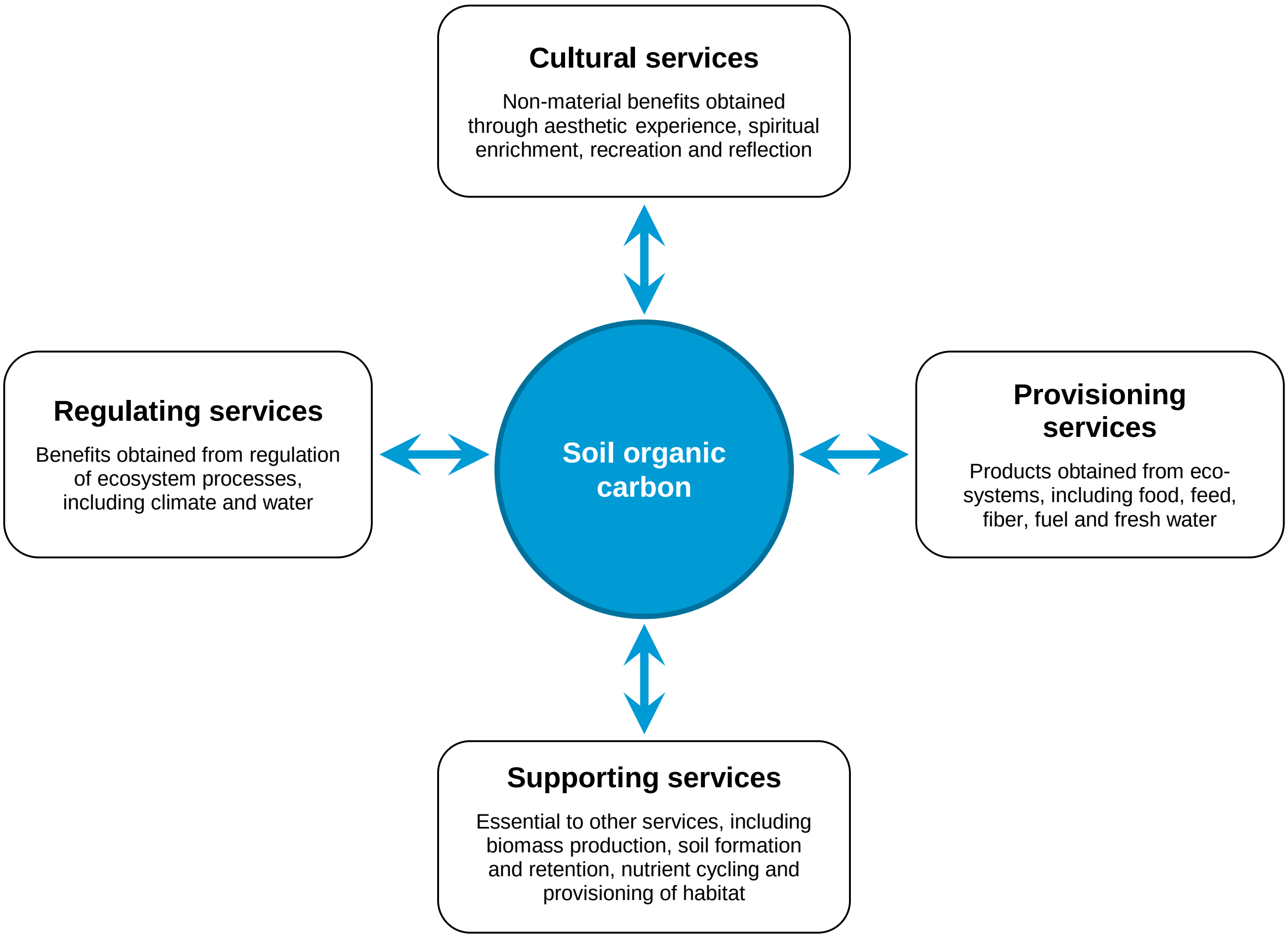
Based on data from three vegetation models, global SOC loss by land-use change over 150 years from 1860 to 2010 has been estimated at 50.7 Pg (FAO & ITPS 2015). However, the future projections of SOC stocks to 1-m depth for the next 75 year period (2010-2085) are highly uncertain (Köchy et al. 2015a). One of the major uncertainties of the simulated changes in SOC stock are attributed to the lack of credible knowledge regarding the long-term effects of CO_2 fertilization on NPP and its variations at the global scale.

In comparison to the changing land use, global SOC stocks to 15-cm depth at sites without any land-use change have reportedly increased by 0.19% C yr^{-1} over recent decades, albeit with values at individual sites ranging between losses of 1.67% C yr^{-1} to gains of 4.09% C yr^{-1} (Chen et al. 2015). Increases in SOC stocks have also been reported for forests and grasslands, but with slight decreases for croplands. It can be concluded, therefore, that climate change thus far has not caused any severe losses in global SOC stocks to 15-cm depth (Chen et al. 2015).

1.2 The Importance of Soil Organic Carbon for Soil-derived Ecosystem Services

Ecosystems provide ecosystem services (ESs) which are defined and classified differently. The 2005 Millennium Ecosystem Assessment grouped ESs into four categories: (i) provisioning services (direct or indirect food for humans, freshwater, wood, fiber, and fuel); (ii) regulating services (regulation of gas and water, climate, floods, erosion, biological processes such as pollination and diseases); (iii) cultural services (esthetic, spiritual, educational and recreational); and (iv) supporting services (nutrient cycling, production, habitat, biodiversity) (MEA 2005). Many studies have been conducted on soil and ESs with the majority of studies focussing on provisioning and regulating ESs, and most research conducted in Europe (Adhikari & Hartemink 2016). Soil ESs can be defined as the benefits that people derive from soils (Dominati et al. 2010). Significant economic value is derived from soil ESs (Jónsson & Davíðsdóttir 2016). ESs provisioned by soils are primarily determined by the core properties including texture, mineralogy and organic matter (OM) (FAO & ITPS 2015).

Figure 1: Categories of Ecosystem Services (ESs) underpinned by soil organic carbon



Modified from Franzluebbers (2010), Millennium Ecosystem Assessment (2005), and Smith et al. (2015)

The SOC stock supports critically important soil-derived ESs, including water filtration, erosion control, soil strength and stability, nutrient conservation, pollutant denaturing and immobilization, habitat and energy source for soil organisms, pest and disease regulation, and climate change adaptation and mitigation by sequestration of atmospheric CO_2 (Adhikari & Hartemink 2016; Franzluebbers 2010; Lal et al. 2012) (Fig. 1).

The benefits of SOC are well known and related to its fundamental role in the function and fertility of terrestrial ecosystems (Janzen 2006). Thus, there are strong interactions between SOC sequestration and quality of soil, water and air resources (Smith et al. 2013). However, maximizing SOC stocks is less critical than maintaining SOC 'flows' to sustain the manifold functions performed by ecosystems as SOC is most useful, biologically, when it decays (Janzen 2006, 2015). Yet, long-term storage of SOC (Lal 2004) and recarbonization of the biosphere (Lorenz & Lal 2010; Lal et al. 2012, 2013) are essential to reducing the risks of excessive build up of the atmospheric CO_2. Furthermore, SOC storage in the sub-soil has longer mean residence time (MRT) than that stored in surface layers (Lorenz & Lal 2005). However, with the exception of C sequestration, there is no well-established relationship between the SOC stock and the level of services attributable to it while the importance of SOC/SOM to soil functioning and the services it supports is self-evident (Kibblewhite et al. 2016). Therefore, maintaining a judicious balance between decomposition and storage is critical for creating the desired economic and ecological benefits. It is the creation of this judicious balance that is at the heart of the debate regarding implementation of initiatives such as '4 POUR 1000 Les sols pour la sécurité alimentaire et le climat - 4 per 1000 Soils for food security and climate' proposed at the COP21 Climate Summit in Paris in December 2015 (http://newsroom.unfccc.int/lpaa/agriculture/join-the-41000-initiative-soils-for-food-security-and-climate).

Soil health is defined as 'the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health' (Doran & Zeiss 2000). Soil fertility refers to the ability of soil to sustain plant growth, i.e., to provide plant habitat and result in sustainable constant yields of high quality. The SOC stock plays a critical role in soil health, fertility, quality, productivity and ESs goals (Johnston et al. 2009). Thus, many soil-derived ESs are improved with an increase in the SOC stock (Franzluebbers 2010). For example, soils with higher SOC stocks are characterized by better tilth, higher nutrient-supplying capacity, improved capacity to withstand drought and store water in the rooting zone, more resilience to environmental perturbations, and abundant biological diversity to support vigorous plants and sustained ESs (Franzluebbers 2010). However, while positive relationships between the SOC stock and soil properties (e.g., nutrient and water storage capacity) indicate that more of these resources may be available for crop growth, data from field experiments showing direct relationship between SOC stock and crop yields are scanty (Oldfield et al. 2015). A broad analysis of European long-term field experiments showed that the soil improving effect of SOM led to a yield increase of up to 10% on sandy soils and up to 6% on loamy soils (Körschens et al. 2013). Further, a 1% increase in SOM of China's croplands on average would lead to an increase in total cereal productivity of 0.43 Mg ha^{-1}, and a decrease of yield variability against disturbance by 3.5% (Pan et al 2009). Highest attainable yields may be only possible in combination with relatively high levels of SOC as indicated by studies at long-term field experiments in Europe and the United States (Brady et al. 2015). Otherwise, beneficial effects of SOC are easily masked by inputs of fertilizers and other amendments. For example, in soils without severe nutrient limitations (because of inputs of fertilizers), SOC levels above 1% may be sufficient to sustain yields (Aune & Lal 1997; Oelofse et al. 2015). However, this may not necessarily be the case where cropping systems rely heavily on nutrient supply from SOC mineralization–such as organic farming and other types of low input agriculture. Further, such a low threshold does not necessarily reflect how much SOC such soils can, or should, sequester for other ESs (Oelofse et al. 2015). Increases in crop yields with increase in SOC stocks in the rootzone have been reported for resource-based agriculture in developing countries (Lal

2006, 2010). The importance of research needs for establishing critical limits in SOC stocks for croplands are widely recognized (Loveland & Webb 2003).

A pertinent question is which attributes of SOC may contribute to improving yields, e.g., are increased yields at higher SOC levels a result of increased nutrient availability following increased mineralisation (Johnston et al. 2009), or do they result from SOC effects on soil physical properties (Schjønning et al. 2012)? Thus, quantitative data are needed to document how increases in SOC stocks and changes in its properties affect agricultural productivity (Oldfield et al. 2015). In general, however, the critical SOC concentration of 2% is widely recognized as the level below which some yield decline may occur (Loveland & Webb 2003). In low-input systems, strong decline in agronomic productivity may occur in soils with depleted SOC reserves (Lal 2006, 2010). Nonetheless, critical yield limiting SOC levels are also affected by climate and soil properties (clay content and mineralogy; Stockmann et al. 2015), and by production systems (Zhang et al. 2016). In general, the critical level is lower for soils of the tropics (1.1%, Aune & Lal 1997) than those of temperate climates (2%, Loveland & Webb 2003).

1.3 The Effects of Soil Organic Carbon on Soil Degradation Threats

Changes in SOC may affect soil degradation threats. Globally, the most significant threats to soils are by (i) erosion (wind and water), (ii) loss of SOM (also referred to as carbon, soil carbon, or soil organic matter), (iii) nutrient imbalance, (iv) salinization, (v) surface sealing (i.e., the permanent covering of the soil with an impermeable surface), (vi) loss of soil biodiversity, (vii) contamination (i.e., the intentional or unintentional introduction of dangerous substances on or in the soil), (viii) acidification, (ix) compaction, and (x) waterlogging (Karlen & Rice 2015). The European Commission (2002) also identified landslides and flooding among key threats to soil. Further, the process of desertification relates to several threats, including soil erosion, decline in SOM, soil salinisation and decline in soil biodiversity. As such desertification is a key cross-cutting issue similar to climate change, land use change and brownfield development (Huber et al. 2008). Net SOC losses to the atmosphere following a decline in SOM contribute to climate change, and may also affect other soil degradation threats. Vulnerable to these threats are, in particular, the soil functions (i) biomass production, including in agriculture and forestry; (ii) storing, filtering and transforming nutrients, substances and water; (iii) biodiversity pool such as habitats, species and genes; (iv) physical and cultural environment for humans and human activities; (v) source of raw materials; (vi) functions of SOC stock (store and sink); and (vii) archive of geological and archaeological heritage (EC 2006).

For the UK and similar regions, Gregory et al. (2015) summarized several reports indicating that specific decreases in aggregate stability of 10–40% can occur with a 1% decrease in SOM content as well as a decrease in the resilience of soil to physical stresses, such as compaction. Soil erosion may also be enhanced by the decrease in aggregate stability. Further, decreases in SOM content can lead to poor soil tilth through undesirable domination of coarser clods, a decrease in friability, clay dispersion and a reduction in porosity (Gregory et al. 2015). The loss in porosity has been reported to range from 1 to 2% for a 1% decrease in SOM content (Whitmore et al. 2010). Such a decline in porosity may lead to a reduction in hydraulic conductivity and the aeration status of the soil which would have an adverse impact on vegetation growth. Decline in SOM can also reduce soil water retention by up to 10% for a difference in SOM content from 7% to 3%. Arable soils of low SOM content are susceptible to slumping upon wetting due to aggregate instability, leading to reduction in water infiltration and increase in surface runoff. However, two inter-connected processes of decline in SOM and structural degradation are often hard to separate (Gregory et al. 2015). Further, loss of SOM can reduce the exchange of important nutrients such as N, P and S. Decline in SOM from 5% to 2% over a 60-yr period at Rothamsted resulted in a 90% decrease in microbial biomass, but no significant effect on microbial diversity or substrate utilization. Smaller fungal biomass and fungal-to-bacteria biomass ratios have been observed in soils of low SOM content compared with those in undisturbed and botanically rich grassland soils in the UK. However, the effects of SOM decline on biodiversity are not fully understood. Loss of SOM can also release toxic elements because SOM plays a key role in the ability of soils to buffer the effects of potentially toxic substances (Gregory et al. 2015). In conclusion, a decline in SOM or SOC stock which is a soil degradation threat itself may specifically contribute to an increase in soil erosion, soil contamination, soil compaction, landslides and desertification, and aggravate the climate change risks.

2 Methods to Measure and Assess Soil Organic Carbon Dynamics

Ideally, SOC stock should be measured by a method that does not require soil sampling, involves relatively low costs and covers large areas with accuracy (Johns et al. 2015). However, analyzing SOC by a single method that can be applied on a wide range of diverse situations, is a major challenge. Further, SOC is not evenly distributed over large areas, depths, soil types and landscape positions (Jandl et al. 2014). Thus, there is a strong interest in developing several methods to measure and assess SOC dynamics.

2.1 Measurement Methods

The temporal changes in SOC and its dynamics can be assessed by repeated soil inventories or monitoring programs on representative sites (i) before and after land-use and/or land cover changes or (ii) by repeated soil sampling over regular time intervals when no such changes occurred. The total soil carbon (TSC) concentration can either be measured in a laboratory (*ex situ*) or by regular measurements using non-destructive, *in-situ* field methods, but there is no standardized approach (Olson et al. 2014). Similarly, standard approaches also do not exist for efficient soil sampling methods at the farm or landscape unit scale (Stockmann et al. 2013). Drawbacks are also associated with extrapolating the SOC data from a number of sampling sites within an area to the desired extent (de Gruijter et al. 2016). A major challenge of any SOC monitoring program is credible accounting for the small-scale variability of soil properties such as rock fragment content, bulk density, and C concentration (Jandl et al. 2014). Further, there is no consensus on the soil depth to which measurements and estimates of SOC stock should be made (Lal et al. 2000). Most soils are sampled to a depth of 0.3 m or less, and samplings below 1 m are an exception. Yet, knowledge about the SOC stock and its dynamics at deeper sub-soil depths are important for several soil types and biomes. Thus, subsoil horizons must also be sampled for a credible assessment of the SOC stock in the entire soil solum (Jandl et al. 2014).

After sampling, soils are prepared for laboratory analysis by removing remains of plant and animal tissues, gently ground and sieved through a 2-mm sieve. The processed soil samples are dried in the air or in an oven at temperatures <40 °C. Samples are then ball-milled and homogenized prior to measuring SOC concentration. The TSC concentration must be corrected for SIC concentration in carbonaceous or alkaline soils, soils that received liming amendments in the past, and those developed from calciferous parent rocks. SIC can be determined by using a modified pressure calcimeter method (Sherrod et al. 2002). The SOC concentration is then calculated as the difference between TSC and SIC, [SOC] = [TSC] – [SIC]. Alternatively, the SOC concentration can be determined by the dry combustion method (Tabatabai & Bremner 1970) after SIC has been removed by HCl pretreatment (Loeppert & Suarez 1996).

Measurements of soil bulk density (ρ_b), depth increments for soil sampling, and rock and root fragments are needed for expression of SOC data on an area basis, i.e., for the calculation of the SOC stock (Mg C ha^{-1}). Soil ρ_b can either be estimated/measured *ex situ* or predicted (e.g., by pedotransfer functions, Calhoun et al. 2001). However, pedotransfer functions have larger errors than estimation and measurement methods (Walter et al. 2016). Recently, a technique was proposed that combines gamma-ray attenuation and visible–near infrared (vis–NIR) spectroscopy to measure *ex situ* the bulk density of 1-m soil cores that are sampled freshly, wet and under field conditions (Lobsey & Viscarra Rossel 2016). However, a practical and robust method for sensing gravel needs also to be developed. Further, instead of using a constant value, accurately determining the rock fragment ρ_b is recommended when rock fragments dominate the total volume of the sample (e.g., in deeper soil depths) to reduce potential measurement errors (Mehler et al. 2014). An accurate assessment of soil volume and ρ_b are as important as those of C concentration of the bulk soil (Jandl et al. 2014). In the absence of information on soil erosion or deposition, assessments of SOC stock dynamics also require the determination of SOC stock on an equivalent soil mass rather than in fixed sampling depths or genetic horizons (Ellert & Bettany 1995; Mikha et al. 2013). Direct measurement of all relevant parameters approximately every 10 yr is recommended for a credible assessment of SOC dynamics (Schrumpf et al. 2011), and ideally determined every 20 yr for a systematic proof of change in SOC stocks (Körschens 2010).

Table 2: Advantages, disadvantages and applications of soil organic carbon determination methods*

Method	Advantages	Disadvantages	Best current applications	Reference
Walkley-Black wet oxidation	Previously widely-used standard; inexpensive; little interferences from carbonates	Measures SOC portion; incomplete oxidation - oxidation factor needed; harmful chemicals; interferences from chlorides, oxides of Mn and Fe^{2+}	Quick approximate assessment	Walkley & Armstrong Black (1934)
Weight-loss-on-ignition dry oxidation	Inexpensive	Measures SOC portion; interferences from carbonates (>400 °C) and from inter-lattice water from clay and mineral structures	Where equipment availability is restricted; saline soils; repeat analyses on same soils	Ball (1964)
Automated dry combustion	Current standard – reliable, rapid	Measures TSC; expensive; high energy use; interferences from carbonates	Large number of samples; non-calcareous soils; soils without added limes	Liebig (1831)

Method	Advantages	Disadvantages	Best current applications	Reference
Mid-infrared (MIR) and near-infrared (NIR) reflectance spectroscopy	High through-put; potential use in-field and for remote sensing	Measure SOC portion; appropriate, correct and matching reference laboratory data needed; relatively large number of samples for calibration needed; inability to deal directly with unknown origin samples interferences from quartz, kaolin and carbonates (MIR), and from non-SOC components (NIR)	Large number of samples; ongoing analyses similar soil types; where soil grinding (MIR) and accuracy not a critical issue (NIR)	Bowers & Hanks (1965)
Laser-induced breakdown spectroscopy (LIBS)	High through-put; potential use in-field	Measures TSC; numerous calibration curves dependent on other method; small soil volume analyzed; health hazards; interferences from carbonates, iron and water	Rapid analysis dried, ground samples; non-calcareous soils	Ebinger et al. (2003)
Inelastic neutron scattering (INS)	Infield analysis	Measures TSC; better results for C-rich soils; health hazards; interferences from carbonates	On-the-go analysis of TSC at the field scale	Wielopolski et al. (2008)
Airborne remote sensing	Use over large area	Measures surface SOC; surrogate indices needed	Broad-scale applications on bare soils	Chen et al. (2000)

*Modified from Chatterjee et al. 2009; Johns et al. 2015; Correction for SIC may be necessary; data on soil volume and ρ_b needed for calculation of the SOC stock

2.1.1 Direct Measurements *Ex Situ*

Ex-situ methods involve measurement of C concentration via dry or wet oxidation methods (Table 2; Chatterjee et al. 2009). Oxidation methods account for the majority of SOC analyses but have several limitations, and interferences that must be addressed for accurate SOC measurements (Johns et al. 2015).

Wet oxidation methods involve the oxidation of SOC by acidified or alkaline solutions of permanganate or dichromate, or hydrogen peroxide in conjunction with chromic acid (Johns et al. 2015). The evolved CO_2 is measured by gravimetric, titrimetric, or manometric methods. For example, the previously widely used Walkley-Black method involved heating the soil sample with a $K_2Cr_2O_7$-H_2SO_4-H_3PO_4 mixture (Walkley & Black 1934). Excess dichromate is back titrated with ferrous ammonium sulfate. However, among major disadvantages of this method are issues with safe disposal or treatment of chromium VI remains (carcinogen and strong oxidant) and, most importantly, the variable recovery of SOC due to interferences. Other wet oxidation methods are also not sufficiently accurate. Similarly, the previously widely used weight-loss-on ignition (LOI) dry oxidation method is not reliable, because carbonates at temperatures >400 ^{o}C and the inter-lattice water from clay and mineral structures, interfere with SOC measurements (Johns et al. 2015).

Currently, the most reliable standard or reference method is the automated dry combustion technique. This method involves mixing the sample with catalysts or accelerator and heating in a resistance or induction furnace between 950 ^{o}C and 1800 ^{o}C in an O_2 stream to convert all SOC into CO_2. The CO_2 can be determined by thermal conductivity, gravimetric, or by infrared absorption spectrometry (Nelson & Sommers 1996). However, the dry combustion method measures SOC concentrations accurately only in the absence of SIC (Loeppert & Suarez 1996). Therefore, some instruments are designed for an automated treatment of samples (acidification) containing SIC for determination of SOC by the difference (Johns et al. 2015). Further, main disadvantages of the modern dry combustion instruments are high initial costs, the cost of consumables, and the high energy used for running the reaction chamber at temperatures of 950 ^{o}C or more.

2.1.2 Direct Measurements *In Situ*

In-situ analytical methods are based on colour (visible reflectance), spectroscopic measurements in the field or by remote sensing (Table 2; Chatterjee et al. 2009). Digital camera images including those obtained with mobile phones have some potential for SOC determination by the colour approach but are also challenged with several limitations (Johns et al. 2015). The spectroscopic methods include soil visible, near- and mid-infrared (Vis-NIR-MIR) reflectance spectrosopy (McCarty et al. 2002), laser-induced breakdown spectroscopy (LIBS; Ebinger et al. 2003) and inelastic neutron scattering (INS; Wielopolski et al. 2008).

Among the reflectance spectroscopy methods, less successful predictions of SOC could be achieved with the Vis region (Soriano-Disla et al. 2014). In contrast, moderately successful calibrations have been reported mainly for C fractions based on combined NIR-MIR with partial least-squares regression (PLSR) modeling. In general, MIR predictions for C (inorganic), SOC, and SOM reportedly perform better than by NIR and Vis-NIR. Further, moderately successful predictions of SOC are reported using portable Vis-NIR and NIR devices under field conditions (Soriano-Disla et al. 2014).

The MIR (2500–25000 nm) and NIR (400–2500 nm) reflectance spectroscopy utilizes spectral regions in diffusely reflected radiation of illuminated soil to quantify soil C (Chatterjee et al. 2009). The technique is mainly used in the laboratory but its application *in situ* as well as from air- and space-borne sensors is growing (Nocita et al. 2015). However, the ability to develop a reliable calibration for organic C when carbonates are present remains an open question (Bellon-Maurel & McBratney 2011). Specifically, the MIR spectra of most soils are dominated by the spectra of inorganic fractions such as carbonates, clays, and silica (Reeves 2012). Thus, MIR reflectance spectroscopy may not be practical for on-site use as soil samples have to be processed (dried and ground) in the laboratory prior to spectral analysis (Reeves 2010). Additional requirements include calibration relying on a relatively large number of samples, a reference method for this calibration, and a method for data analysis such as PLSR (Johns et al. 2015). Specifically, soils must be well represented by the calibration samples used to build the predictive MIR/PLSR models (Baldock et al. 2013).

Similarly, the major limitation of NIR reflectance spectroscopy is the continual need for calibration and quality control (Bowers & Hanks 1965). Prediction model accuracy, in particular, is currently insufficient for NIR reflectance spectroscopy to replace routine laboratory analysis and/or to make *in-situ* measurements, whatever the type of soil (Gobrecht et al. 2014). Furthermore, IR radiation penetrates only 0.2-1 cm into the soil matrix, and there lies a lot of uncertainty about *in-situ* determination at deeper soil depths. For archived samples, temporal changes in SOC content to 25-cm depth could be detected using NIR in Danish soils (Deng et al. 2013). However, significant discrepancies have been observed in the corresponding SOC change patterns for samples from 25-50 cm depth compared to traditional laboratory measurements. Recently, Vis-NIR has been used involving close to 20,000 soil samples collected from the conterminous United States at one fixed point in time (Wijewardane et al. 2016). Previous Vis-NIR modeling of soil databases at the national scales used legacy soil samples not collected at the same time frames. Additionally, data on ρ_b are needed for calculation of SOC stocks. The main issue using NIR or MIR field sensors is to be able to simultaneously measure ρ_b or, better, to directly measure the volumetric concentration of C in soil (Bellon-Maurel & McBratney 2011). Further, the capacity of the NIR or MIR spectroscopic models to generalize and predict the SOC content of new samples depends largely on the similarity in the composition of the soil used to derive the model, and that which it is attempting to predict (Guerrero et al. 2014). Recently, Vis-NIR has been used involving close to 20,000 soil samples collected from the conterminous United States at one fixed point in time (Wijewardane et al. 2016). Previous Vis-NIR modeling of soil databases at the national scales used legacy soil samples not collected at the same time frames. Thus, there are numerous uncertainties about the use of MIR or NIR reflectance spectroscopy for general use and *in-situ* measurements of SOC stock and its dynamics.

Soil C determination by LIBS is based on analyzing the unique spectral signature of C when a laser beam at a specific wavelength is focused on soil (Ebinger et al. 2003). However, deploying this technique in the field is hindered by the requirement of numerous calibration curves based on soil texture. Further, rock fragments, roots and other materials cause variability in the LIBS signal. Also, the laser beam penetrates only 0.1 cm into soil, and only small volumes are analyzed. There are also health hazards associated with its use. This technique is in its early stages of development, and additional research is needed for overcoming sample heterogeneity and measurement of SIC concentration prior to its use as a portable technique for SOC measurement (Johns et al. 2015). Thus, how SOC stock dynamics in soil profiles can be measured and assessed by LIBS remains to be unclear and needs further research.

The INS analyzes TSC based on spectroscopy of gamma rays resulting from fast neutrons interacting with the C nuclei (Wielopolski et al. 2008). Radiation penetrates at least 30 cm into soil, but a calibration line is needed to convert C concentrations into stocks and also to correct for the presence of coarse fragments and SIC. Major challenges are (i) removal of interference associated with γ ray contributions from other soil elements and processes, and (ii) the heterogeneous nature of the soil C footprint measured by INS (Yakubova et al. 2016). There are also health hazards for soil biota associated with its use (Johns et al. 2015). Thus, it remains to be seen whether INS can be developed into a suitable method, in particular, to measure SOC stock and its dynamics in the entire soil profile. The INS method has an advantage of repeated *in-situ* measurements over time (Yakubova et al. 2014).

Remote sensing such as remote sensing hyperspectral imagery and proximal sensing has been used to measure SOC at least in the surface layer based on reflectance of various spectral bands (Vis and IR regions) and their correlation with soil properties. It could also be applied to soil samples removed but not physically changed (Johns et al. 2015). Airborne remote sensing may be done by aeroplane, helicopter or satellite-based measurements, and more recently using unmanned flying equipment such as drones. However, prediction of SOC at different spatial scales has not been achieved, and surrogate indices such as vegetation type and species, and measurements of soil moisture contents are also needed (Chatterjee et al. 2009). The need for laboratory calibration severely limits the applicability of remote and proximal sensing methods (de Gruijter et al. 2016). Those approaches are clearly limited for use only in the surface soil and are most applicable to surfaces with vegetation removed (Johns et al. 2015). Thus, it is uncertain whether SOC stock changes in soil profiles may ever be assessed based on airborne remote sensing data.

The conventional factor of 1.724 is sometimes used to convert measurements of SOC into estimates of SOM (Pribyl 2010). This is based on the assumption that OM consists of 58% C. However, this assumption applies only to some soils or only to particular components of SOM. In fact, convenience, authority, and tradition rather than strength of evidence are in large part responsible for the widespread acceptance of the factor of 1.724. Pribyl (2010) reviewed the literature and reported that the median value for the conversion factor was found to be 1.9 from empirical studies and 2 from more theoretical considerations. Specifically, a factor of 2, based on the assumption that OM is 50% C, would in almost all cases be more accurate than the conventional factor of 1.724 (Pribyl 2010).

2.2 Proxy Methods

Monitoring changes in the SOC stock can be challenging given the slow rate at which changes occur (Jandl et al. 2014). Thus, SOC models of different complexity are available with some requiring only commonly available site data for parameterization. The Rothamsted Carbon Model (RothC) and the CENTURY model are two of the most widely used SOC models (Coleman & Jenkinson 1995; Parton et al. 1987). The (surface soil) SOC dynamics of a large area can be simulated. However, RothC has been modified recently to a multi-layer model to describe SOC dynamics in the top meter of soil (Jenkinson & Coleman 2008).

At the regional scale, two types of models can be used to simulate changes in SOC stocks: (i) macro scale models that are designed at a coarse scale and use simplistic equations, and (ii) ecosystem models that are designed at the plot or farm scale and use complex functions (Jandl et al. 2014). Information on long-term management is crucial to quantify the uncertainty associated with estimates based on SOC models. Observed SOC changes from soil monitoring programs may be used to improve the performance of SOC models. The performance of SOC models can also be tested by assessing their ability to simulate long-term SOC dynamics using existing long-term data sets. However, long-term experiments such as long-term ecological research (LTER) sites are rarely replicated and this may limit the confidence in SOC model predictions (Jandl et al. 2014). Further, it is unlikely that any single model will be adequate for all applications (Hillier et al. 2016).

3 Theoretical Suitability of Soil Organic Carbon Changes for Monitoring Land and Soil Degradation

Degradation implies an undesirable condition compared with a starting point (Prince 2016). To detect a relative condition, a not-degraded reference is needed, without which states of degradation have no meaning. However, the detection of non-degraded reference sites that are at their potential is problematic (Wessels et al. 2007).

Soil is a distinct living entity that is among the core building blocks of land. Thus, ecosystem services delivered specifically by soils must be differentiated from those services generally provided by land, e.g., productivity of ecosystems, biodiversity, water quality etc. (Robinson et al. 2014). Soil degradation is a subset of land degradation which is a subset of environmental degradation (Johnson et al. 1997). However, soil degradation is not properly distinguished from land degradation in assessment exercises (Gomiero 2016). Frequently, soil degradation is confused with land degradation that concerns a more holistic phenomenon which may or may not include soil degradation (Krasilnikov et al. 2016). Soil degradation inherently reduces or eliminates soil functions and their ability to support ESs essential for human well-being (GSP 2015), and nature conservancy. Soil degradation is a global issue caused by many factors including excessive tillage, inappropriate crop rotations, uncontrolled grazing or crop residue removal, deforestation, mining, construction and urban sprawl (Karlen & Rice 2015). The degree to which human benefits derived from the capacity of soils to deliver ecosystem goods and services lost due to soil degradation varies strongly with geographical location (Banwart et al. 2015). However, there is no single definition for soil degradation, e.g., soil degradation may be defined as "any change or disturbance to the soil perceived to be deleterious or undesirable" (Johnson et al. 1997). Otherwise, FAO & ITPS (2015) defined soil degradation as "the diminishing capacity of the soil to provide ecosystem goods and services as desired by its stakeholders". Soil degradation implies a decline in soil quality with an attendant reduction in ecosystem functions and services. Almost universal indicators of soil degradation are erosion and decline in SOC or SOM stocks (Karlen & Rice 2015). Indicators need to be: (i) acceptable to experts, (ii) routinely and widely measured, and (iii) have a currency with the broader population to achieve global acceptance and impact (Stockmann et al. 2015).

The four conceptual types of soil degradation physical, chemical, biological and ecological can be distinguished (Lal 2015). Soil physical degradation results in a reduction in structural attributes including pore geometry and continuity, thus aggravating a soil's susceptibility to crusting, compaction, reduced water infiltration, increased surface runoff, wind and water erosion, greater soil temperature fluctuations, and an increased propensity for desertification. Soil chemical degradation is characterized by acidification, salinization, nutrient depletion, reduced cation exchange capacity, increased Al or Mn toxicities, Ca or Mg deficiencies, leaching of NO_3-N or other essential plant nutrients, or contamination by industrial wastes or by-products. Soil biological degradation reflects depletion of the SOC pool, loss in soil biodiversity, a reduction in soil C sink capacity, and increased GHG emissions from soil into the atmosphere. Finally, ecological degradation reflects a combination of other three types, and leads to disruption in ecosystem functions such as elemental cycling, water infiltration and purification, perturbations of the hydrological cycle, and a decline in net biome productivity (Lal 2015).

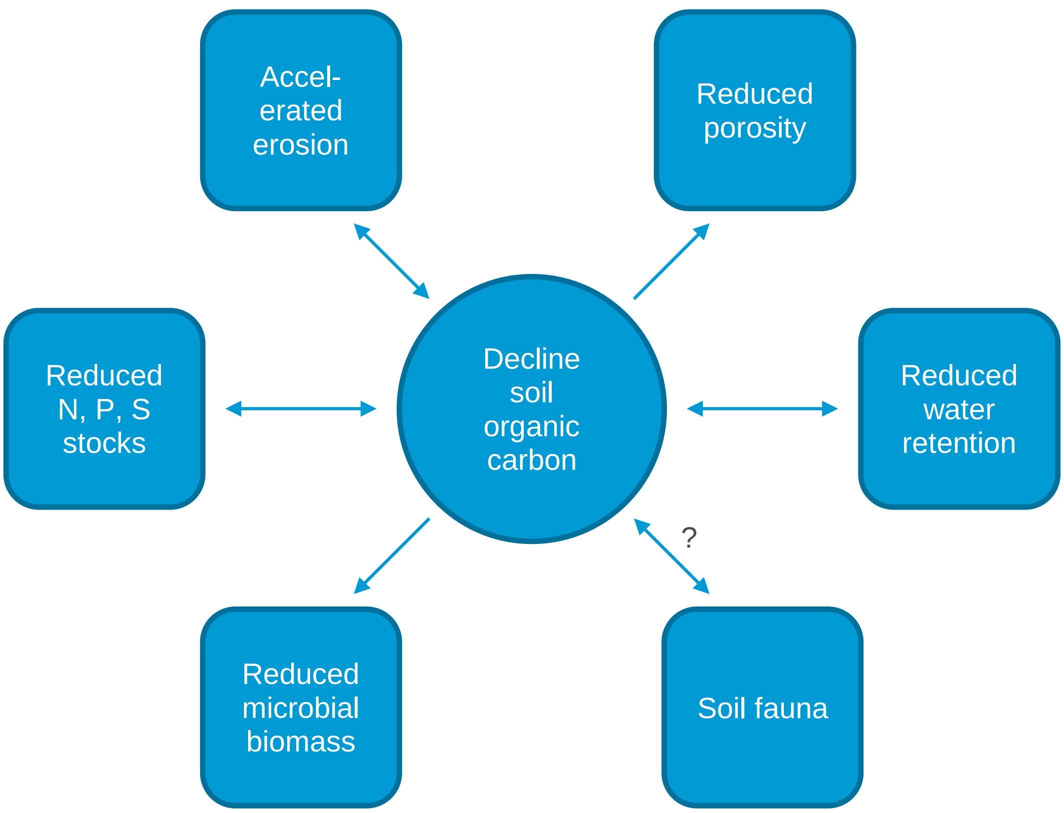
The major drivers of soil degradation are (i) climate aridization, (ii) unsustainable agricultural practices, (iii) industrial and mining activities, (iv) expansion of crop production to fragile and marginal areas, (v) inadequate maintenance of irrigation and drainage networks, and (vi) overgrazing (Krasilnikov et al. 2016). However, there are no credible estimates of the extent of degraded soils (FAO & ITPS 2015), and the rate of degradation at regional, national or global scales. Minimizing or eliminating significant soil degradation is essential to maintaining the services provided by soils. Further, preventing soil degradation is substantially more cost-effective than rehabilitating soils after degradation has occurred. The cost of inaction is high (Nkonya et al. 2016). Soils that have experienced degradation may have their core functions and their contributions to ESs restored through the application of appropriate rehabilitation techniques (GSP 2015). Specifically, to mitigate soil degradation appropriate land uses must be selected and soil management practices improved so that the SOC stock is increased, soil biology is enhanced, and all forms of erosion are reduced (Karlen & Rice 2015).

Similar to soil degradation, there is no single definition of "land degradation". Initial attempts at defining land degradation were directed towards the productive capacity of soils, and later towards the holistic concept of goods and services provided by ecosystems (Nachtergaele et al. 2011a). A short, easily understood, internally consistent definition that captures the realities of current use is "land degradation is any change or disturbance to the land perceived to be deleterious or undesirable" (Johnson et al. 1997). The concept of land, per se, includes mainly the lithosphere and pedosphere, but it also includes those parts of the biosphere, hydrosphere and atmosphere that are ecologically linked to the land and soil. Land degradation has been defined by ISRIC as a long-term loss of ecosystem function and productivity caused by disturbances from which land cannot recover unaided (Bai et al. 2008). Sutton et al. (2016) used the human appropriation of net primary productivity (HANPP), i.e., the ratio of actual NPP to potential NPP, derived from population distributions and aggregate national statistics as proxy measure of land degradation. The land degradation measure suggested that globally $6.3 trillion per year of ES value were lost to impaired ecosystem function (Sutton et al. 2016). The United Nations Convention to Combat Desertification (UNCCD) defined land degradation as the reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes arising from human activities (UNCCD et al. 2016). The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) emphasized to account also for the loss of ESs (Díaz et al. 2015). However, not exclusively SOC but the sum of C contained in vegetation, litter, and soil are used as national indicator for observing the ES C sequestration change (Karp et al. 2015). Further, land degradation is a function of the context in which it occurs and the values of those who perceive it, i.e., one person's degradation may be another person's opportunity (Reed et al. 2013). It is unclear how a single definition can include the potentially conflicting perspectives of those who use the land, and those who may benefit from a wide range of ESs for those located far away from the places where land degradation is occurring. Thus, land degradation needs to be considered in an integrated way, taking into account all ecosystem goods and services – biophysical as well as socio-economic (FAO 2011b).

3.1 Suitability of Soil Organic Carbon Changes for Monitoring Soil Degradation

The SOC is a key indicator for maintaining soil physical, chemical and biological quality. A high SOC content improves the process of soil formation (supporting service), and other chemical and physical soil properties, such as nutrient storage (supporting service), water holding capacity (supporting and regulating service), aggregation, and sorption of organic or inorganic pollutants (regulating service) (Smith et al. 2015). Thus, a reduction in the SOC stock may have potential negative effects on soil-derived ESs and be indicative for soil degradation (Fig. 2).

Figure 2: Decline in soil organic carbon stock and soil degradation processes



In fact, SOC may be one of the significant universal indicators of soil degradation. In comparison with other indicators (e.g., soil pH, cation exchange capacity, elemental toxicity), SOC is easily understood by policy makers and the wider community (Koch et al. 2013). The quantity of SOC is arguably the most important soil indicator because of its central role in a range of soil functions, it is also one of the most common soil property measurements, and it could be argued that C itself is known to the global population (Stockmann et al. 2015). SOC loss, in particular, is one of the most important contributors to soil degradation (Banwart et al. 2015), and to the costs of soil degradation. For example, almost 50% of the total soil degradation costs in England and Wales were linked to SOC loss (Graves et al. 2015). Thus, negative changes in the SOC stock are potentially relevant to monitoring soil degradation as SOC loss has negative effects on soil functions and increases in threats of soil degradation. For example, SOM decline (SOC loss) in mineral soils in Europe has (i) medium negative effects on salinization and on the gene pool (biodiversity), and (ii) large negative effects on water erosion, wind erosion, desertification, flooding and landslides, biomass production, and the soil function storing/filtering/transforming nutrients, substances and water (Stolte et al. 2016). In comparison, SOM decline (SOC loss) in European peat soils has (i) low negative effects on biomass production, (ii) medium negative effects on wind erosion, salinization, and the soil function source of raw materials, and (iii) large negative effects on water erosion, gene pool (biodiversity), and the soil function storing/filtering/transforming nutrients, substances and water. Further, SOM decline (SOC loss) in European peat soils can also have medium positive effects on biomass production depending on peat management, and the fertility and physical properties of the soil underneath the original peat layer (Stolte et al. 2016). However, quantitative evidence of the relation between SOM decline (i.e., SOC loss) and soil degradation for global regions is scanty.

Nevertheless, not all types of soil degradation are equally affected nor to a similar degree by a SOC loss. Some examples for the effects of a decline in SOM content on proxies for soil degradation and on soil threats are listed in Table 3.

Table 3: Effects of a decrease in soil organic matter content on proxies for soil degradation and on soil threats

Soil property/threat	Change	Comment
Aggregate stability	10-40% decrease	1% decrease in SOM content
Predicted soil loss by water erosion	50% increase	Decrease in SOM content from 4% to 2%
Wind erodible fraction	Increase from 0.55 to 0.65	Decrease in SOM content from 5% to 1%
Friability index	Decrease by 0.3 units	1% decrease in SOM content
(Macro)Porosity	1-2% loss	1% decrease in SOM content
Water retention	Up to 10% reduction	Difference in SOM content from 7% to 3%
Biodiversity Soil biological function	?	Not fully understood

Soil property/threat	Change	Comment
Microbial biomass	90% decrease	SOM loss from 5% to 2%

Estimated based on data reported in Stolte et al. (2016), Gregory et al. (2015), and Whitmore et al. (2010)

Aggregate stability and microbial biomass are potentially most strongly affected by a decline in SOM content or SOC loss but data of all soil functions, ESs and soil threats from all global regions are needed for a comprehensive assessment. Further, by a decline of SOC concentration in the root zone below critical thresholds of ~2% (20 g C kg^{-1}) in temperate soils and ~1.1% (11 g C kg^{-1}) in soils of the tropics, some decline in soil quality, yield and agronomic productivity may occur (Lal 2006). However, direct quantitative evidence based on field experiments is scanty (Loveland & Webb 2003), i.e., there are numerical relationships between SOC and soil properties but clear firm evidence of a threshold above or below which the contribution of SOC increases or decreases significantly is rare. Specifically, the magnitude of yield increases by SOC-induced improvement in soil quality depends on soil type, crop, management, antecedent SOC concentration, and the weather during the growing season (Lal 2014). There are only few experiments specifically conducted to establish the relationship between SOC concentration and agronomic yield. Most of the available data relating crop yields with SOC concentration comprise indirect information from other studies conducted to assess the impact of agronomic practices on soil properties (Lal 2010). Some evidence for a strong relation between crop yields and the amount of SOC in the root zone have been observed for diverse soils in several countries including China, India, Nigeria, Russia and Thailand. Thus, within a particular soil, the level of SOC can have a profound influence on the capacity of the soil to produce food, feed, fiber and fuel (Franzluebbers 2010). When soils are maintained with high surface-SOC rather than degraded with accelerated SOC oxidation from repeated tillage operations, productivity can also be enhanced due to non-nutrient attributes of the SOC stock (Franzluebbers 2010). Thus, in certain situations a decline in SOC concentration in the root zone causes soil degradation, i.e., a decline in crop yields. The contributions of the SOC concentration in the root zone to agronomic productivity are particularly high for soils: (i) of coarse rather than heavy-texture, (ii) with lower than higher antecedent SOC concentrations, (iii) receiving lower rather than higher rates of chemical fertilizers, (iv) managed under rainfed rather than irrigated conditions, and (v) of poor rather than good quality (Lal 2010).

It remains unclear whether SOC change (i.e., SOC loss) can be a universal sensitive and responsive indicator of soil degradation because different types of soil degradation differ in their sensitivity and responsiveness to SOC change. Further, the severity of some types of soil degradation may depend to different degrees on SOC loss. For example, the decrease in the SOC content worked well as criteria for strongly eroded soils in the USSR (Krasilnikov et al. 2016). However, for weak erosion in the absence of morphological evidence it did not work well as the natural variation of SOC content was high and depended on multiple factors. Previous attempts to characterize soil degradation by a soil deterioration index were not widely accepted as the un-degraded baseline and certain soil properties were arbitrarily chosen while other properties were omitted (e.g., Islam & Weil 2000). Further, SOC itself was among the properties included in the calculation of the soil deterioration index. Also, it is not always observed that a strong correlation exists between agronomic yield of crops and SOC concentration in the root zone (Lal 2010). Thus, a decline in SOC concentration in the root zone of crops may or may not be a relevant, sensitive and responsive indicator for a decline in crop yield, i.e., implying that some soil ecological degradation has occurred. Similarly, SOC is not the exclusive indicator of soil quality as it does not necessarily directly interact with all processes affecting soil quality. Specifically, SOM or the SOC stock affects nutrient cycling, pesticide and water retention, and soil structure but not plant water use efficiency, crop emergence, N mineralization and immobilization rates, and rooting volume for crop production (Karlen et al. 1997). For example, changes in SOC content have been related to a biological soil quality index based on Collembola species but not on another biological soil quality index based on microarthropods (Gardi et al. 2002). Otherwise, a biological quality index computed based on SOC(calculated)/SOC(observed) is reportedly sensitive to measure severe soil degradation processes in volcanic andisols and aridisols which occurred as a consequence of anthropogenic activities when laurel and pine forests were replaced by shrubs (Armas et al. 2007). Thus, not the single indicator SOC but Soil Quality Indices (SQIs) have been proposed to synthesize soil attributes (SOM content and stock, ρ_b, respiration rate, soil depth, electrical conductivity, pH etc.) into a format that enhances the understanding of soil processes to inform on appropriate management or policy interventions (Obade & Lal 2016). Similarly, %SOC has been proposed among soil indicators for agricultural land reflecting natural soil resilience in the long term (Schiefer et al. 2015).

In conclusion, it is unlikely that SOC change alone can reflect the complexity of soil degradation. Soil degradation is caused by the interplay of bio-physical, socio-economic and political factors, and degradation problems are by definition site-specific and occur at different scales (Stolte et al. 2016). Thus, whether SOC loss is suitable for monitoring soil degradation needs additional research, in particular, by establishing the link between SOC change and the different types of soil degradation processes, soil threats, soil functions and soil-derived ESs. Similar to SQIs, a soil degradation index including data on SOC loss among other soil changes may be more suitable for monitoring soil degradation.

3.2 Suitability of Soil Organic Carbon Changes for Monitoring Land Degradation

Land degradation may include degradation of the land elements soils, rocks, rivers and vegetation. In this context, Caspari et al. (2015) proposed the dynamics of SOC content as a good example for an integrative indicator of land degradation, i.e., an indicator able to cover diverse and vital processes at the same time. It is often argued that dynamics of SOC content is not only at the nexus of soil chemical, physical and biological processes but connected to aspects such as water holding capacity, floods and droughts, productivity, or soil stability and biodiversity. Further, the dynamics of SOC content are influenced by land management. Thus, Caspari and colleagues proposed that significant changes can be detected within a couple of years, but also emphasized that there is not one indicator alone that could act as the ultimate proxy for land degradation. For example, the Land Degradation Neutrality (LDN) project used agreed progress indicators for SOC stock, land use cover and land productivity (Smith 2015). However, measuring against the indicator for SOC content was problematic because there is no global dataset. Further, for the Global Land Degradation Information System (GLADIS), soil health status was evaluated mainly by the status and trends of SOC but with a due reference to some other properties such as nutrient availability, salinity and workability (Nachtergaele et al. 2011b). Thus, a combination of biophysical and socio-economic indicators to cover the land degradation was strongly recommended. However, the actual distribution and severity of land degradation does rarely match. Where remote sensing data suggest land productivity increases, this would have to be, therefore, cross-checked for potentially undesirable land use/land cover changes and /or concomitant decreases in SOC contents (Caspari et al. 2015).

It is, thus, unclear how SOC changes may affect land degradation processes as, in particular, SOC losses are among the many drivers of land degradation. Drivers of land degradation include also proximate drivers, such as topography, land cover and vegetation, soil resilience, climate, and poor management, and underlying drivers, e.g., poverty, decentralization, access to agricultural extension service, land cover changes, and commodity market access (Turner et al. 2016). Indicators of these biophysical, social, and economic types of drivers include measures of vegetation cover, administrative borders, population density, soil properties, biodiversity, climate conditions, land management practices, topography, road density, access to information, land tenure, national policies, institutions, population density, and farmer perceptions. Thus, mapping and quantification of degraded lands has not been done based solely on the single indicator SOC change but based on (i) expert opinion; (ii) satellite derived NPP; (iii) biophysical models; and (iv) mapping abandoned cropland (Gibbs & Salmon 2015). However, soil degradation which itself may be affected by SOC loss has been often neglected in approaches for assessing land degradation based on satellite derived NPP (Bai et al. 2008). Further, mapping abandoned cropland has often neglected soil degradation outside of croplands. Thus, while SOC change may be to some degree relevant as an indicator for monitoring land degradation, its sensitivity and responsiveness are unclear. In conclusion, whether SOC loss is suitable for monitoring land degradation needs additional research, in particular, by establishing the link between SOC change and the numerous land degradation processes and drivers.

4 The Global Data Availability for Soil Organic Carbon

The spatial distribution of SOC stocks is derived from maps (printed or electronic) where areas with similar soil characteristics are aggregated to form soil units, and the SOC mass of the area of the soil unit is calculated by multiplication of the area of the soil unit by its unit-area SOC stock (Amundson 2001). In the past, soil maps have been compiled largely based on the experience of soil surveyors, taking into account topography, climate, land use history, land management, vegetation, parent material, and soil typical characteristics (McBratney et al. 2003). The spatial soil units are linked to their defining properties which are based on measurements of soil profiles or an evaluation by experts. Measurements from several profiles within the same soil unit have been statistically aggregated (e.g., averaged). Missing profile data may also be estimated using pedotransfer functions from other measured soil characteristics (Köchy et al. 2015b). Repeated soil sampling campaigns (5-10 years interval) are needed to provide a consistent assessment of SOC condition of soils for different land uses (Schrumpf et al. 2011; van Wesemael et al. 2011).

4.1 Readily Available Global Datasets on Soil Organic Carbon

Globally harmonized datasets on SOC stocks can be produced and their spatial distribution be estimated based on soil maps. The accuracy of spatially interpolated maps of SOC stocks depends on how well the soil units are represented by soil profiles including complete characteristics (Köchy et al. 2015b). The World Inventory of Soil Emission Potentials (WISE) database was recently complemented with some 8000 ‘new’ profiles, originating mainly from North America and ‘High Latitude’ regions (Batjes 2009; 2016). About 21,000 profiles were available to estimate global SOC stocks to 2-m depth. However, there were several soil geographic and taxonomic gaps in the data set, and the spatial distribution of the profiles was uneven. Further, the full complement of soil analytical attributes required (i.e., data on SOC, ρ_b, volumetric gravel fraction and soil depth) was seldom available for many profiles and, thus, a gap-filling taxotransfer scheme had to be applied. It was also not possible to include depth to bedrock in the analyses due to a paucity of data in the various source materials (Batjes 2016). Further, many profile descriptions have been compiled from 1925 to 2005, and, thus, early data may no longer reflect current conditions, where C input and decomposition rates may have changed (Köchy et al. 2015b). Since 1986, efforts are under way to expand the database of data-rich soil profiles and to use pedotransfer instead of taxotransfer functions (Nachtergaele 1999).

Before the publication of the Harmonized World Soil Database (HWSD; FAO and IIASA, 2012), many global estimates on SOC stocks were based on the Digital Soil Map of the World (DSMW; Digital Soil Map of the World 2007) or the Soil Map of the World (SMW; FAO 1997). The Oak Ridge National Laboratory Distributed Active Archive Center compiles, archives, and distributes data on the physical and chemical properties of soils which includes several SOC datasets (http://daac.ornl.gov/cgi-bin/dataset_lister_new.pl?p=19). Earlier spatial databases included a map of the SOC stocks on a 5 arcminute (5‘ by 5‘) grid derived from the DSMW in conjunction with WISE produced by the International Geosphere-Biosphere Programme (IGBP; Global Soil Data Task Group 2000). Further, the US Natural Resources Conservation Service (NRCS) reclassified the SMW at 2‘ and combined it with a soil climate map (Reich 2000). The produced map shows the distribution of nine classes of SOC stocks. The Global Soil Dataset for Earth System Models (Shangguan et al. 2014), with a resolution of 0.5‘, combined the DSMW with regional soil maps and global and regional profile databases from several sources beyond those used in the HWSD, including the national databases of the USA, Canada, and Australia. Soil profile data and mapping units were matched in several steps. Further, several harmonization steps were applied to the data to derive soil C concentration, ρ_b, and gravel content and depth for each soil mapping unit data (Köchy et al. 2015b).

The HWSD is one of the most exhaustive, harmonized, and spatially explicit global databases (Köchy et al. 2015b). It is the latest and most detailed soil inventory at the global scale, and widely used as an international reference. For the topsoil (0–30 cm) and the subsoil (30–100 cm), the HWSD contains values for SOC, ρ_b, and gravel content for dominant and secondary soil types on a raster of 0.5‘. Data sources for the HWSD are earlier global soil maps that were published by or in cooperation with the FAO, the European Soil Database, the Soil Map of China, Soil and Terrain Database (SOTER) regional studies, WISE profile data, and WISE pedotransfer and taxotransfer functions. However, the HWSD does not yet include the extensive national databases of USA, Canada, and Australia. The HWSD is produced by associating existing maps of soil types (some reclassified to FAO standards) with soil characteristics derived from the WISE database containing about 9,600 soil profiles. The reliability of the information contained in the database is, however, variable. Specifically, the parts of the database that still make use of the SMW such as North America, Australia, West Africa and South Asia are considered less reliable, while most of the areas covered by SOTER databases are considered to have the highest reliability (Central and Southern Africa, Latin America and the Caribbean, Central and Eastern Europe) (Köchy et al. 2015b).

For the first time, Köchy et al. (2015b) described the frequency distribution of SOC stocks within broad classes of land use/land cover and C-rich environments based on the HWSD. The suitability of this map for detecting changes in SOC stocks critically depends on soil monitoring. Specifically, *in-situ* measurements of SOC, soil depth, and ρ_b must be improved, collected, and made available for calculating the global SOC stock (Jandl et al. 2014). For the purposes of detecting actual change in SOC stocks, their uncertainty should be quantified (Köchy et al. 2015b). Ideally, SOC, ρ_b, and coarse fragments should be measured at the same point or sample to reduce effects of spatial variability. Predictive mapping techniques, including geostatistics, modeling, and other quantitative methods, especially in conjunction with proximal (radiometry, NIR spectroscopy) or hyperspectral remote sensing of soil properties can potentially reduce uncertainties in SOC mapping introduced by soil classification and help in interpreting spatiotemporal patterns. Mapping of soils should be coordinated, in particular, with the direct or indirect mapping of SOC input and its controlling factors (land use, land cover, crop type, land use history and land management) as well as extent and soil depth of wetlands, peatlands, and permafrost (Köchy et al. 2015b). Monitoring location, extent, and water table variation of wetlands at the global scale, and of permafrost and the active layer is crucial for assessments of global SOC stocks, decomposition models, and certainty of changes (Köchy et al. 2015a).

Recently, Batjes (2016) compiled an updated harmonized dataset of derived SOC stocks to 0-0.3, 0-0.5, 0-1, 0-1.5 and 0-2 m depths for the world at a nominal resolution of 30 by 30 arc sec (WISE30sec). This data set is considered appropriate for assessments at a broad scale (<1:1 M). The derived SOC stocks are best possible estimates based on the current selection of measured soil profile data, 7-layer model, taxotransfer procedures, and spatial data. The information may be used to address pressing challenges including food security, land degradation, water resources, and climate change (Batjes 2016).

Uncertainty in SOC stocks could further be reduced if all soil types and regions were well represented by soil profile data (Köchy et al. 2015b). However, many soil profile data collected by governments and projects remain unused because they are not available digitally. Their use is restricted because of data protection issues, or because they are only known to a very limited number of soil scientists. Existing approaches such as the Northern Circumpolar Soil Carbon Database (NCSCDB), the GlobalSoilMap.net project (Arrouays et al. 2014), and the Global Soil Partnership (coordinated by the FAO) are important steps to improve the situation. These activities would benefit further if all publicly funded, existing soil profile data were made publicly available to the greatest possible extent. Another source of uncertainty is introduced because profile data and soil maps have been generated by a multitude of methods (Köchy et al. 2015b). Further, if different methods are preferably used for particular soil types or regions, small differences multiplied by large areas can result in significant differences at the global level. Thus, international activities to harmonize methods of sampling, calculation, and scaling are needed. The harmonized methods must then be applied in soil sampling. Preferably, samples should be archived so that soils can be reanalyzed with improved or new methods or for checking data by more than one laboratory (Köchy et al. 2015b).

4.2 Readily Available Regional Datasets for Soil Organic Carbon

There are strong discrepancies in the regional coverage of SOC information (Jandl et al. 2014). Also, different approaches for soil sampling and chemical analyses make regional comparisons highly uncertain. Even more difficult is quantifying regional SOC stock changes over time. The information on SOC is geographically unbalanced, and an immediate challenge is the harmonization of already existing regional soil monitoring programs and soil databases (Jandl et al. 2014). Specifically, the main difficulty in assessing changes in SOC stocks at regional scale is not linked to the accuracy of SOC analysis in the laboratory but to the design of an efficient sampling system (van Wesemael et al. 2011).

A single sampling campaign of paired sites is used to estimate country-specific land use or management effects on SOC stocks, which is not adequate (Olson et al. 2014). The most common sampling design of soil monitoring networks intended to monitor regional/national SOC stocks is either stratified according to soil/land use/climate or grid based (van Wesemael et al. 2011). Specifically, SOC and ancillary data are collected to provide a nationally consistent assessment of SOC condition across the major land-use/soil type combinations. Repeated sampling campaigns (5–10 years interval) are used with densities of one site per 10–1,040 km^2. Large countries with a low sampling density (<1 site per 100 km^2; e.g., Australia, New Zealand, USA) generally prefer a stratified design in order not to miss important units. Otherwise, 43% of the European networks reported in the Environmental Assessment of Soil for Monitoring (ENVASSO) project including countries such as Germany and Sweden have a grid sampling design (Morvan et al. 2008). However, the geographical distribution of the soil monitoring sites in Europe is not uniform. Some countries have rather dense networks (e.g., England and Wales, Northern Ireland, Austria, Denmark, Malta), whereas other large countries have relatively few monitoring sites (Spain, Italy, Greece). For monitoring changes in SOC stocks, a systematic sampling grid would be appropriate. Nevertheless, SOC/SOM content is monitored almost everywhere in Europe, and only 4,147 new measurements would be required to reach a recommended coverage of one site per 300 km^2. However, ρ_b is not measured in about half of the European countries, and 10,101 new measurements of ρ_b would be needed to monitor the SOC stocks (Morvan et al. 2008). Otherwise, process-based SOC models can be run for the individual points of the soil monitoring network (van Wesemael et al. 2011). Examples from the USA and Belgium show that uncertainties in SOC change range from 1.6–6.5 Mg C ha^{-1} for the prediction of SOC stock changes on individual sites to 11.72 Mg C ha^{-1} or 34% of the median SOC change for soil/land use/climate units. For national SOC monitoring, stratified sampling sites appears to be the most straightforward attribution of SOC values to units with similar soil/land use/climate conditions (i.e., a spatially implicit upscaling approach; van Wesemael et al. 2011).

Some regional and national soil datasets including that on SOC are compiled by FAO's Soils Portal (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/regional-and-national-soil-maps-and-databases/en/) and the International Soil Reference and Information Centre (ISRIC; http://www.isric.org/data/data-download). Data for evaluating SOC change in Asian countries are limited because countries do not generally monitor SOC stock and changes (ITPS & GSP 2015). Also, there is little information in the Near East and North Africa regions relating to changes in SOC. Further, only limited field data on SOC stocks are available for North America (ITPS & GSP 2015).

In conclusion, major readily available datasets on SOC are available for some regions and nations. However, similar to global datasets on SOC, suitability of the data for monitoring SOC changes is uncertain. Specifically, revised methodology including those for soil sampling, and updated remote sensing and field information are needed to enhance the credibility of the data. Until the database on SOC is strengthened, the use of proxy data for SOC may be a potential „easy-to-use" approach. For example, for many climate change assessments management aspects of the land cover, i.e., land use data are essential (Verburg et al. 2011). Land use may be very different on the same land cover and may have highly different implications for C sequestration. Recent efforts to create data sets of land management are an important step forward including global and regional inventories of irrigated areas, global data on crop yields and fertilizer use, and methods to derive parcel size and structure from remote sensing images (Verburg et al. 2011). Based on empirical analysis of global patterns of sustained direct human interaction with ecosystems, Ellis & Ramankutty (2008) generated a global map of "anthropogenic biomes" as humans have restructured the terrestrial biosphere and substantially altered, e.g., global patterns of species composition and abundance, primary productivity, and the biogeochemical cycles of C. It has been hypothesized that anthropogenic biomes will differ substantially in terms of basic ecosystem processes (e.g., NPP, carbon emissions, reactive nitrogen). Thus, the anthropogenic biomes may serve as proxies for SOC stocks under different land uses.

5 Addressing Soil Organic Carbon or its Proxies in a Monitoring Framework of the Sustainable Development Goals

Seventeen Sustainable Development Goals (SDGs) have been adopted by countries on September 25, 2015 (UN GA 2015). Aim of the SDGs is to end poverty, protect the planet, and ensure prosperity for all. Each goal has specific targets to be achieved from 2015 to 2030. Progress in the implementation of the SDGs shall be monitored by a global indicator framework. UN's High-Level Political Forum (HLPF) was mandated to play the central role in overseeing follow-up and review processes at the global level (UN Economic and Social Council 2016). A key component of the process is an annual progress report which will inform the follow-up and review in the context of the HLPF. The progress report is to be based on a proposed global indicator framework of over 230 indicators. This is an ambitious framework for monitoring and review of implementation (ICSU & ISSC 2015). Measurability will, particularly, depend on the availability of data and capacity to measure the targets. In particular, the data demands relating to the SDGs are unprecedented (UN Economic and Social Council 2016). To establish monitoring mechanisms, Lu and colleagues suggested that analysis and interpretation in the SDG tracking progress must be provided at the same time, ideally by an independent government-backed organization, to consider the data in context (Lu et al. 2015). Specifically, global collaborations between governments and scientific bodies will be essential in setting up monitoring programmes, and in assisting developing nations to implement them (Stafford-Smith et al. 2016). However, countries' capabilities to acquire and process data vary greatly. Especially in developing countries, government investments are needed for tracking changes on a large scale, such as land use and land cover change, climate change and impacts, and natural resources management, all of which affecting soils and SOC stocks. Therefore, the availability of technology and the development of infrastructure are among the essential building blocks for the successful implementation of the SDGs in developed and developing countries (Sarvajayakesavalu 2015). The SDG's evaluation process should take place at multiple scales from a distributed network, where cross-scale learning and coordination is important. Challenges, such as the lack of fully developed infrastructure to support networking, high-performance computing, and the use of GIS, the lack of manpower to operate and support a database management system, and the absence of policies regarding infrastructure in developing nations and underdeveloped countries must be addressed. Developing countries will need to collaborate with developed countries to build capacity. Scientists and governments need to design monitoring and sampling approaches with robustness in mind, and to verify data (Lu et al. 2015). Thus, the SDGs can be implemented by all countries, giving particular focus to developing countries, with right action and a holistic approach that well balances economic, social, and environmental aspects (Sarvajayakesavalu 2015).

5.1 Monitoring Achievements towards Reaching the Sustainable Development Goals

The monitoring procedures to document achievements in reaching the SDGs have to be included in the policy cycle (Bouma & Montanarella 2016). The policy cycle includes (i) the signaling phase in which problems are identified; (ii) the design phase in which options for possible corrective action are defined; (iii) the decision phase in which a selection of options is made by policy makers; (iv) the implementation phase in which the selected option is being realized, and (v) the evaluation phase in which the entire process is analysed in terms of a learning procedure (Bouma et al. 2007). This may have to include monitoring procedures to document achievements. Of crucial importance will be the way in which progress towards achieving each SDG will be measured (Bouma & Montanarella 2016). The adoption of an agreed set of indicators becomes, therefore, of fundamental relevance for the implementation and evaluation phase of the SDGs. Recently, the UN Statistical Commission approved a draft global indicator framework intended for the follow-up and review of progress towards the SDGs at the global level (UN Statistical Commission 2016). Introducing soil related indicators for the SDGs that explicitly mention soil as a component would have been desirable, but faced the well-known lack of basic soil data and adequate soil monitoring systems in many nations of the world. Models can be used to fill the gaps in spatial coverage of soil data, but these give also very variable results (Smith et al. 2016). In fact, rates of soil degradation and replenishment were also not among the previously introduced sustainability indicators for the whole planetary system (Dahl 2012). Thus, a more realistic approach may be to use proxy indicators addressing the SDGs in a more holistic and integrated manner (Bouma & Montanarella 2016).

Monitoring progress towards the SDGs has to be performed at four levels – national, regional, global, and thematic, with indicators as their backbone (SDSN 2015). Global monitoring would require a harmonized and universal set of indicators, i.e., Global Monitoring Indicators. To ensure effective global monitoring, the Global Monitoring Indicators would be tracked in every country and reported periodically at the global level and by each country. Complementary National Indicators will allow each country to track country-specific challenges. However, neither the list of monitoring indicators nor the mechanisms of SDG monitoring has been agreed upon. Nevertheless, there is some consensus that focus of monitoring will be at the national level while complementary monitoring will occur at regional and global levels (SDSN 2015).

Among the principles of Global Monitoring Indicators is that those should be underpinned by a broad international consensus on their measurement and be based on international standards, recommendations, and best practices to facilitate international comparison (SDSN 2015). Where possible, indicators should be broadly consistent with systems of national accounts, systems of environmental economic accounting, and other systems-based information. Another principle is that indicators should be consistent to enable measurement over time, and where well-established data sources are unavailable, establishing a baseline is an urgent priority (SDSN 2015). As discussed previously, there is no consensus on the relation between SOC stocks and land and/or soil degradation, on the measurement interval to determine changes in SOC stocks, and on procedures for measurements of SOC stocks at regional, national and global levels. For example, almost every country has its own analytical methods for soils and these methods may vary from one laboratory to the next within one country (Batjes 2016). This is partly so because soil analytical methods are often soil type specific. Further, reliability of soil data is considered lowest for those sections of the world that still draw on the DSMW, including Australia, North America as well as large sections of South East Asia and West Africa (Batjes 2016). Thus, it is necessary to establish the relation between changes in SOC stocks and land and/or soil degradation, to standardize procedures for establishing a baseline on SOC stocks at regional, national and global levels, and to establish a protocol how temporal changes in SOC stocks will be monitored (e.g., Stockmann et al. 2015).

Most importantly, the well-known lack of basic soil data and adequate soil monitoring systems in many nations of the world must be addressed in a monitoring framework for the SDGs. Important gaps exist for systematic data collections on a routine, harmonized, and comparable basis, particularly for key environmental metrics including soil (SDSN 2015). Specifically, existing global and national datasets on SOC stock are unlikely to be useful as a baseline but may be helpful as a basis for risk assessment and modelling (FAO 2011a). Thus, major investments in the national and international capacity to collect and analyze soil data would be required to develop the indicator SOC stock. However, new data on SOC stocks do not need to be produced every year in the absence of drastic land use and land cover changes. In such cases producing data every five to ten years and doing robust projections, extrapolations or modeled estimates may be sufficient. Successive measurements should be taken at intervals that are relevant to the crop rotation cycle. However, SOC stocks may have to be measured annually in regions and nations where large areas are affected by processes causing major soil disturbance such as those related to deforestation (Wei et al. 2014), and land take and soil sealing (Lorenz & Lal 2016). Thus, the SOC stock should be re-measured at appropriate intervals to be determined in relation to the soil type, crops grown, likely impacts and rates of impacts, and compared to the baseline and/or previous measurements (FAO 2011a).

5.2 Suitability of Soil Organic Carbon for Monitoring Cross-cutting Issues

For most of the SDGs, there is no direct link with soils. However, soils can contribute to the realization of several of the SDGs, i.e., those with reference to food, health, water, climate and land management (Keesstra et al. 2016). Mainly linked to soils and their functioning in natural environment is Goal 2 „End hunger, achieve food security and improved nutrition and promote sustainable agriculture“ (Blum 2016). However, the first annual progress report toward the SDGs was based on a selection of indicators for which data were available as of May 2016 (UN Economic and Social Council 2016). It was based mostly on indicators classified as Tier I (i.e., indicators with an established methodology and data already widely available) or Tier II (i.e., indicators with an established methodology but insufficient data coverage). With regard to Goal 2, reported were only data on hunger, malnutrition, livestock breeds, investments, and distortions in world agricultural markets (UN Economic and Social Council 2016). To some extent related to soil and land are Goal 6 „Ensure availability and sustainable management of water and sanitation for all‘ and Goal 7 „Ensure access to affordable, reliable, sustainable and clean energy for all“. Previously, changes in SOC stock (content) have been proposed as indicator for sustainable land management with references to Goal 13 ("Take urgent action to combat climate change and its impacts") and Goal 15 ("Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forest, combat desertification, and halt and reverse land degradation and halt biodiversity loss") (Müller et al. 2015). However, data on the extent of sustainable use of terrestrial ecosystems, on desertification and land degradation were not available for the first annual progress report (UN Economic and Social Council 2016). Further, no reference to soils is made in the adopted list of targets under Goal 13. Nevertheless, soil management aimed at increasing SOC stocks is important to meet Goal 13 (Keesstra et al. 2016).

Increases in SOC stocks may contribute to achieving some of the other SDGs as the SOC stock is an important indicator of soil quality. Specifically, Target 2.4 "By 2030, ensure sustainable food production systems and implement resilient agricultural practices . . . that progressively improve land and soil quality", and Target 15.3 "By 2030, combat desertification, restore degraded land and soil . . . strive to achieve a land degradation-neutral world" may be promoted by increases in SOC stocks (Lal 2016). With regard to the SDG monitoring framework, the Sustainable Development Solutions Network (SDSN) proposed tracking by indicators appearing under more than one goal and target. However, the indicators for Target 2.4 „Proportion of agricultural area under productive and sustainable agriculture“ and for Target 15.3 „Proportion of land that is degraded over total land area“ were both categorized as Tier III Indicators, i.e., indicators for which there are no established methodology and standards or methodology/standards are being developed/tested (IAEG-SDG 2016). Otherwise, the indicator SOC stock may effectively be used to track cross-cutting issues and support integrated, systems-based approaches to implementation. However, the SOC stock was not among the proposed list of 100 indicators (SDSN 2015). Recently, UNCCD et al. (2016) proposed how countries can apply a standardized approach to reporting SDG Indicator 15.3.1 („Proportion of land that is degraded over total land area“), one which focuses primarily on the use of three sub-indicators (i.e., land cover and land cover change, land productivity, and C stocks above and below ground). This included also the quantity of C in the pool soil (i.e., SOM). It was concluded that further work is needed to provide a standardized approach and “good practice guidance” to derive the sub-indicators and help build monitoring and reporting capacities at the national, regional and global levels (UNCCD et al. 2016).

The SDGs are globally applicable and will have to be implemented by national governments during the next years. However, as discussed previously data on SOC stocks and adequate systems for monitoring changes in SOC stocks are lacking for many regions and nations. Similarly, essentially lacking is monitoring SOC changes by an independent scientific community following the implementation of mandatory good agricultural and ecological practices by farmers in order to access the direct payment scheme of the Common Agricultural Policy (CAP; Bouma & Montanarella 2016). Thus, changes in SOC stocks appear currently not be suitable to monitor land and soil degradation within the SDG framework. Alternatively, the ESs concept has been proposed as being appropriate as a proxy to interdisciplinary address the SDGs (Bouma & Montanarella 2016). This would mean to define the role of soils in contributing to the provision of ES and then to consider soil functions such as those listed by the European Commission (EC 2006). The soil function "Acting as carbon pool" among other functions contributes to sustainable development as it contributes to the regulating ESs on which sustainable development depends. The more general regulating ESs include: (i) Filtering of nutrients and contaminants, (ii) Carbon storage and greenhouse gases regulation, (iii) Detoxification and the recycling of wastes, and (iv) Regulation of pests and disease populations. For analyzing the processes involved in realizing the SDGs, Bouma & Montanarella (2016) proposed to apply the DPSIR framework (Van Camp et al. 2004). Here, D represents drivers of land use change, P are the resulting pressures on the land, S represents the state of the land, I is the impact, and R indicates a response in terms of development of strategies and operational procedures for the mitigation of perceived threats. The present state S is not only determined by soil factors but can be defined by the ESs it can provide by mobilizing relevant soil functions. Future developments that are considered in terms of different scenarios, each one associated with characteristic drivers, pressures and impacts are of particular interest. These different scenarios represent different visions on sustainability (Bouma & Montanarella 2016).

Cross-cutting issues can be monitored by a combination of Global Monitoring Indicators and Complementary National Indicators (SDSN 2015). The indicator SOC stock may contribute to monitoring progress regarding some important SDG priorities, i.e., (i) climate change adaptation and mitigation, (ii) food security and nutrition, and (iii) sustainable land use, forests and other terrestrial ecosystems. For example, SOC stocks may be part of the Global Monitoring Indicator "Net GHG emissions in the

Agriculture, Forestry and other Land Use (AFOLU) sector (tCO_2e)" which itself is part of SDG Goal 13. Further, SOC stock may also be part of the Complementary National Indicator "GHG emissions intensity of areas under forest management ($GtCO_2e$ ha^{-1})". Regarding the cross-cutting issue food security and nutrition, SOC stock may be part of the Global Monitoring Indicators "Crop yield gap (actual yield as % of potential or water limited potential yield)", "Nitrogen use efficiency in food systems", and the yet to be developed indicator "Crop water productivity (tons of harvested product per unit irrigation water)". These indicators are linked to the cross-cutting hunger/nutrition goal. Further, Global Monitoring Indicators to SOC stock may contribute are "Annual change in forest area and land under cultivation (modified Millennium Development Goal Indicator)" linking to the cross-cutting issue expansion of agricultural land, and "Annual change in degraded or desertified arable land (% or ha)" linking to the cross-cutting issue quality of agricultural land. The SOC stock may also contribute to the Complementary National Indicator "Cereal yield growth rate (% p.a.)". With regard to the important SDG priority sustainable land use, forests and other terrestrial ecosystems, SOC stock may be part of the Global Monitoring Indicators "Nitrogen use efficiency in food systems" linking to the cross-cutting issue impacts of land used for agriculture, the yet to be developed indicator "Crop water productivity (tons of harvested product per unit irrigation water)" linking to impacts of agriculture on other ecosystems, "Net GHG emissions in the AFOLU sector (tCO_2e)" linking to GHG emissions from forest and other land use, and "Annual change in degraded or desertified arable land (% or ha)" linking to land degradation and desertification. The SOC stock may also relate in part to sustainable land use, forests and other terrestrial ecosystems by the Complementary National Indicator "GHG emissions intensity of areas under forest management ($GtCO_2e$ ha^{-1})" (SDSN 2015).

In 2014, SDG indicators have been assessed to provide an initial, rough illustration of the indicator and data availability at that time, showing in which areas information was more readily available and where information was potentially sparse (SDSN 2015). Assessments were based on a limited number of countries, most of which were high-income. Indicators were ranked from A-C or were listed as “to be determined”. The SOC stock may be currently listed as “to be determined” based on the aforementioned data gaps for many regions and countries. Similar, no preliminary assessment of data availability for the indicators "Nitrogen use efficiency in food systems" and "Annual change in degraded or desertified arable land" was possible. In contrast, the Global Monitoring Indicator "Net GHG emissions in the AFOLU sector (tCO_2e)" received rank “A”, signifying that 80% of countries have at least 2 data points / the indicator is feasible to measure, whereas "Crop yield gap" and "Crop water productivity" were ranked by a “C”, signifying that less than 50% of countries have at least 2 data points / the indicator will be very difficult or infeasible within the time frame. Further, in a recommended tiered indicator system with three tiers (SDSN 2015), SOC stock may be classified to fall under Tier III, signifying an indicator for which international standards (concepts and definitions) still need to be developed.

In conclusion, the design of a global monitoring framework on SOC stock changes within the SDG monitoring and review framework will depend on an improved understanding on the spatial distribution of SOC stocks and their relationship with the SDGs. For monitoring changes, baselines for SOC stocks must be established in many regions and nations together with implementation of the necessary data collection and analysis infrastructure. Only recently was a benchmark established on the status of the world‘s soil resources which may be compared in the future based on periodical assessments and reports on soil functions and soil health at regional, national and global levels (FAO & ITPS 2015). This assessment may be particularly relevant for the SDGs. Specifically, great differences were reported for data and data availability on soil resources and soil change information at national level. For example, systematic sampling/surveying and monitoring does take place for some major land uses (forests, arable lands) in most EU countries, the United States and Canada, China, Australia and New Zealand. However, results are not always made available in the public domain (FAO & ITPS 2015). Similar, designing monitoring frameworks using proxies for SOC such as soil-derived ESs is not yet possible as scientific understanding on the relationship between SOC stocks and ESs is limited, and data on ESs are not available at national level. Thus, formal reporting mechanisms for SOC stocks and ESs must be urgently initiated. Nations should also work towards a national-level goal of achieving a stable or positive net SOC balance (Montanarella et al. 2016).

Table 4: Suitability of soil organic carbon as indicator to monitor land and soil degradation

Pros
Critical role in soil health, fertility, function, quality, productivity and soil-derived ecosystem services
Fundamental role in function and fertility of terrestrial ecosystems
Easily understood by policy makers and the public
Links to costs of soil degradation
Awareness-raising for land and soil degradation
Indication of land and soil degradation hotspots
Cons
Limited quantiative evidence for relation to agricultural productivity, soil degradation threats, and land and soil degradation
Soil organic carbon processes at biosphere to biome scales not well understood
Different types of soil degradation differ in sensitivity and responsiveness to soil organic carbon loss
Not an universal sensitive and responsive indicator of land and soil degradation
No universially agreed, harmonised method for measuring soil organic carbon and for assessing temporal and spatial dynamics
Lack of baseline data and monitoring systems in many nations

6 Conclusions

In principle, the SOC stock has the potential to be a globally relevant and feasible indicator within a monitoring system on land and soil degradation because the SOC stock (i) is related to many fundamental soil functions, (ii) among the indicators of soil health, and (iii) at the nexus of many soil-derived ESs (Table 4). However, using the SOC stock as a measurable parameter to assess the not directly measurable phenomena land and soil degradation is confronted with a myriad of challenges discussed previously. Most importantly, the relationship between changes in SOC stocks and land and soil degradation is not well established. Thus, there is an urgent need to improve the understanding about this relationship before SOC stocks, soil functions and soil-derived ESs can be considered in the SDG framework. Specifically, better data on land and soil degradation must be collected by universally agreed, harmonised approaches (Caspari et al. 2015). Standardized methods at the global level and a bottom-up technique that starts at the local level should be combined to enable the adaptation of global analysis land and soil degradation data to the local level. Type, extent, degree and causes of degradation should be monitored for a comprehensive assessment of degrading land and soil (Caspari et al. 2015). As discussed previously, the SOC stock is central to many ES provided by soils, and a key indicator for maintaining soil physical, chemical and biological quality. Thus, SOC has been proposed by some as a significant universal indicator for soil degradation but quantitative evidence for the relation between SOC loss and land and soil degradation for global regions is scanty. Further, SOC may not only indicate land degradation but itself may be affected by land degradation. However, this may occur not necessarily *vice versa*. For example, external factors (e.g., ‚acid rain‘)

may alter the water quality of terrestrial ecosystems without affecting the SOC stock. In contrast, a SOC loss has the potential to alter both water quality and quantity. Clearly, more data are needed to assess the suitability of the SOC stock as a globally relevant and feasible indicator for monitoring land and soil degradation.

Using SOC as an indicator to complement the post-2015 development agenda would require that the sampling depth, the sampling method, the lab measurement method etc. are recorded to allow for global harmonisation (Caspari et al. 2015). However, the SOC processes at the biosphere to biome scales are not well understood (O'Rourke et al. 2015), contributing to the incomplete understanding on the relation between SOC changes and land and soil degradation. Better understanding exists at least for SOC processes operating at the pedon, aggregate and particle scales. At the landscape scale, the influence of large and small-scale processes has the greatest interaction and is exposed to the greatest modification through soil and land use management. Policies implemented at regional or national scales tend to focus at the landscape scale without due consideration of the larger scale factors controlling SOC or the impacts of policy for SOC at the smaller SOC scales. Thus, a framework is needed that can be integrated across a continuum of scales to optimize SOC management (O'Rourke et al. 2015), and relate changes in SOC stocks to land and soil degradation.

Another important issue that must be addressed is the importance of the SOC stock at deeper soil depths, and the importance of the subsoil SOC stock for land and soil degradation. For example, the LDN project proposed to measure SOC content to 30-cm depth (Smith 2015). However, while SOC stocks closer to the soil surface respond more strongly to perturbations, subsoil SOC stocks below 30-cm depth may be altered within decades by changes in land-use and management (Meersmans et al. 2009). Thus, it has been proposed that subsoil SOC stocks must be included in agricultural SOC studies (Wiesmeier et al. 2013). Further, there is strong evidence that in temperate regions subsoil can contribute to more than two-thirds of the plant nutrition of N, P and K, especially when the topsoil is dry or nutrient-depleted (Kautz et al. 2013). Plant nutrition depends on SOM and, thus, any changes in SOC stocks at deeper depths may also contribute to land and soil degradation and/or be affected by it. However, subsoil processes have been neglected in the past and data on SOC stocks at deeper depths on local, regional and global scales are even more scanty than those for topsoils. Nevertheless, subsoil SOC stocks may have to be included in a monitoring framework on land and soil degradation.

To sum up, the SOC stock may be relatively easy communicated to policy makers, and be a suitable indicator for awareness-raising regarding land and soil degradation. However, the indicator SOC stock is not a composite indicator to draw attention to the important policy issue land and soil degradation, to offer more rounded assessment of performance, and present the big picture in a manner accessible to diverse audiences (Lehtonen et al. 2016). Classification as composite indicator for land and soil degradation is also questionable as causal relationships between SOC stocks and land and soil degradation cannot be easily identified, and cannot alone provide a sufficient knowledge basis for specific policy decisions. Rather, the SOC stock should be classified as a performance indicator placing the observations of SOC stock changes on a normative scale, and, thus, allow judging progress towards a norm (i.e., a land and soil degradation reduction target within the SDG framework). Performance indicators are generally designed to strengthen accountability, but can also serve other functions typically attributed to policy evaluation, in particular learning and policy improvement (Lehtonen et al. 2016). However, the performance indicator SOC stock does not meet many of the intended general functions of indicators. Specifically, knowledge is scanty on monitoring and evaluation of performance, supporting policy evaluation, providing early warning functions, political advocacy, control and accountability, transparency, and improving the quality of decisions. Further intended functions attributed to the performance indicator SOC stock which are poorly met include guidance to policy analysis and formation, improvement of government effectiveness, setting targets and establishment of standards, promotion of the idea of integrated action, and focusing of policy discussion (Lehtonen et al. 2016). Thus, the SOC stock can currently not serve as a clear 'signal' that enable or prescribe an action or management function, and condense information, helping policy-makers to decide whether or not to act on land and soil degradation. Whether the performance indicator SOC stock is suitable to simplify and facilitate communication by reducing ambiguity with regard to land and soil degradation needs, therefore, additional research.

Nevertheless, the SOC stock may play a conceptual role as indicator for land and soil degradation by fostering the percolation of new information, ideas and perspectives into the arenas in which decisions on land and soil degradation and on SDGs are made (Lehtonen et al. 2016). This may be achieved by helping to shape the conceptual frameworks and mental models of actors, mostly through (i) dialogue, public debate, and argumentation; (ii) by providing background information; and (iii) by creating shared understandings. The indicator SOC stock may also play a political role with regard to land and soil degradation as part of attempts by policy actors to influence agenda-setting and problem-definition, highlight neglected issues, or (de)stabilise and (de)legitimise prevailing frameworks of thought and actors. The political role of SOC stock as indicator for land and soil degradation also encompasses necessary efforts to strengthen the legitimacy of democratic decision-making, and advocacy for socially progressive objectives, i.e., for sustainable development and the SDG framework. A broader, indirect role of the indicator SOC stock may be to serve as boundary object, i.e., by combining 'hard facts' and modelling with collective reasoning and 'speculation' (Lehtonen et al. 2016). Thus, science, policy and society may be connected by the boundary object SOC stock as indicator for land and soil degradation within the SDG framework. In summary, the indicator SOC stock can help to 'open up' policy discourses and perspectives on land and soil degradation by highlighting uncertainties, trade-offs, and neglected issues in policy making. It can act as boundary object in informational governance, through mediating between the various social worlds (Lehtonen et al. 2016). More often than influencing policy on land and soil degradation directly, the indicator SOC stock can produce its effects through various indirect pathways. The SOC stock may give an indication of hotspots of degradation.

In conclusion, the following recommendations are made:

- **The SOC is crucial for the performance of terrestrial ecosystems**
- **Increasing SOC stocks strenghtens food security, and contributes to climate change adaptation and mitigation**
- **Both the database and public relations must be strenghtened to enhance recognition of the crucially important SOC by business, politics and society**
- **Soil degradation should be assessed by a composite soil degradation index including data on SOC among other soil properties**
- **Land degradation should be assessed by a composite land degradation index including data on SOC among other data for soil properties, land use cover and land productivity**
- **The SOC should be used for awareness raising on land and soil degadation, in particular, for indicating degradation hotspots**
- **To increase the acceptance of the indicator SOC knowledge on processes affecting SOC and their relation to land and soil degradation must be improved, and routine, harmonized and comparable approaches for systematic SOC data collections must be established**
- **Additional research is needed to assess the suitability of SOC as indicator to monitor progress towards realization of the SDGs with reference to food, health, water, climate and land management**

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