

RESEARCH ARTICLE

Soil organic carbon stock as an indicator for monitoring land and soil degradation in relation to United Nations' Sustainable Development Goals

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Abstract

Seventeen Sustainable Development Goals (SDGs) adopted in September 2015 aim to end hunger and poverty, to protect the Planet, and to ensure peace and prosperity for all. The soil organic carbon (SOC) stock is a major planetary resource supporting many critically important ecosystem services (ESs) and underpins realization of some of the SDGs at the national level. Thus, decrease in the SOC stock is among the significant universal indicators for land and soil degradation and compromises efforts to achieve the SDGs especially those with reference to food, health, water, climate, and land management. However, there is currently no well-established relationship (i.e., quantitative evidence) between the SOC stock and the level of ESs attributable to it. Further, basic soil data and monitoring systems including those of SOC stock and its changes are not available for many regions and nations. This uncertainty affects the suitability of using the SOC stock as absolute indicator to monitor changes in land and soil degradation and, particularly, in relation to the SDG monitoring framework. Thus, although the SOC stock is arguably an important indicator for land and soil degradation among others, more research and data on a national level are needed to establish the relationship between the SOC stock and the targets to monitor progress towards achieving the SDGs with reference to food, health, water, climate, and land management. To the best of our knowledge, this is the first review on the suitability of the SOC stock as an indicator for monitoring land and soil degradation with regard to the SDG framework.

KEYWORDS

ecosystem services, land degradation, soil degradation, soil organic carbon, Sustainable Development Goals

1 | INTRODUCTION

Seventeen Sustainable Development Goals (SDGs) and 169 targets of the 2030 Agenda for Sustainable Development were adopted by the United Nations on September 25, 2015 (United Nations General Assembly [UNGA], 2015). The SDGs aim to end hunger and poverty, to protect the planet, and to ensure peace and prosperity for all. Each SDG has specific targets that need to be achieved in the period

between 2015 and 2030, and progress towards achieving the goals depends strongly on successful implementation on national scale (Gao & Bryan, 2017). Needed are science-driven targets tailored to national contexts supported by national governance. However, achieving multiple SDG targets nationally faces many challenges (Gao & Bryan, 2017). Specifically, understanding trade-offs (negative correlations between SDG indicators) as well as synergistic relations (positive correlations between SDG indicators) is important for

achieving sustainable development outcomes in the long term (International Council for Science, 2017; Pradhan, Costa, Rybski, Lucht, & Kropp, 2017). Progress in the implementation of the SDGs will be monitored by a global indicator framework. Indicators and tools for their assessment are among the requirements to achieve the SDGs (Jónsson, Davíðsdóttir, Jónsdóttir, Kristinsdóttir, & Ragnarsdóttir, 2016). United Nations' High-Level Political Forum was mandated to play the major role in monitoring subsequent activities and reviewing developments towards achieving the SDGs at the global level (United Nations Economic and Social Council, 2016). A key component of the process is an annual progress report that will document the follow-up and prepare a review. This progress report is based on a proposed global indicator framework of a first set of 230 indicators (United Nations Economic and Social Council, 2016), and the first report was published in 2016 (United Nations Department of Economic and Social Affairs, 2016). However, the process of developing an SDG monitoring system may result in an ever-expanding set of observations that are a burden for nation states. Thus, Reyers, Stafford-Smith, Erb, Scholes, and Selomane (2017) recommended to use essential variables to focus SDG monitoring. Otherwise, Schmidt-Traub, Kroll, Teksoz, Durand-Delacre, and Sachs (2017) introduced the SDG Index and Dashboards for assessing countries' baselines for the SDGs. This assessment indicated that the 149 countries for which adequate data were available face fundamental challenges in achieving the SDGs. Both Index and Dashboards will be updated every year for monitoring progress (Schmidt-Traub et al., 2017).

Achieving the SDGs, especially those with reference to food, health, water, climate, and land management, will depend on sustainable use and protection of the natural resources including the finite and fragile soil resources. The sustainable management of soils is directly relevant for half of the SDGs and supposedly also indirectly relevant for other SDGs (Jónsson et al., 2016). The 2030 Agenda for Sustainable Development adopted targets with the goals to restore soils that have been degraded, aiming to achieve a land degradation-neutral world and establish agricultural practices that improve soil quality and minimize soil contamination (UNGA, 2015). Thus, indicators are needed to evaluate the sustainable management of soils towards achieving the SDGs (Jónsson et al., 2016).

Using soil-related indicators for assessing progress towards achieving the SDGs that explicitly refer to soil is hindered by the lack of basic soil data and reliable monitoring systems in many nations. Models are suitable to fill the knowledge gaps in spatial distribution of soil data, but these give also variable results (P. Smith et al., 2016). One of Earth's most important natural resources, the soil organic carbon (SOC) stock, is central to the composition of soil, water, and air resources and supports critically important soil-derived ecosystem services (ESs; Adhikari & Hartemink, 2016; Lal, 2004; P. Smith et al., 2013). The creation of a judicious SOC balance is at the heart of the debate regarding implementation of programs such as '4p1000 Initiative - Soils for Food Security and Climate' (4p1000) proposed at the COP21 Climate Summit in Paris in December 2015 (www.4p1000.org). Thus, decreases in SOC stocks are one of the land and soil degradation indicators, compromise aims of the 4p1000 Initiative, and also hinder the progress towards achieving many of the SDGs, particularly those with reference to food,

health, water, climate, and land management. In fact, the SOC stock was proposed as indicator to monitor land and soil degradation and as a globally relevant and feasible indicator within a monitoring system on land and soil degradation with regard to the SDG framework (Lorenz & Lal, 2016). However, the unconditional use of the SOC stock as indicator for land and soil degradation is debatable for several reasons. First, major readily available datasets on SOC stock are available only for some regions and nations (Food and Agriculture Organization of the United Nations [FAO] & Intergovernmental Technical Panel on Soils [ITPS], 2018), and the suitability of data for monitoring SOC stock changes is unclear. Second, there are no common definitions of land and soil degradation and no common procedures on how to determine land and soil degradation at different spatial scales. Third and most importantly, linking changes in SOC stocks to land and soil degradation drivers and processes remains challenging.






Discussions in the following sections are composed of (a) the importance of the SOC stock, (b) major issues regarding data on SOC stocks and their suitability to monitor land and soil degradation, and (c) the relation of the SOC stock to the SDGs and its suitability as indicator to monitor progress towards achieving them. Finally, strategies will be discussed how to enhance the recognition of SOC in policy interventions and in achieving the SDGs, especially those with reference to food, health, water, climate, and land management.

2 | THE SOC STOCK, SOIL-DERIVED ECOSYSTEM SERVICES, AND SOIL DEGRADATION THREATS

The literature abounds for studies on soil and ESs with the majority of those focusing on provisioning and regulating ESs, and most research conducted in Europe (Adhikari & Hartemink, 2016). Soil ESs can be defined as the benefits people obtain from soils (Dominati, Patterson, & Mackay, 2010); those have significant economic value (Jónsson & Davíðsdóttir, 2016) and are also important to nature conservancy. The SOC stock is central for soil health, fertility, quality, and productivity. The SOC stock also supports soil-based ESs such as the supporting ES of nutrient cycling; the provisioning ES of food, fresh water, wood, and fiber; and the regulating service of flood control and the attenuation of water quantity (Rawlins, Harris, Price, & Bartlett, 2015). Thus, increases in SOC stocks potentially improve soil health, reduce soil erosion, energize soil biota, enhance soil storage functions, promote filtering and transformation of pollutants, and enhance sequestration of carbon dioxide (CO₂; Table 1).

Private, common, and public goods may all benefit from increases in SOC stocks. 'Global goods' or 'global commons' refer to resources beyond national sovereignty (Boer, Ginzky, & Heuser, 2017). Examples are the atmosphere or the high seas. Public goods are enjoyed in common as the consumption of them by one person leads to no subtractions from any other person's consumption of public goods (Samuelson, 1954), a property known as nonrivalry. Further, it is not possible to exclude somebody from consuming a public good, that is, the nonexcludability property of pure public goods. Environmental goods are common examples for public goods. In contrast to the public

TABLE 1 Increased soil organic carbon stocks and their effects on soil characteristics and associated benefits for private, common, and public goods

| Soil characteristic | Tendency | Private good | Common good | Public good |
|--|---|--------------|-------------|-------------|
| Soil health |  | ++ | ++ | 0 |
| Erosion risk |  | ++ | ++ | ++ |
| Soil biota |  | + | + | + |
| Storage, filtering, and transformation |  | + | ++ | ++ |
| Carbon dioxide sequestration |  | 0 | 0 | ++ |

good, the private good is excludable and rivalrous. For example, an owner of the private good food can exclude others from using it, and once the food has been consumed, it cannot be used again. Otherwise, common goods are rivalrous but nonexcludable resources as, for example, harvesting fish stocks in the deep ocean is difficult to restrict but those stocks are finite and diminishing. The increase in SOC stock benefits both private and public interests, and both common and public goods must be financed by common and public means ('public money for public goods'). For example, payments for ESs may be used to increase the SOC stock. However, there is no common framework for economic valuation the ESs of soils (Robinson et al., 2012). The economic value of soil's ESs remains also unnoticed (Kumar, 2010), but placing a monetary value on ESs is the basis of incentive mechanisms to convince land managers to maintain or provide the ES of SOC storage at levels beneficial to society (Swinton, Lupi, Robertson, & Hamilton, 2007).

With the exception of the role of SOC sequestration for producing food and for climate change adaptation and mitigation (FAO, 2017a), there is no clear relationship between the SOC stock, the levels of ESs, and soil health functions attributable to it (Kibblewhite, Chambers, & Goulding, 2016; <http://soilhealthinstitute.org/wp-content/uploads/2017/05/Action-Plan.pdf>). Specifically, data from field experiments showing direct relationship between SOC stocks and crop yields are scanty (Lal, 2006, 2010b; Oldfield, Wood, Palm, & Bradford, 2015). A broad assessment of European long-term field studies showed that the soil improving effect of soil organic matter (SOM) led to a yield increase of up to 10% for soils of sandy texture and up to 6% for loamy soils (Körschens et al., 2013). Further, a 1% increase in SOM of China's croplands may result in a 0.43-Mg ha⁻¹ increase in cereal productivity (Pan, Smith, & Pan, 2009). Otherwise, inputs of fertilizers and other amendments interfere with the detection of beneficial effects of SOC. For example, in soils without severe nutrient limitations (because of inputs of fertilizers), SOC contents higher than 1% may be adequate to maintain yields (Aune & Lal, 1997; Oelofse et al., 2015).

Some increases in crop yields due to increases in SOC stocks in the root zone have been reported for resource-based agriculture in developing countries (Lal, 2006, 2010). However, it is unclear which

properties of SOC contribute to improving yields; for example, are higher yields at higher SOC levels caused by increased nutrient availability due to increased mineralization (Johnston, Poulton, & Coleman, 2009), or do the soil physical properties improved by SOC result in higher yields (Schjøning et al., 2012)? 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). Further, in low-input systems, strong decline in agronomic productivity may occur in soils with strongly depleted SOC reserves (Lal, 2006, 2010). However, 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). Minimum, threshold, or critical levels of between 1% and 5.1% SOM for crop production have been specified (Hijbeek et al., 2017). In general, levels are lower for soils of tropical regions (1.1% SOC; Aune & Lal, 1997) than those of temperate climates (2% SOC or about 3.4% SOM; Loveland & Webb, 2003).

Similar to affecting soil ESs, SOC losses may enhance soil degradation threats. Global key threats to soils are by (a) erosion, (b) loss of SOM, (c) nutrient imbalance, (d) salinization and sodification, (e) sealing/land take, (f) soil biodiversity loss, (g) contamination, (h) acidification, (i) compaction, and (j) waterlogging (Karlen & Rice, 2015). The European Commission (2002) also identified landslides and flooding among key threats to soil. For the United Kingdom and similar regions, Gregory et al. (2015) summarized several reports indicating that decreases in aggregate stability by 10–40% can occur when the SOM content decreases by 1% (Table 2). Soil erosion, that is, the most significant threat to soils (FAO & ITPS, 2015), may also be aggravated by a loss of SOM (Skidmore & Woodruff, 1968). For example, decreases in SOM content from 4% to 2% may result in a 50% increase of the predicted soil loss by water erosion (Stolte et al., 2016). Further, decreases in SOM content from 5% to 1% may result in increases in the fraction prone to erosion by wind (i.e., the fraction of the uppermost 2.5 cm of soil that can potentially be transported by wind) from 0.55 to 0.65. Decreases in SOM content can also lead to poor soil tilt through undesirable domination of coarser clods, a decrease in friability index by 0.3 unit by 1% decreases in SOM content, dispersion of clay, and reductions in porosity (Gregory et al.,

TABLE 2 Proxies for soil degradation and soil threats affected by changes in soil organic matter (SOM) contents

| Soil property/threat | Effect | Decrease in SOM content |
|---------------------------------------|----------------------------|-------------------------|
| Aggregate stability | 10–40% decrease | 1% |
| Predicted soil loss by water erosion | 50% increase | From 4% to 2% |
| Wind erodible fraction | Increase from 0.55 to 0.65 | From 5% to 1% |
| Friability index | Decrease by 0.3 unit | 1% |
| (Macro)porosity | 1–2% loss | 1% |
| Water retention | Up to 10% reduction | From 7% to 3% |
| Soil biological function/biodiversity | Not fully understood | ? |
| Microbial biomass | 90% decrease | From 5% to 2% |

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

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 can result in reduced hydraulic conductivity and a lower aeration status of the soil, which would have an adverse impact on vegetation growth. The decline in SOM content from 7% to 3% can result in the reduction of soil water retention by 10%. On the contrary, increases in available water capacity with those in SOC content are very small (Minansy & McBratney, 2018a). In this meta-analysis, three quarters of the studies reported values of 0.7 to 2 mm H₂O 100 mm per soil due to an increase of 10 g SOC kg⁻¹ soil. The limited effects of increases in SOC contents on increases in available water capacity were also indicated based on data from a study of 17 long-term field experiments (Eden, Gerke, & Houot, 2017; Minansy & McBratney, 2018b). Thus, effects of losses in SOC on soil water storage and related impacts on hydrological cycles may be less than thought previously (Minansy & McBratney, 2018a).

Arable soils low in SOM are prone to slaking upon wetting due to the instability of aggregates, leading to a reduction in water infiltration and increase in surface runoff (Pieri, 1992). However, the interconnected processes of decline in SOM and structural soil degradation are often hard to differentiate (Gregory et al., 2015). Loosing SOM can also reduce the exchange capacity for the important plant nutrients N, P, and S. Decline in SOM content from 5% to 2% over 60 years at Rothamsted was associated with a decrease in microbial biomass by 90%, but microbial diversity or substrate utilization were not affected. However, the effects of SOM decline on biodiversity are not fully understood. Losses of SOM can also release harmful elements because SOM contributes to buffering the effects of toxic substances in soil (Gregory et al., 2015). In conclusion, a decline in SOM or SOC stock, which is a soil degradation threat itself, may particularly contribute to increases in soil erosion, contamination, compaction, landslides, and desertification and aggravate the climate change risks.

3 | AVAILABILITY OF SOC STOCK DATA

3.1 | Measuring SOC stock

Analyzing SOC stocks by one method that can be applied on a wide range of diverse situations is a major challenge but not yet possible (Johns, Angove, & Wilkens, 2015; Lorenz & Lal, 2016). The SOC concentration can be measured either in a laboratory (ex situ) or by regular measurements using nondestructive, in situ field methods, but there is no standardized approach (Olson, Al-Kaisi, Lal, & Lowery, 2014). Methods and standard approaches also do not exist (a) for efficient soil sampling at the scale of the farm or landscape (Stockmann et al., 2013), (b) for extrapolating SOC data from several sampling sites within an area to a desired area (de Groot et al., 2016), (c) for credible accounting for the variability of rock fragment content, soil bulk density (ρ_b), and SOC concentration on a small scale (Jandl et al., 2014), and (d) on the soil depth to be considered (Lal, Kimble, Follett, & Stewart, 2000). Further, in calcareous or alkaline soils, those that received liming amendments in the past, and those developed from calciferous parent rocks, the total soil carbon concentration must be

corrected for soil inorganic carbon concentration but no standard approach exists (Loeppert & Suarez, 1996; Stetson & Osborne, 2015; Tabatabai & Bremner, 1970). Measurements of ρ_b , depth increments for soil sampling, and percentages of rock and root fragments are also needed for the calculation of the SOC stock (Mg C ha⁻¹). Instead of applying a constant value, determining the rock fragment density (ρ_{RF}) is recommended when the volumes of rock fragments dominate the total volume of the sample to reduce potential measurement errors (Mehler, Schöning, & Berli, 2014). Specifically, the accurate assessment of soil volume and ρ_b are as important as those of SOC concentration of the bulk soil (Jandl et al., 2014). Poeplau, Vos, and Don (2017) proposed a method to overcome the widespread overestimation of SOC stocks due to erroneous determinations of ρ_b and stone content. Further, in the absence of information on soil erosion or deposition, and in cases where land use and management result in changes in ρ_b , assessments of SOC stock dynamics also require the determination of the SOC stock based on equivalent soil mass, rather than for fixed sampling depths or genetic horizons (Ellert & Bettany, 1995; Mikha, Benjamin, Halvorson, & Nielsen, 2013). Measurements of relevant parameters approximately every 10 years were recommended by Schrumppf, Schulze, Kaiser, and Schumacher (2011) for a credible assessment of SOC stock dynamics. Ideally, those parameters should be determined every 20 years for a systematic proof of change in SOC stocks (Körschens, 2010). To facilitate effective policy developments, the accepted and precise methods have to be harmonized. Globally applicable standards and guidelines may also have to be developed to estimate changes in SOC stocks in a more consistent manner at the farm, region, country, and continent scales and to ensure data credibility (Bispo et al., 2017).

Direct measurements of SOC concentrations ex situ by oxidation methods account for the majority of analyses but have several limitations and interferences that must be addressed for accurate SOC measurements (Johns et al., 2015). Examples for ex situ methods are the previously widely used Walkley-Black method (Walkley & Black, 1934) and the weight loss-on-ignition dry oxidation method (Johns et al., 2015). Currently, the most reliable standard or reference method is the automated dry combustion technique (Loeppert & Suarez, 1996; Nelson & Sommers, 1996). In situ analytical methods may depend on color (visible reflectance), spectroscopic measurements of soils in the field, or by remote sensing (Johns et al., 2015). The spectroscopic methods include soil visible, near- and mid-infrared reflectance spectroscopy (McCarty, Reeves, Reeves, Follett, & Kimble, 2002), laser-induced breakdown spectroscopy (Ebinger et al., 2003), and inelastic neutron scattering (Wielopolski et al., 2008). Recently, a proximal sensing method was described, which combines a self-acting sensing system for soil cores with statistical analyses and modeling to characterize SOC stocks at small depth increments and across land surfaces (Viscarra Rossel, Lobsey, Sharman, Flick, & McLachlan, 2017). However, there are numerous uncertainties about their general use for in situ measurements of SOC stock and its dynamics. Further, it is uncertain whether SOC stock changes in soil profiles may ever be assessed based on airborne remote sensing data (Johns et al., 2015).

In lieu of measuring, SOC stock models of different complexity may be used. Many biogeochemical models are compartment models

(Manzoni & Porporato, 2009). These models assume that SOM is transformed following first-order kinetics. The SOM pool is divided into those for organic matter, microbial biomass and crop residues, and other homogenous pools. Each pool is assigned a decomposition rate. Some models also consider decomposer biomass in detail, specifically, its relationship with organic matter and inorganic nutrients (Manzoni & Porporato, 2009). Models also relate microbial diversity to compartments, for example, such as those for functional or taxonomic groups that interact in food webs (Louis, Maron, Viaud, Leterme, & Menasseri-Aubry, 2016). However, many models have not been validated by comparing with empirical datasets, whereas others mainly consider fixed parameters. Among major issues are knowledge gaps in linking functional with taxonomic diversity and in representing processes occurring at smaller scales (Louis et al., 2016). More sophisticated and mathematically complex models do not always result in improved model performance or support more credible interpretation of observed patterns (Manzoni & Porporato, 2009). Also, some processes cannot be simulated with traditional models as the role of soil microorganisms must be clearly addressed such as those related to the priming effect, mortality of soil microorganisms, and dynamics of dissolved organic carbon (P. Smith, Lutfalla, Riley, Torn, & Soussana, 2018). Thus, it is unlikely that any single model will be adequate for all applications (Hillier et al., 2016).

3.2 | Global SOC stock data

Globally harmonized datasets on SOC stocks can be produced and their spatial distribution simulated based on soil maps. The Harmonized World Soil Database is among the most exhaustive, harmonized, and spatially explicit global databases (FAO, International Institute for Applied Systems Analysis, International Soil Reference and Information Centre, Institute of Soil Science Chinese Academy of Sciences, & Joint Research Centre, 2012). It is the latest and most detailed global soil inventory and widely applied as international reference. For the first time, Köchy, Hiederer, and Freibauer (2015) addressed the frequency distribution of SOC stocks within classes of land use, land cover, and C-rich environments based on the Harmonized World Soil Database. Recently, Batjes (2016) compiled a harmonized dataset of SOC stocks to 0- to 0.3-, 0- to 0.5-, 0- to 1-, 0- to 1.5-, and 0- to 2-m depths for the world using a nominal resolution of 30 by 30 arcsec (World Inventory of Soil Emission Potentials WISE30sec). Such information can be used to address food security, land and soil degradation, water resources, and climate change (Batjes, 2016). However, international activities are needed to standardize methods used for sampling, calculation, and scaling. The FAO has established a working group for developing a technical manual on SOC management in which methodological aspects will also be covered (FAO, 2017b). Ideally, an archive for soil samples should be included so that soils can be reanalyzed by applying different methods or for interlaboratory comparisons (Köchy et al., 2015). Recently, FAO and ITPS (2017) reported SOC stocks in the top 0.3-m depth for the Global Soil Organic Carbon Map, which is also a process involving more than 100 countries.

3.3 | Regional SOC stock data

The regional coverage of SOC information is incomplete (Jandl et al., 2014). 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 (<http://www.isric.org/data/data-download>). Data for evaluating changes in SOC for Asia are particularly scanty as countries do often not monitor SOC stock and its changes (FAO & ITPS, 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 only available for some regions and nations. However, the suitability of currently available data for monitoring SOC is uncertain. Specifically, revised methodology for sampling and updated information on remote sensing and field properties are needed to enhance the credibility of the data for SOC stocks.

4 | CHANGES IN SOC STOCKS IN RELATION TO LAND AND SOIL DEGRADATION

4.1 | Soil degradation

Soil degradation is a worldwide issue resulting from a range of practices including excessive tillage, unsuitable crop rotations, missing animal grazing control, removal of crop residues, deforestation, mining activities, construction activities, and expansion of urban areas (Karlen & Rice, 2015). Soil degradation reduces soil functions and their ability to support ESs essential for human well-being (Lal, Lorenz, Hüttl, Schneider, & von Braun, 2013; Global Soil Partnership, 2015) and nature conservancy. The supply of soil functions depends on soil properties (Schulte et al., 2015). However, there is no single definition for soil degradation; for example, FAO and ITPS (2015) defined soil degradation as 'the diminishing capacity of the soil to provide ecosystem goods and services as desired by its stakeholders.' Almost universal indicators for soil degradation are erosion and reductions in SOC or SOM stocks (Karlen & Rice, 2015). However, there are no credible estimates of the extent of degraded soils (Oldeman, Hakkeling, & Sombroek, 1991; FAO & ITPS, 2015) and rates of degradation at regional, national, or global scale. For mitigating soil degradation, suitable land uses must be selected, and soil and land use management practices be improved so that the SOC stock increases, soil biology is strengthened, and soil erosion is reduced (Karlen & Rice, 2015). Preventing soil degradation is far more cost-effective than rehabilitating degraded soils, and the cost of inaction is high (Nkonya, Mirzabaev, & von Braun, 2016).

A reduction in the SOC stock may have potentially negative effects on soil-derived ESs and be indicative for soil degradation as a high SOC content improves the process of soil formation (supporting ES) and chemical and physical properties, that is, plant nutrient storage (supporting ES), soil water holding capacity (supporting and regulating ESs), soil aggregation, and sorption of pollutants (regulating ES; P.

Smith et al., 2015). Thus, the SOC stock may be a universal indicator for soil degradation. Specifically, the quantity of SOC may be among the most important soil indicators because of its central role for many soil functions (Stockmann et al., 2015). SOC is also among widely applied soil property measurements, and C itself may be known to the global population. SOC loss, in particular, is an important contributor to soil degradation (Banwart et al., 2015) and to the economic burden because of soil degradation. For example, almost half of the incurred costs for soil degradation in England and Wales has been linked to SOC losses (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 (a) medium negative effects on salinization and on the gene pool (biodiversity) and (b) 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 (a) low negative effects on biomass production, (b) medium negative effects on wind erosion, salinization, and the soil function source of raw materials, and (c) large negative effects on water erosion, gene pool (biodiversity), and the soil function filtering and buffering of nutrients, substances, and water. Otherwise, SOM decline (SOC loss) in European peat soils can also have medium positive effects on biomass production depending on peat management and soil fertility and soil physical properties underneath the original peat layer (Stolte et al., 2016). However, global data on the relation between SOM decline (SOC loss) and soil degradation are scanty.

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 soil properties as proxies for soil degradation and on soil threats are listed in Table 2. Aggregate stability and microbial biomass are potentially most strongly affected by a decline in SOM content, but data of all soil functions, ESs, and soil threats from all global regions are needed for a comprehensive assessment. However, evidence for the relationship between SOC and soil quality, yield, and agronomic productivity based on field experiments is scanty (Loveland & Webb, 2003); that is, there are numerical relationships between SOC and some soil properties but unequivocal evidence of thresholds above or below, which the contribution of SOC increases or decreases is rare. Nevertheless, the level of SOC in a specific soil can potentially influence its capacity to produce food, feed, fiber, and fuel (Franzluibbers, 2010; Lal, 2004, 2013, 2010).

It remains unclear whether SOC loss can be a universal sensitive and responsive indicator for 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, Makarov, Alyabina, & Nachtergaele, 2016). However, for less severe erosion without 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 undegraded baseline and certain soil properties were arbitrarily chosen whereas other properties were omitted (e.g., Islam & Weil, 2000). Further, SOC itself was among the properties for computing the soil deterioration index. Objective assessments may be possible by expressing the impacts of soil degradation in terms of measurable changes in soil properties (Stoorvogel, Bakkenes, ten Brink, & Temme, 2017).

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 may affect cycling of nutrients, retention of pesticides and water, 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). The changes in SOC content have been related to a biological soil quality index (SQI) based on *Collembola* species but not on another biological SQI based on microarthropods (Gardi, Tomaselli, Parisi, Petraglia, & Santini, 2002). Otherwise, the biological quality index computed based on SOC (calculated)/SOC (observed) was sensitive to severe soil degradation processes in volcanic Andisols and Aridisols that were triggered by human activities when laurel (*Laurus nobilis* L.) and pine (*Pinus*) forests were replaced by shrubs (Armas et al., 2007). Thus, not the single indicator SOC but SQI has been proposed to synthesize soil attributes such as SOM content and stock, ρ_b , respiration rate, soil depth, electrical conductivity, and pH to inform on appropriate management or policy interventions based on an enhanced understanding of soil processes (Obade & Lal, 2016). For example, %SOC among other soil indicators has been proposed for agricultural land with regard to long-term natural soil resilience (Schiefer, Lair, & Blum, 2015).

To sum up, it is unlikely that SOC loss alone can reflect the complexity of soil degradation. Soil degradation is the result of the interaction between biophysical, socioeconomic, and political factors, and degradation is site specific by definition and occurs at various scales (Stolte et al., 2016). Nonetheless, SOC is the most critical factor. 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 SQI, a soil degradation index including data on SOC loss among other soil changes may be more suitable for monitoring soil degradation.

4.2 | Land degradation

Similar to soil degradation, there is no commonly accepted definition for 'land degradation.' For example, it has been defined 'as a long-term decline in ecosystem function and productivity' (Bai, Dent, Olsson, & Schaepman, 2008). Sutton, Anderson, Costanza, and Kubiszewski (2016) used the human appropriation of net primary productivity (NPP), that is, the ratio of actual NPP to potential NPP, derived from the distribution of the population and national statistics as a proxy measure for land degradation. Based on the land degradation measure, Sutton et al. estimated that annually US \$6.3 trillion of ESs value were lost globally to degraded ecosystem function. 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, Convention on Biological Diversity, FAO, & Scientific and Technical Advisory Panel of the Global Environment Facility, 2016). The Intergovernmental Platform on Biodiversity and Ecosystem Services 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 is used as national indicator for observing the ES C sequestration change (Karp et al., 2015). Further, land degradation depends on the context in which it occurs and the values of those who are affected by it; that is, degradation may have negative effects on one person but at the same time may be an opportunity for another person (Reed et al., 2013). Thus, it is unclear how a single definition can refer to the conflicting perspectives of individuals and groups who use the land and those who benefit from ESs for those situated far away from the regions where land degradation is happening.

Land degradation may include degradation of the land elements, that is, soils, rocks, rivers, and vegetation. In this regard, Caspari, van Lynden, and Bai (2015) proposed the dynamics of SOC content as a good example for an integrative indicator of land degradation, that is, an indicator able to cover diverse and vital processes at the same time. However, there is not one indicator alone that could act as the ultimate proxy for land degradation. For example, the Land Degradation Neutrality (LDN) project has the goal to monitor the achievement of LDN (Lal, Safriel, & Boer, 2012). Monitoring depends on the assessment of changes in land-based progress indicators. Indicators (metrics) include land cover (land cover change), land productivity (NPP), and C stocks (SOC stocks; Orr et al., 2017). However, measuring against the indicator for SOC content may be problematic because there is no global dataset as discussed previously. Further, for the Global Land Degradation Information System, soil health was assessed primarily by status and changes in SOC but with clear reference to other soil properties including nutrient availability, salinity, and workability (Nachtergaele et al., 2011). Thus, a combination of biophysical and socioeconomic indicators was strongly recommended to cover the land degradation. However, the actual distribution and severity of land degradation do rarely match. Where remote sensing data suggest land productivity increases, this would have to be, therefore, cross-checked for potentially undesirable changes in land use and/or land cover and concomitant decreases in SOC (Caspari et al., 2015).

It is, thus, unclear how SOC changes may affect land degradation processes as SOC losses are among the many drivers of land degradation. Land degradation drivers include, for example, proximate drivers, such as topography, land cover, soil resilience, climate, and management, and also underlying drivers, for example, poverty, decentralization, access to agricultural extension services and commodity markets, and changes in land cover (Turner et al., 2016). Indicators for these types of drivers are related to vegetation cover, administrative borders, population density, soil properties, biodiversity, climatic conditions, land management practices, topography, road density, information access, land tenure, national policies, institutions, population density, and farmer perceptions. Thus, mapping and quantification of degraded lands have not been done based solely on the single indicator SOC change but based on (1) the opinion of

experts; (b) NPP derived from satellite data; (c) simulations using biophysical models; and (d) mapping of abandoned cropland, resulting in significant discrepancies (Gibbs & Salmon, 2015). Although 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.

5 | ADDRESSING SOC IN THE MONITORING FRAMEWORK TOWARDS ACHIEVING THE SDGs

The widespread lack of basic soil data and reliable soil monitoring systems must be addressed in a monitoring framework towards achieving the SDGs. Important gaps exist for credible data collections, particularly for soil and other key environmental metrics (Sustainable Development Solutions Network [SDSN], 2015). As discussed previously, existing global and national datasets on SOC stock can probably not serve as a baseline. Thus, major investments in the capacity to collect and analyze soil data would be required to develop the indicator SOC stock for monitoring progress towards achieving the SDGs nationally and globally. 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. Collecting data every 5 to 10 years and generating credible estimates may be sufficient. Measurements should be repeated at intervals relevant to land use and cover changes, for example, 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, Shao, Gale, & Li, 2014) and land take and soil sealing (Lorenz & Lal, 2017) and should be monitored globally as climate change-induced soil warming may also result in SOC losses (Crowther et al., 2016). Thus, determination of SOC stocks should be repeated at appropriate intervals related to soil types, vegetation cover, probable impacts, and their rates and compared with a baseline and/or previous determinations and measurements (FAO, 2011).

There is no direct link with soils for the majority of the SDGs. However, soils can support the realization of several of the SDGs, that is, those with reference to climate, food, health, land management, and water (Keesstra et al., 2016). Some of the SDGs focus on terrestrial biophysical systems in which soils and, in particular, SOC play a role (Goals 7, 8, 12, 13, and 15; Table 3). Some other SDGs are linked to soils and their functions in the natural environment, for example, Goal 2 'End hunger, achieve food security and improved nutrition and promote sustainable agriculture' (Blum, 2016). Related to land and soil is Goal 6 'Ensure availability and sustainable management of water and sanitation for all.' Previously, changes in SOC stock (content) have been proposed as indicator for sustainable land management with reference to Goals 13 and 15 (Müller et al., 2015). However, no reference to soils is made in the adopted list of targets under Goal 13, but soil management aimed at increasing SOC stocks is important towards achieving this SDG (Keesstra et al., 2016). Also, increases in SOC stocks may contribute to achieving some of the other SDGs as the

TABLE 3 Sustainable Development Goals (SDGs) related to soil organic carbon (i.e., the ecosystem service 'carbon storage and greenhouse gas regulation' and the soil function 'acting as carbon pool'; Keesstra et al., 2016)

| SDG ^a | |
|------------------|--|
| 7 | Ensure access to affordable, reliable, sustainable and modern energy for all |
| 8 | Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all |
| 12 | Ensure sustainable consumption and production patterns |
| 13 | Take urgent action to combat climate change and its impacts |
| 15 | Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss |

^aUNGA (2015).

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 increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality' and Target 15.3 'By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and 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 SDSN proposed using indicators associated with more than one goal and target to assess development towards achieving the SDGs. 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. No established methodology and standards or methodology/standards are currently being developed/tested for Tier III indicators (IAEG-SDG, 2016). Otherwise, the indicator SOC stock may effectively be used to track comprehensive issues and contribute to integrated, system-based approaches to implementation. Nevertheless, the SOC stock was not among the proposed list of indicators (SDSN, 2015). UNCCD et al. (2016) proposed how countries can use a standardized approach to report the SDG Indicator 15.3.1 ('Proportion of land that is degraded over total land area'). This approach focuses on the use of the three subindicators land cover and land cover change, land productivity, and above and below ground C stocks. The quantity of C in the pool soil (i.e., SOM) was also considered. It was concluded that additional work is needed to develop a standard approach and 'good practice guidance' to deduce the subindicators, and contribute to monitoring and reporting capacities at national, regional, and global levels (UNCCD et al., 2016).

Similar to monitoring land and soil degradation within the SDG framework, monitoring SOC stock changes by an independent scientific community is lacking in many European countries following the implementation of mandatory good agricultural and ecological practices directly financially rewarding farmers through the Common Agricultural

Policy (Bouma & Montanarella, 2016). National SOC monitoring systems for agricultural soils, for example, exist in England, France, Germany, Hungary, Scotland, Sweden, Switzerland, and Wales (FAO, 2017a). 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 contribution of soils to ES provision and then to consider soil functions such as those listed by the European Commission (Commission of the European Communities, 2006). The soil function 'acting as carbon pool' contributes to sustainable development among other functions as it contributes to the regulating ESs on which sustainable development depends. The more general regulating ESs include (a) filtering of contaminants and nutrients, (b) storing carbon and regulating greenhouse gases, (c) detoxifying and recycling of wastes, and (d) regulating pests and disease populations. For analyzing the processes involved in realizing the SDGs, Bouma and Montanarella (2016) proposed to apply the DPSIR framework (Van Camp et al., 2004). Here, D refers to land use change drivers, P refers to pressures on the land, S refers to the state of the land, I refers to the impact, and R indicates responses for mitigating soil threats. The present state of the land S is not only determined by soil factors but can also be defined by the ESs it provides through soil functions. Future developments are of a particular interest (Bouma & Montanarella, 2016). For example, the BonaRes initiative in Germany (www.bonares.de) aims at evaluating the effects of drivers on soil functions on the basis of the DPSIR framework (Vogel et al., 2018).

Cross-cutting issues may be monitored by combining Global Monitoring Indicators with Complementary National Indicators (SDSN, 2015). The indicator SOC stock may contribute to monitoring progress regarding some important SDG priorities, that is, (a) climate change adaptation and mitigation, (b) food security and nutrition, and (c) sustainable use of land, 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 (tCO₂e),' which itself is part of SDG 13. Further, SOC stock may also be part of the Complementary National Indicator 'GHG emissions intensity of areas under forest management (GtCO₂e 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)' (Lobell, Cassman, & Field, 2009), 'Nitrogen-use efficiency in food systems,' and not yet developed indicator 'Crop water productivity (Mg of harvested product per unit irrigation water).' These indicators are linked to the cross-cutting hunger/nutrition goal. Further, Global Monitoring Indicators to whom 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.)' and be part of the Global Monitoring Indicators (a) 'Nitrogen use efficiency in food systems' linking to the cross-cutting issue effects of land under agricultural use, (b) 'Crop water productivity' linking to impacts of agriculture on other ecosystems, (c) 'Net GHG emissions in the AFOLU sector' linking to GHG emissions from land, and (d) 'Annual change

in degraded or desertified arable land' linking to land degradation including desertification. The SOC stock may also relate in part to sustainable use of land, forests, and other terrestrial ecosystems by the Complementary National Indicator 'GHG emissions intensity of areas under forest management' (SDSN, 2015).

Previously, SDG indicators have been assessed to provide information on indicator and data availability at that time, highlighting where information was available and where it was scanty (SDSN, 2015). Assessments were based on a small number of countries, particularly, high-income countries. Indicators were ranked from A to C or were listed as 'to be determined.' The SOC stock was previously listed as 'to be determined' based on the aforementioned data gaps for many regions and nations. In a recommended tiered indicator system with three tiers, the SOC stock may be classified to fall under Tier 3, that is, an indicator in need for development of international concepts, definitions, and standards (SDSN, 2015).

In conclusion, the design of a global monitoring framework on SOC stock changes within the SDG monitoring and review framework will depend on a better understanding of the spatial distribution of the SOC stocks and any 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 world's soil resources that may be compared in the future based on periodical assessments and reports on the status of soils at regional, national, and global levels (FAO & ITPS, 2015). This assessment may be particularly relevant for the SDGs. However, great differences were reported in data quality at national level. Specifically, reliable assessments do take place for the major land uses forests and arable lands in most EU countries, the United States and Canada, China, Australia, and New Zealand. However, data and results are not generally 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 but improving, 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 develop national-level goals to achieve a stable or positive SOC balance (Montanarella et al., 2016).

6 | CONCLUDING REMARKS

Focusing on the SOC stock while addressing both land and soil degradation and the realization of soil-related SDGs is challenging based on the numerous issues discussed in the previous sections. Some steps to improve the recognition of the importance of the SOC stock in this regard are given below.

6.1 | SOC stock and ESs

The SOC stock can be a relevant and feasible indicator within a monitoring system on soil and land degradation because the SOC stock is (a) related to many important soil functions, (b) among the indicators for soil health, and (c) at the nexus of 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. Most importantly, the relationship between the dynamic of the SOC stock and land and soil degradation is not well established. Thus, the understanding about this relationship must be improved to consider SOC stocks, soil functions, and soil-derived ESs in the SDG framework. Specifically, better data on land and soil degradation must be collected by universally agreed, harmonized approaches (Caspari et al., 2015). Standardized methods at the global level and techniques that start at the local level should be combined to enable the adaptation of global 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). Central to many ESs provided by soils is the SOC stock, a key indicator for biological, chemical, and physical quality of soils. Thus, SOC has been suggested as a significant universal indicator for soil degradation, but data for the relation between changes in SOC and soil degradation for global regions are scanty. Further, SOC may not only indicate land degradation but itself may also 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 meaningful and applicable indicator for monitoring land and soil degradation.

6.2 | Assessing the SOC stock

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, and so forth are recorded to allow for global harmonization (Caspari et al., 2015). However, SOC processes at scales from the biosphere to biomes are not entirely known (O'Rourke, Angers, Holden, & McBratney, 2015), contributing to the incomplete understanding on the relation between SOC changes and land and soil degradation. Better understanding exists for SOC processes at smaller scales. At the landscape scale, for example, the influence of processes has the strongest interaction and is exposed to the strongest modification through soil and land use management. Policies at regional or national scale tend to focus on the landscape scale without properly considering the larger scale factors controlling SOC or the impacts of SOC policies at the smaller SOC scales. Thus, a framework for integration across scales is needed to improve the management of SOC (O'Rourke et al., 2015) and relate changes in SOC stocks to land and soil degradation.

6.3 | SOC stock in the subsoil

Another important issue that must be addressed is the importance of the SOC stock at deeper soil depths for land and soil degradation (Lorenz & Lal, 2005). For example, the LDN project proposed to measure SOC content to 30-cm depth (J. Smith, 2015). However, although 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 soil management practices (Meersmans et al., 2009). Thus, Wiesmeier et al. (2013) proposed that subsoil SOC stocks must be included in agroecosystem studies. Further, there is strong evidence that in temperate regions, subsoils contribute to more than two thirds of nitrogen, potassium, and phosphorus nutrition of plants, particularly under dry or nutrient-depleted topsoil (Kautz et al., 2013). Plant nutrition depends on SOM, and thus, changes in SOM or SOC stocks at deeper depths potentially 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.

6.4 | Translating science into action

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 the composite indicator to draw attention to the important policy issue land and soil degradation, easily communicated to and understood by a broader audience (Lehtonen, Sébastien, & Bauler, 2016). Classification as composite indicator for land and soil degradation is also under discussion as causal relationships between SOC stocks and land and soil degradation cannot be easily identified and cannot support policy decisions. Rather, the SOC stock should be classified as a performance indicator placing the observations of SOC stock changes on normative scales. Thus, progress towards a norm (i.e., a land and soil degradation reduction target) can be monitored. Performance indicators are generally targeted to enhance accountability. They are also suitable to serve other functions regarding policy evaluations, that is, learning and policy improvement (Lehtonen et al., 2016). However, knowledge is scanty on assessing performance, supporting policy, functioning of early warning signs, fostering political advocacy, control and accountability, transparency, and enhancing the quality of decisions. Among poorly met policy evaluation functions attributed to the performance indicator SOC stock are recommendations for policy making and analysis, enhancement of government effectiveness, target and standard setting, support for integrated action, and zooming in on policy discussion (Lehtonen et al., 2016). Thus, the SOC stock can currently not serve as a clear unique 'signal' supporting policy decisions for acting on and managing of land and soil degradation. Whether the performance indicator SOC stock is suitable to strengthen communication by reducing lack of clarity with regard to land and soil degradation needs, therefore, additional research.

6.5 | Communication and outreach

Nevertheless, the SOC stock plays a conceptual role as indicator for land and soil degradation by fostering the input of information, ideas, and perspectives into realms where decisions on land and soil degradation and on SDGs are made (Lehtonen et al., 2016). This may be

achieved through (a) public dialogue, (b) background information, and (c) cocreation of knowledge. The indicator SOC stock may also play a political role with regard to land and soil degradation when policy makers influence agenda setting and problem definition, highlighting overlooked issues, or (de)stabilize and (de)legitimize predominant frameworks of knowledge and actors. The enhancement of the political role of the SOC stock as indicator for land and soil degradation includes also approaches to strengthen the legality of decision making and support, in particular, for sustainable development and the SDG framework. A broader, indirect role of the indicator SOC stock may be to serve as boundary object, that is, by combining facts and simulations with collective reasoning and speculation (Lehtonen et al., 2016). Thus, within the SDG framework, science, policy, and society may be connected by the boundary object SOC stock as indicator for land and soil degradation. In summary, the indicator SOC stock can open up policy discourses and perspectives on land and soil degradation by addressing lack of clarity, compromises, and less well-covered topics in policy making. The SOC stock can act as boundary object in governance, through mediating between the social worlds (Lehtonen et al., 2016). More often than influencing policy on land and soil degradation directly, the indicator SOC stock can interact with indirect pathways. The SOC stock may particularly indicate hotspots of land and soil degradation.

The following recommendations are made:

1. The central role of the SOC stock for soil health should be used to identify land and soil degradation hotspots among other indicator soil properties.
2. Research is needed to enhance the knowledge on the importance of SOC stock changes for land and soil degradation and for achieving the SDGs with reference to food, health, water, climate, and land management.
3. Soil degradation should be assessed by a composite soil degradation index including data on SOC stock changes among other soil properties.
4. Land degradation should be assessed by a composite land degradation index including data on SOC stock changes among other data for soil properties, land use cover, and land productivity.
5. The SOC stock in the subsoil and those of urban areas should be determined and its importance for soil-based ESs assessed.
6. To increase the acceptance of the indicator SOC stock, the knowledge base on processes affecting SOC stocks and their relation to land and soil degradation must be strengthened, and routine, harmonized, and comparable approaches for systematic SOC stock data collections must be established.

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